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Augmented Shock Wave Severance of Materials

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Abstract

This paper describes a new approach for severing or weakening a variety of materials. The technique employs embedding explosive cords into parallel grooves that are cut into a surface of a material. The cords are initiated simultaneously to produce shock waves that progress toward the centerline between the cords and the lower surface of the material. Intersecting incident and reflected waves augment at the centerline to fail or weaken the material in tension. No harmful debris is produced on the opposite side of the material from the explosive cords. The primary focus of the effort described in this paper was to fracture the F-16 aircraft trilaminate canopy. Also, complete severance was achieved in 2024-T4 aluminum plate stock. Possible applications are through-canopy egress and crew module severance from military aircraft and separation of rocket vehicle stages and payloads. This approach offers important advantages over explosive methods currently in use.

Introduction

A number of challenges exist in severing materials in aerospace applications. Canopy requirements for advanced aircraft have seriously impacted the capabilities of emergency crew egress, under the limitations of state-of-the-art canopy jettison and through-canopy approaches. Protection against bird strikes and the need for flat, angular surfaces for radar avoidance has driven designers to use stronger materials and greater thicknesses. As canopies get heavy, the 0.3-second time limit for jettison is exceeded, even with increased thrust from piston/cylinder mechanisms and solid rocket motors. Furthermore, the size of piston/cylinder mechanisms and solid rocket motors exceeds allowable physical envelopes within the aircraft. With an increase in rocket motor thrust, downwash is approaching the limits of human tolerance. Through-canopy ejection is currently accomplished with internally mounted explosive cords (which pepper crewmembers with high-velocity debris) in material thicknesses that are half those being considered for advanced aircraft (0.3 versus 0.6 inch). A fracturing method that would allow through-canopy ejection would eliminate ejection delays and simplify canopy system interfaces to the aircraft. The most efficient state-of-the-art severance approaches for metals, as described in[1], use flexible, linear, shaped charge (FLSC). FLSC, a chevron cross section explosive cord, is mounted within a bracket to a surface to be cut. These assemblies are complicated, add weight to flight systems, and are subject to damage during assembly and maintenance. A simplified system is needed to reduce or eliminate these disadvantages.

The augmented shock wave fracture/severance mechanism, first described in[2], is shown in Fig. 1. The two externally embedded mild detonating cords are initiated simultaneously to induce explosive shock waves that propagate into the material and are reflected off the inboard surface. The shock waves augment at the centerline between the cords within the material. As these waves pass each other a strain rarefaction zone is created, which causes the material to fail in tension. This fracture mechanism was successfully applied in the explosive-fracturing of 0.75-inch thick stretched acrylic and 0.5 and 0.9-inch commercial grade polycarbonate in the reference study. This study also revealed that the properties and, consequently, the fracturing characteristics of these two materials were considerably different. The stretched acrylic fractures in strata (parallel to the surfaces) on impact from the explosive input, while the polycarbonate is much tougher and fractures perpendicularly to the surface.

The through-canopy approach envisioned for this investigation is shown in Fig. 2. This F-16 aircraft canopy, the thickest, strongest, operational canopy in existence, has external grooves to embed explosive cords. The concept is to produce predetermined fracture lines over the crewmember's position to weaken the canopy, but leave it intact against air loads. On being struck by the headrest of

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*Senior Pyrotechnic Engineer, Associate Fellow, AIAA the ejecting seat, the canopy would split on the centerline, forward and aft fracture lines, and allow the newly created panels to petal open on hinge lines at the sills.

The metal severance approach envisioned for this investigation was to fracture strips of aluminum plate. Possible applications would be for aircraft capsule separation, as described in[1], or, when rolled into cylinders, for the separation of rocket stages.

The objectives of this effort are twofold:

1. Primarily, to develop and demonstrate a canopy fracture approach to allow through-canopy ejection.
2. Secondarily, to develop and demonstrate a simplified approach for metal severance.

Apparatus

The apparatus used in this investigation were the explosive materials, aircraft canopy materials, the aluminum, and the test fixtures. For all tests, the explosive cord was embedded by cutting grooves with hemispherical end mills (the diameter of the explosive cord) and potting the cord into place with room-temperature vulcanizing silicone compound (RTV, Dow Corning 3145), assuring that a thin film of RTV was on the bottom of the groove. The groove containing the explosive cord was filled flush with the surface. The grooves cut into the F-16 canopy were accomplished by a hand-held router with a 6-inch diameter base. Reference surfaces to maintain the router perpendicularity on the surface of the compound curvature were achieved by bonding hard rubber strips on each side of the groove. The router was thus able to contact the same continuous line on each strip through multiple passes of the cutting operation.

Explosive Materials

The explosive materials used in this study were mild detonating cord and Dupont Detasheet. Mild detonating cord is cylindrical in cross section, like resin-core solder, with explosive material as the core. The sheath material for this study was lead. The explosive quantities are small, measured in grains/foot (15.4 grains per gram). These cords propagate at velocities of 25,000 feet/second, producing a several-microsecond impulse at pressures of millions of pounds per square inch. The explosive materials used were cyclotetramethylenetetranitramine (HMX) and pentaerythritoltetranitrate (PETN). The following are the cords used in this study and their respective diameters:

7.65 grains/foot HMX, 0.100 inch diameter
10.0 grains/foot PETN, 0.090 inch diameter
15.0 grains/foot HMX, 0.120 inch diameter

These two explosive materials have approximately the same output performance per grain, as defined in[3]. They were used in this study because of their availability. Actual aircraft applications should use hexanitrostilbene (HNS), due to its greater high-temperature stability.

The Dupont Detasheet, which contains 65% PETN with a rubber filler, is easily molded for use in initiating the explosive cords at the corners of the fracture patterns. For these experiments, the Detasheet was pressed by hand into 0.3-inch diameter cavities machined at the corners. The explosive cord centerlines were angled together from the parallel spacing into the corner points. Thus, once initiated at any corner, the detonation fronts within the cords travel exactly side by side to the next corner point, which then initiates the next lengths of cords. Flight applications should use HNS, installed within sealed steel cups, at the corners.

Transparency materials

The materials evaluated were F-16 aircraft canopies and flat polycarbonate stock. The F-16 canopy is a trilaminate. The material thicknesses gradually decrease from the sill to the crown. The material thicknesses at the sill were:

Acrylic	0.145
Polyurethane	0.050
Polycarbonate	<u>0.540</u>
Total	0.735 inch

The material thicknesses at the crown were:

Acrylic	0.095
Polyurethane	0.050
Polycarbonate	<u>0.430</u>
Total	0.575 inch

Panels, measuring 6 × 6 and 18 × 18 inches, were cut from full canopies for use in evaluating functional variables. The approximate strength of the trilaminate, as determined by dogbone pull tests, was 5,000 pounds/inch width of material, or 10,000 psi structural strength.

The 0.875 × 6 × 6-inch polycarbonate samples were military grade stock.

Aluminum

Aluminum stock, 2024-T351 alloy and conditioning, was from commercial mill runs. Thicknesses tested were 1/4 and 3/16 inch.

Test fixtures

Figure 3 shows the approach used for testing 6 × 6-inch panels. Four 1/8 × 1 × 6-inch aluminum plates were clamped along two sides. Test firings of the 18 × 18-inch "mini-panels" were conducted by placing the panels on a flat surface, supporting the panels along two edges. Cradles were constructed for pushing out the full canopy and mini-panels to evaluate their residual strengths, following the explosive inputs. A 9-inch width mockup of a seat headrest was fabricated and used to push against the full canopy. A second headrest mockup fixture, shown in Fig. 4, was created for the evaluation of the mini-panels. A 2-inch, centerline spike with a tapered wedge was fabricated to split open the center fracture line, as the head rest advanced into the canopy. Also shown in Fig. 4 is the mini-panel test cradle, which supported the panel around the entire periphery. The full canopy cradle provided support at two full-width bearing lines at the aft edge and just behind the major break in the canopy profile.

Experimental Procedures

The approach for this effort was subdivided into the evaluation of each material.

F-16 canopy material

The initial explosive fracturing experiments used 6 × 6-inch panels, then a full-scale canopy, and finally 18 × 18-inch mini-panels.

The evaluation of explosive fracture variables began with the 6 × 6-inch panels. The 10 grains/foot explosive cord produced an acceptable input level. Cord depth and spacing variables were evaluated by:

1. Cutting a single, variable-depth groove, increasing from 0.100 to 0.250-inch.
2. Cutting two divergent grooves, increasing the spacing from 0.30 to 1.00 inch between centerlines.
3. Selecting the optimum depth and spacing by conducting parallel groove tests.

Once the depth and spacing were established in the first two tests they were optimized in the third test series.

The groove pattern for the full-scale canopy test configuration is shown in Fig. 2. Following the functional test, an attempt was made to push through the fractured panels with a 5,200-pound weight and a mockup of a seat headrest; the canopy was inverted. The force was applied at the rear of the canopy, where the seat would contact during ejection. The push test did not induce failure at the fracture lines. Following this test, specimens were cut from each length of fracture line and pull tested. Residual strengths were compared to the 5,000 pounds/inch original strength of the canopy material.

Additional testing was conducted on 18 × 18-inch mini-panels to evaluate problems recognized in the full-scale test on fracturing through the corner areas, where the explosive cords intersected. These tests were conducted to make the push tests more manageable for small load-test machines. The mockup headrest was centered in the mini-panel for the push tests. The major emphasis was on intersecting the cords at the corners at 45 to maintain cord spacing. To induce additional fracturing at the corners, "T"-shaped grooves were cut and filled with Detasheet. See Fig. 5. The pushout strengths of the mini-panels were compiled and compared.

0.875 × 6 × 6-inch polycarbonate

Based on the experience gained in the above effort, tests were conducted on 0.875 × 6 × 6-inch polycarbonate specimens. The first test was conducted with the 15 grains/foot explosive cord embedded into the surface. The centerline spacing between the cords was 1.5 inches. A second test was conducted by creating a trilaminate by RTV-bonding 0.125-inch cast acrylic, 0.063-inch polyurethane and the 0.875-inch polycarbonate. Grooves were cut at the same centerline spacing into the acrylic to the top surface of the polyurethane.

Aluminum

The 1/4 and 3/16-inch 2024-T351 aluminum plates were cut into 6 × 8-inch specimens for evaluation. Tapered plate and variable-depth and spacing groove evaluations were conducted to determine optimums. Also, tests were conducted to evaluate metal grain direction; explosive fracture lines were set in parallel and perpendicular to the grain direction.

Results

F-16 canopy

A total of 57 test firings were conducted.

The variable-depth test revealed that the residual strength of material increased as the groove was cut deeper into the polycarbonate, as shown in Fig. 6. The optimum groove depth was through the acrylic to the top of the polyurethane, the left-most point on the curve.

The divergent-groove test and subsequent 6 × 6-inch panel tests provided the optimum spacing between the cords at 0.600 inch. Closer spacing produced inboard spall. Wider spacing left higher residual strengths.

The full-scale canopy test, Fig. 7, revealed excellent fracturing had occurred in each running length between corners. The amount of crazing in the fracture areas was very uniform. The residual tensile strength averaged 460 pounds/inch for all fracture lines, or approximately 9% of the parent strength of the material. However, since no cracks propagated through the corners of the pattern, the residual strength at those points remained high.

The mini-panel test series accomplished a reduction in residual strength at the corners of the fracture pattern, as shown in Fig. 8. Figure 9 shows the results of a typical mini-panel test with explosive cord intersections that were similar to the full-scale canopy. All test specimens were essentially the same, except for number 4, which added the “T” grooves shown in Fig. 7. Considerably more fractures were induced in this specimen across the corner areas, as shown in Fig. 10.

0.875 × 6 × 6-inch polycarbonate

Figure 11 shows the results of tests on the 0.875-inch thickness polycarbonate. Embedding the explosive cord in the specimen on the right induced some augmented shock waves in the center area, and a crack occurred below one explosive cord. The material surrounding the explosive was crushed away, indicating the polycarbonate toughness. The specimen on the left was the fabricated trilaminate test. Total severance was achieved without any indication of crushing at the sites of the explosive cord (the two lines drawn on the surface).

Aluminum

Total severance was achieved in the 1/4-inch plate under the following optimum conditions:

- 10 grains/foot explosive cord
- 0.280-inch spacing between explosive cords
- A third groove (0.090 diameter, 0.050-inch deep) was added on the inboard side centerline
- The grooves were parallel to the metal grain direction for maximum efficiency
- The machined grooves reduced the strength of the plate from 16,000 to 7,200 pounds/inch, prior to testing

Total severance was achieved in the 3/16-inch plate under the following conditions:

- 7.65 grains/foot explosive cord
- Same groove spacing, including third groove
- The machined grooves reduced the strength of the plate from 11,200 to 3,500 pounds/inch, prior to testing

Conclusions

This investigation has confirmed the principle of augmented shock wave fracture and severance of polycarbonate in thickness to 0.875 inch and aluminum, 2024-T351, in thicknesses to 0.250 inch. Demonstrated was the effectiveness of embedding dual, parallel explosive cords in the outer surface of these materials and inducing tensile weakening and total severance of the material through internal incident and reflected shock waves, without producing harmful inboard debris. Variables, such as explosive load and explosive cord spacing, were optimized for each material. Residual strength of the material can be tailored; increasing the cord spacing yielded higher residual strength. In evaluating the F-16 aircraft canopy, the polyurethane layer within the trilaminate enhanced the coupling of explosive pressure impulses into the polycarbonate. This layer is so efficient that it remains intact after the explosive input, and no cratering is induced into the polycarbonate. The explosive cord can thus be embedded only within the outer layer of acrylic, which contributes very little to the strength of the canopy. The potential applications of this fracture/severance principle are in aircraft escape and rocket vehicle staging and payload release. In aircraft escape, this method can fracture materials that are up to three times thicker than current approaches. It is now possible to use polycarbonate canopies for through-canopy ejection. Fracture patterns within canopies can be designed to control the opening and retention of panels as the seat egresses. Also, metal severance for cockpit release, as used in the F-111 aircraft can be simplified. In all applications, the augmented fracture/severance principle provides more rugged, lighter weight, lower-maintenance assemblies over systems of comparable performance.

References

[1] Schimmel, Morry L.: "The F-111 Crew Module: Major Challenge for Thermally Stable Explosives." Presented at the Symposium on Thermally Stable Explosives, U.S. Naval Ordnance Laboratory-White Oak, Silver Spring, Maryland. June 23–25, 1970.

[2] Bement, Laurence J.; Schroeder, James D.; and Schimmel, Morry L.: "Explosive Fracturing of Aircraft Canopy Materials." Presented at the 1992 SAFE Symposium, Las Vegas, NV, November 2–4, 1992.

[3] Bement, Laurence J.: "Monitoring of Explosive/ Pyrotechnic Performance." Presented at the Seventh Symposium on Explosives and Pyrotechnics, Philadelphia, Pennsylvania, September 8–9, 1971.

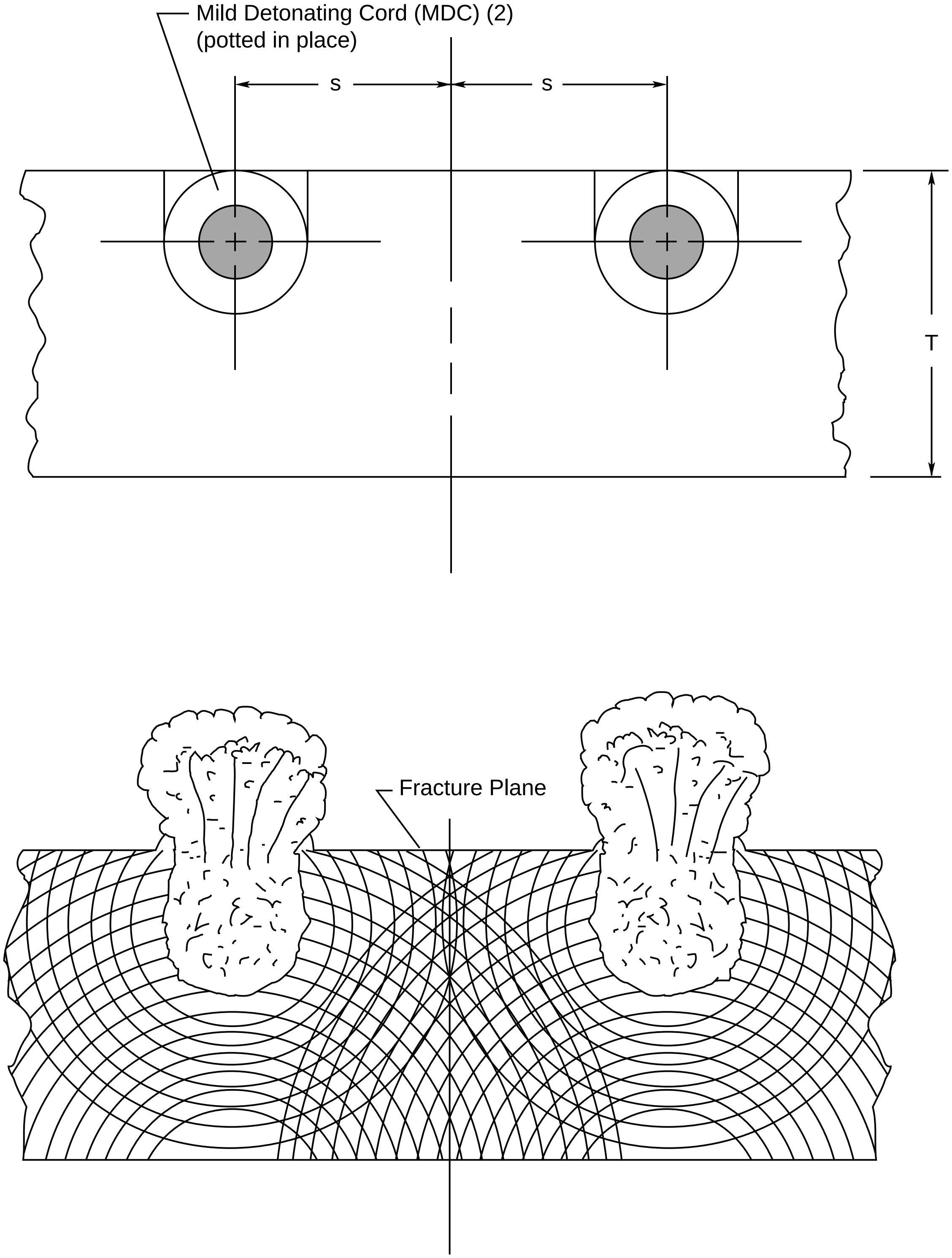

Figure 1. Cross sectional view of augmented shock wave severance principle.

Figure 2. Concept for explosive fracture of F-16 aircraft canopy to allow through-canopy ejection.

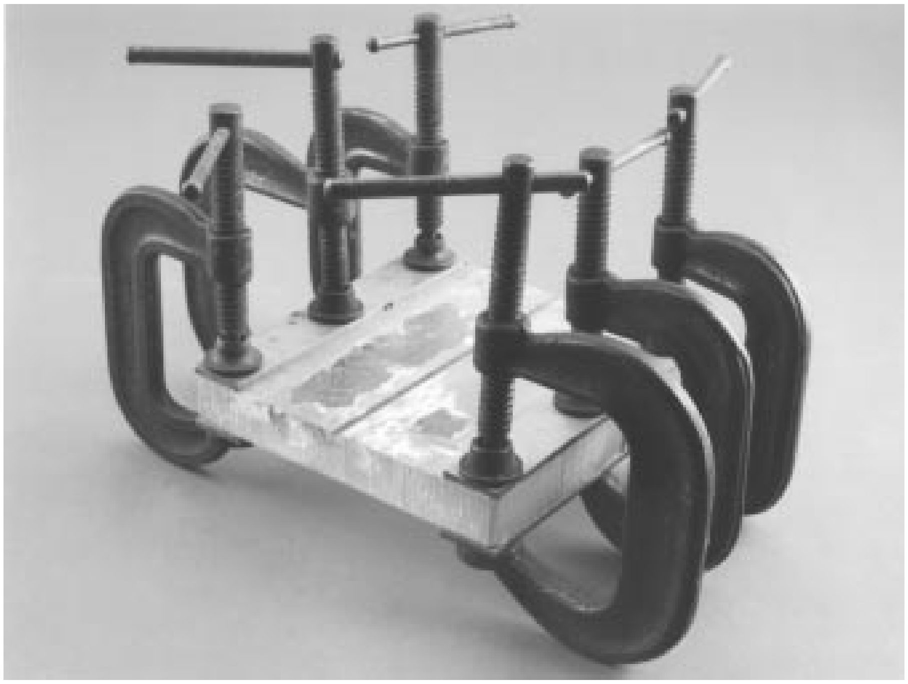

Figure 3. Test setup for explosive fracturing of canopy materials.

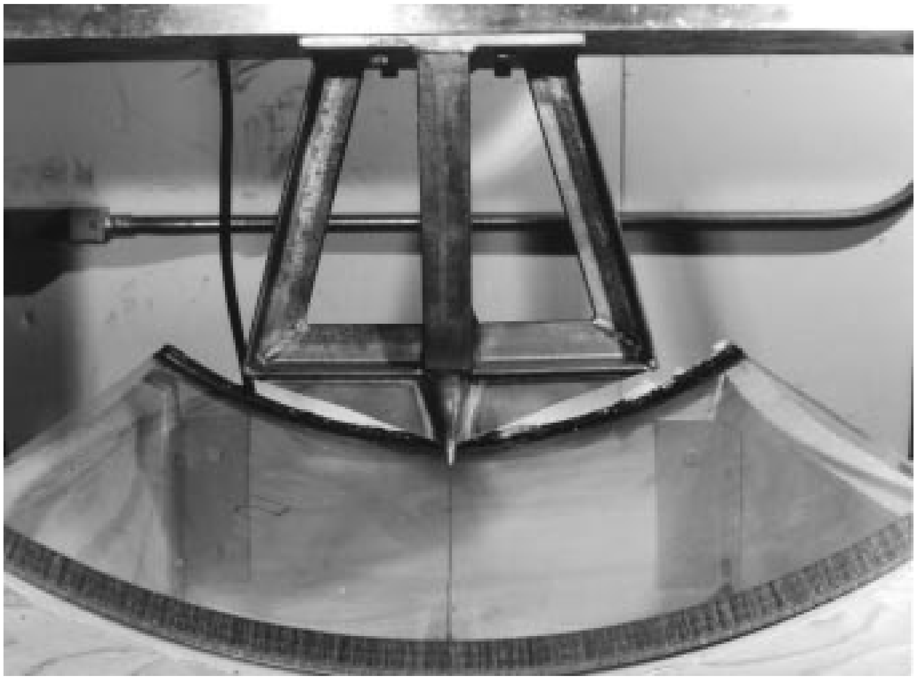

Figure 4. Mockup of seat headrest interface used in push-out tests to split and force open fractured canopy.

Figure 5. View of grooves in mini-panel. The parallel grooves will contain explosive cord. The "T" grooves and circular cavities will contain data sheet.

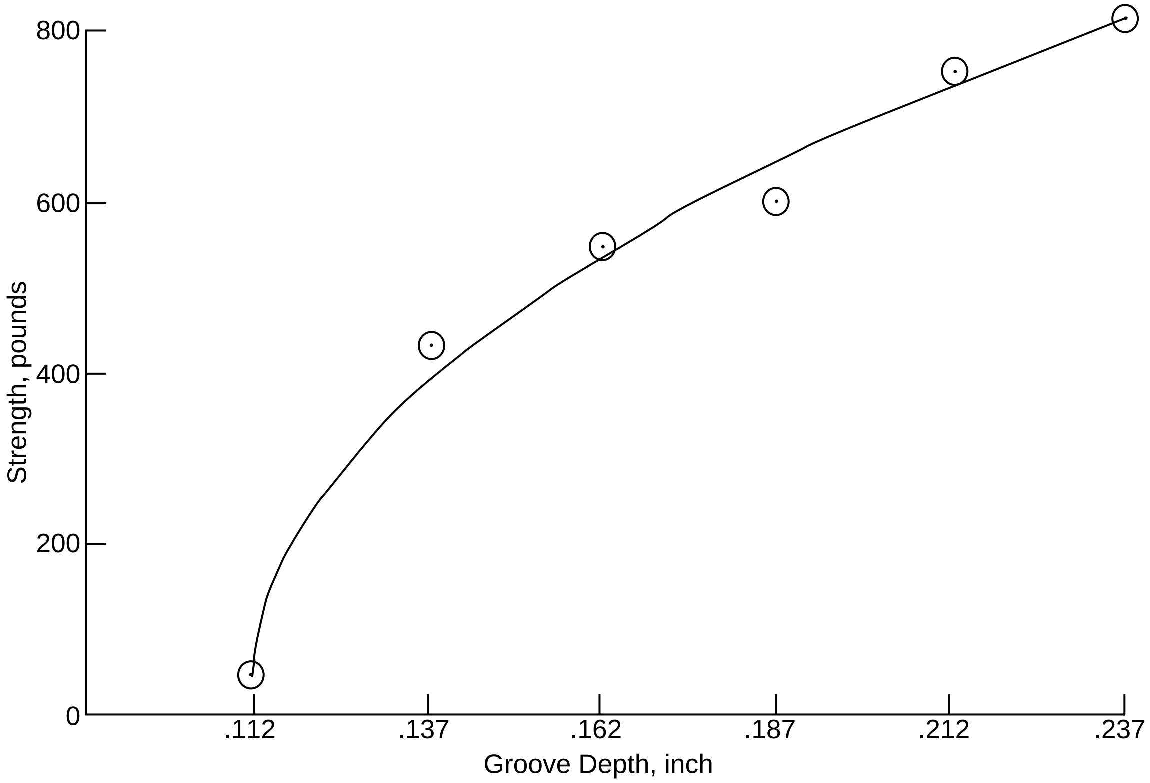

Figure 6. Results of single-cord, variable-depth in F-16 canopy material.

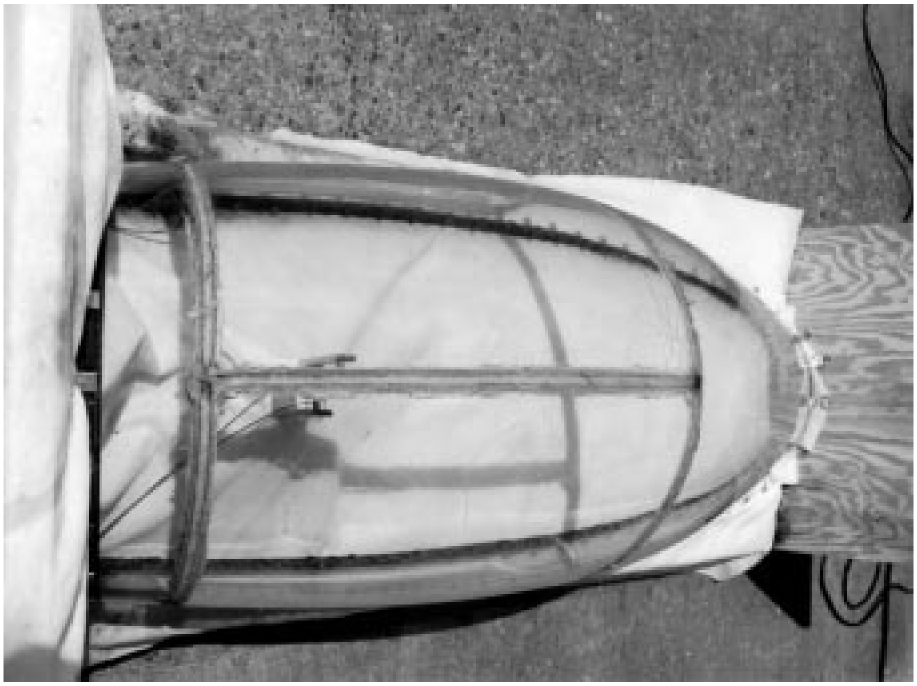

Figure 7. View of explosively fractured areas in F-16 aircraft canopy.

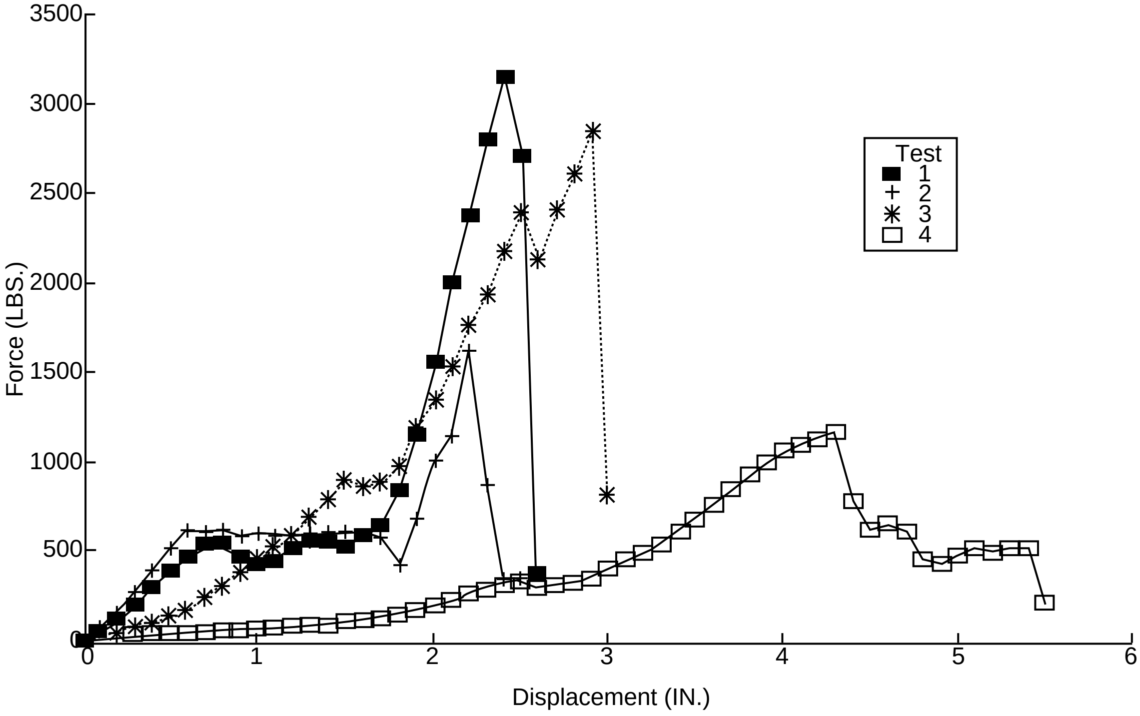

Figure 8. Force versus headrest mockup displacement on mini-panel push-out tests.

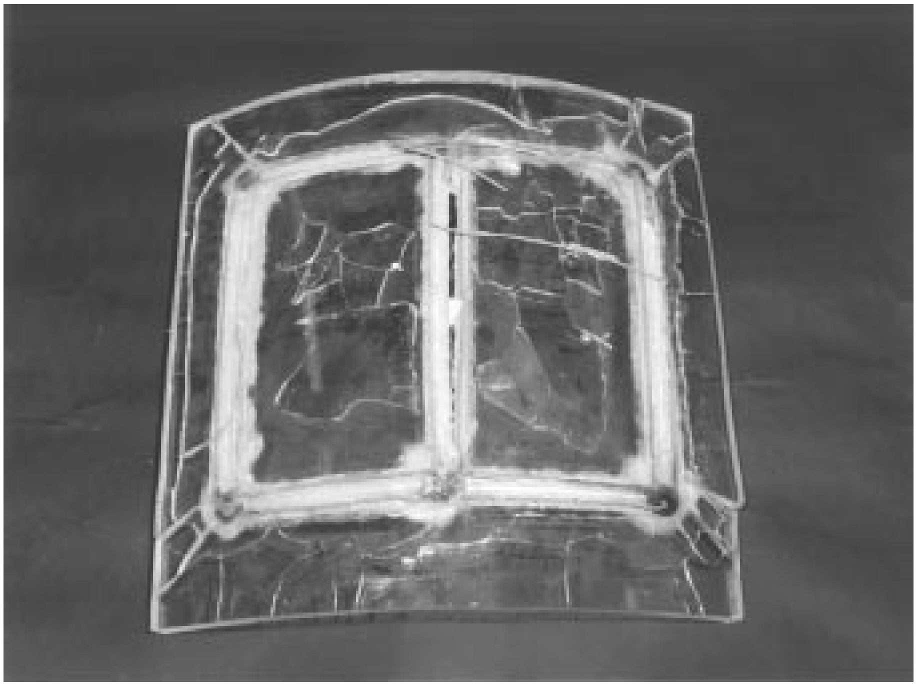

Figure 9. Results of explosively fractured mini-panel test, using full-scale canopy pattern.

Figure 10. Results of explosively fractured mini-panel test, using "T" configuration in corners.

Figure 11. Results of explosive fracturing tests on 0.875-inch polycarbonate. The explosive cord was embedded in the plate on the right and in the trilaminate test at the left. The bottom photograph is an edge view of the results of the trilaminate test.