N95-28488

ADVANCED WING DESIGN SURVIVABILITY TESTING AND RESULTS

S26-05

p. 15

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SUMMARY

Composite wings on current operational aircraft are conservatively designed to account for stress/strain concentrations, and to assure specified damage tolerance.

The technology that can lead to improved composite wing structures and associated structural efficiency is to increase design ultimate strain levels beyond their current limit of 3500 to 4000 micro-in./in. (μin./in.) to 6000 μin./in. without sacrificing structural integrity, durability, damage tolerance, or survivability. Grumman, under the sponsorship of the Naval Air Development Center (NADC), has developed a high-strain composite wing design for a subsonic aircraft wing using novel and innovative design concepts and manufacturing methods, while maintaining a state-of-the-art fiber/resin system. The current advanced wing design effort addressed a tactical subsonic aircraft wing using previously developed, high-strain wing design concepts in conjunction with newer/emerging fiber and polymer matrix composite (PMC) materials to achieve the same goals, while reducing complexity. Two categories of advanced PMC materials were evaluated: toughened thermosets, and engineered thermoplastics. Advanced PMC materials offer the technological opportunity to take maximum advantage of improved material properties, physical characteristics, and tailorability to increase performance and survivability over current composite structure.

Damage tolerance and survivability to various threats, in addition to structural integrity and durability, were key technical issues addressed during this study, and evaluated through test. This paper focuses on the live-fire testing, and the results performed to experimentally evaluate the survivability of the advanced wing design.

The objective of the live-fire testing is to demonstrate the ability of the advanced wing design/material combination to survive a 23-mm high-energy incendiary (HEI) single hit (while under load) without the use of S-glass/epoxy (S-Gl/Ep) crack-arrestment strips. The intended purpose of the S-Gl/Ep strips is to increase the design's overall damage tolerance to ballistic impact by arresting the growth of damage and preventing it from growing to catastrophic proportions. Inclusion of these strips within the laminate is labor intensive and adds both weight and cost to

the design. Ballistic testing of toughened thermoset panels (with and without crack-arrestment strips) and a thermoplastic panel (without crack-arrestment strips) provides a direct comparison of realistic data to evaluate the effectiveness of the design/material combination to eliminate the crack-arrestment strips and simplify the overall design.

INTRODUCTION

PMC materials have found increasing application in the aerospace industry because of their high strength and stiffness-to-weight ratios and potentially lower unit costs. While attractive weight savings have been realized, on a component basis, PMC structures have not yet met their full potential in terms of weight savings. This has been due in part to conservatism in design, which has resulted in strain levels being suppressed to account for reduced performance under hot/wet conditions and the presence of notches and/or damage.

The technology that can lead to improved wing structures and associated structural efficiency by increasing design ultimate strain levels beyond their current limit of 3500 to 4000 μin./in. has been demonstrated through the development of novel and innovative design concepts and manufacturing techniques, while maintaining the same fiber/non-toughened resin system, without sacrificing structural integrity, durability, damage tolerance, or survivability (battle damage tolerance). Concepts/features considered included the use of compliant high-strain-to-failure laminates, locally concentrated and banded 0-deg plies, integral cover-to-substructure concepts to minimize/eliminate fastener holes, and S-Gl/Ep softening strips at locations where holes are required to accommodate fasteners. Damage tolerance was achieved through a multi-path design utilizing S-Gl/Ep crack-arrestment strips to isolate and contain battle damage. In addition, Kevlar stitching was incorporated through the crack-arrestment strips to stop growth of delaminations (at the high operating strain level) resulting from low-energy impact damage (LEID).

An extensive design, development, and verification test effort has been an integral part of this development program. Design development testing consisted of over 140 coupons and 32 major elements prior to the design, fabrication, and test of a full-scale wing box subcomponent. The development testing successfully met their objectives to:

- Derive material allowables for notched high-strain laminates with S-Gl/Ep softening strips
- Correlate and confirm the adequacy of the analytical procedures used to define and analyze the design concept
- Demonstrate structural integrity of critical design areas
- Demonstrate the ability of the high-strain wing to sustain cyclic loading consistent with the aircraft's design life

- Demonstrate the effectiveness of the stitched S-Gl/Ep crack-arrestment strips for LEID and battle damage
- Establish the confidence to proceed to the fabrication and test of the full-scale wing box subcomponent.

The successful fabrication and testing of the four-spar subcomponent [a 241-cm (95-in.)-long, 91.4-cm (36-in.)-wide, 33-cm (13-in.)-deep representative segment of the high-strain wing box center section] verified the structural integrity, durability, and LEID tolerance of the high-strain wing design under combined loading and fuel pressure. It also demonstrated the manufacturing approach, and the battle damage tolerance while under load and pressurized.

Coincident with this effort, the trend toward increased structural efficiency and damage-tolerant structures emphasized the need for, and vigorous development of, new/improved composite materials consisting of high-performance graphite fibers in combination with toughened resin systems. Compared with composite material systems used on operational aircraft, these emerging new/improved fibers offer increased strength, stiffness, and strain-to-failure in the presence of a notch. New/emerging resin systems--both toughened thermosets and thermoplastics--have increased toughness, and improved elevated temperature/wet retention of properties. The potential benefits that can be realized by combining these newer/emerging fibers and tougher resin systems with previously developed high-strain wing design to maximize structural efficiency and simplify the design to reduce fabrication costs (while maintaining to greatest extent possible the durability, damage tolerance, and survivability demonstrated by the original high-strain wing design) were evaluated during a subsequent advanced wing design and experimental evaluation effort also sponsored by the NADC. Coupon and element testing, similar to that of the high-strain wing effort, was performed and addressed the same key issues: structural integrity, durability, damage tolerance, and survivability. This paper focuses on the battle damage tolerance testing accomplished, and presents the results.

ADVANCED WING DESIGN DEVELOPMENT

The planform and basic geometry for the Grumman/Navy A-6E attack aircraft wing baselined for this design and experimental evaluation effort is illustrated in figure 1. The wing has a span of 16.2 m (53 ft), a fold span of 7.7 m (25.3 ft), and a total area of 49.1 sq m (528.9 sq ft). The thickness-to-chord (T/C) ratio is 9% at the root and 5.9% at the tip, with a maximum thickness of 30.5 cm (12 in.) at the root. Wing control surfaces include inboard and outboard slats, flaps, flaperons, and speedbrakes at the wing tips. The wing is comprised of three major sections: an inner panel/center section that is one piece from fold joint to fold joint, and two outer panel sections. The structural torque box is a multi-spar construction with seven spars in the center section, nine in the inner panel, and seven in each outer panel. There is a total

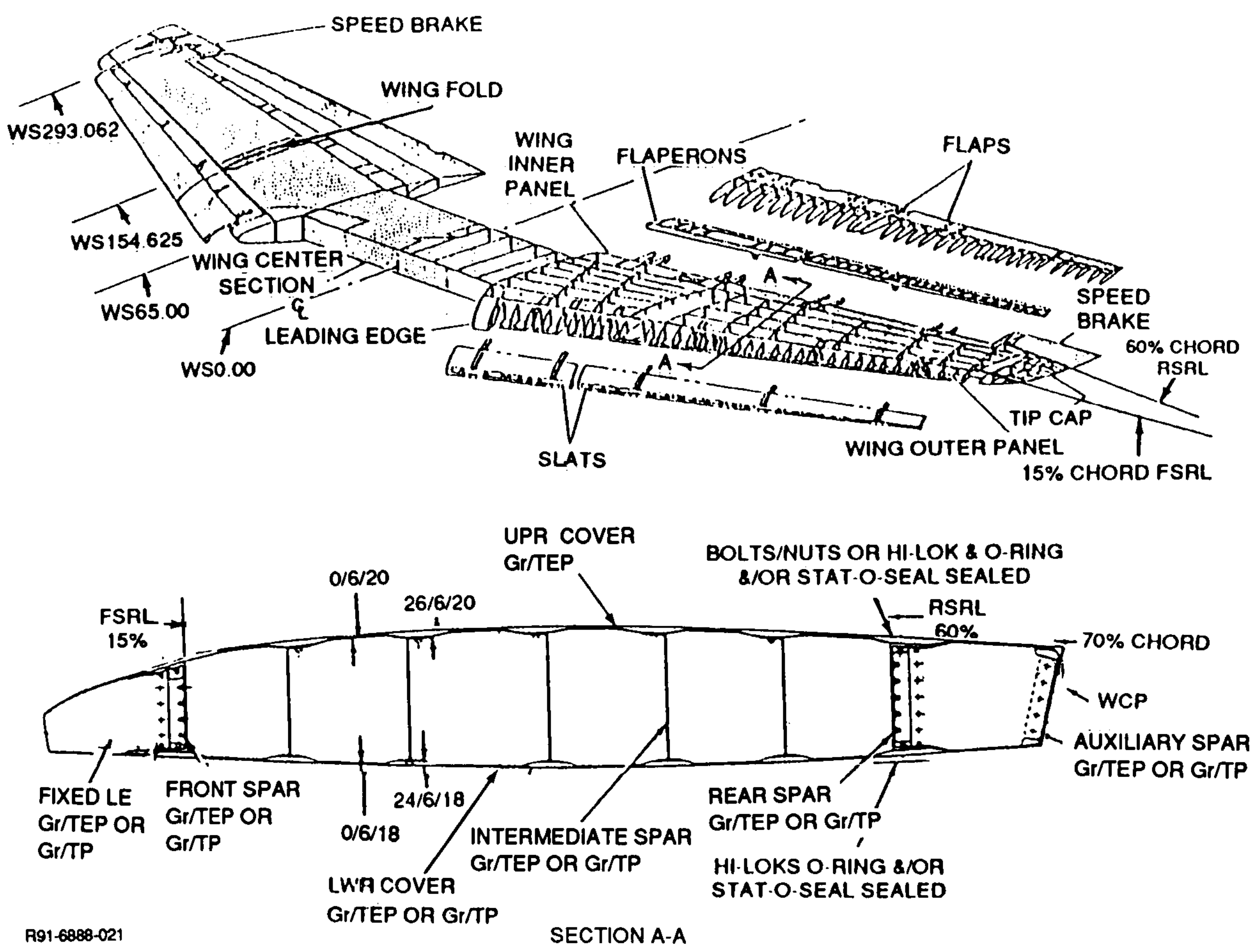

Figure 1 Baseline Wing Structural Arrangement

of 27 ribs, 13 of which are in the inner panel/center section, and 7 in each outer panel.

Design criteria established for this effort are presented in table I. The environmental conditions were based on the operational temperatures, mission profiles, and typical deployment areas. Damage tolerance requirements are similar to current composite wing requirements, i.e., ultimate load capability with the presence of LEID. Survivability requirements, for battle damage, required the structure to carry design limit load (DLL) following a single hit from a 23-mm HEI projectile with a super-quick fuse, and withstand the hydrodynamic ram effects due to the high-energy impact of the fuel-filled wing. Supportability requirements dictated that one cover be removable for maintenance and repair. In addition, removable access panels for maintenance of internal wing systems were included in the design. Finally, the wing box is an integral fuel-containing structure and was therefore designed to withstand maximum fuel pressures encountered during refueling or flight conditions.

The type of construction selected for the design and experimental evaluation effort is also illustrated in figure 1. The upper and lower

TABLE I. – AWD Design Criteria

WEIGHT:	20% WEIGHT REDUCTION FROM CURRENT SOA COMPOSITE DESIGN
STRAIN LEVEL:	6000 MICRO-IN./IN. DESIGN ULTIMATE STRAIN FOR TENSION & COMPRESSION COVERS
ENVIRONMENTAL CONDITIONS:	71°C (160°F) & 1.3% MOISTURE
DAMAGE TOLERANCE:	SUSTAIN DUL AFTER LOW-ENERGY IMPACT
SURVIVABILITY:	EXPERIENCE SINGLE HIT BY 23-MM HEI PROJECTILE & RETAIN CAPABILITY TO CARRY DESIGN LIMIT LOAD
MAINTENANCE:	ONE COVER REMOVABLE FOR INSPECTION & REPAIR
FUEL CONTAINMENT:	DESIGNED TO WITHSTAND MAX FUEL PRESSURES; HYDRODYNAMIC RAM EFFECTS CONSIDERED

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covers are designed as discrete cap laminates with the outer fibers working to a design ultimate strain level of 6000 µin./in. The basic cover between spar supports is a compliant high-strain-to-failure laminate consisting of ±45- and 90-deg plies only. This type of laminate has the advantages of minimizing load in the unsupported region of the cover, while maximizing buckling coefficients and being highly damage tolerant. The required 0-deg axial load-carrying plies are concentrated and banded at discrete locations over spar supports. The lower cover is attached to the substructure using blind composi-lok fasteners with O-rings under the heads for sealing. To satisfy the Navy requirement to have one cover removable for maintenance and repair, the upper cover is attached to the substructure using mechanical fasteners through nut-plates attached under the spar flanges.

The front and rear spars are unstiffened channel sections designed to be non-buckled to ultimate load. The front spar is fabricated in five segments: one in the center section, and one for each inner and outer panel. The rear spar is fabricated in three segments: one for each outer panel, and a one-piece segment on the center section/inner panel from fold to fold. The front and rear spars also serve as fuel tank boundary elements and seal the tank. An integrally molded groove seal in the flanges of the front and rear spars provides sealing and adequate structural behavior at minimum cost. The intermediate spars are channel sections with flat unstiffened webs non-buckled to ultimate load. Of the 27 ribs, 17 are composite and 10 are titanium. Titanium ribs are used at the two wing fold locations, the outboard tank boundaries, and at store locations.

The wing box attaches to the fuselage at four locations. Titanium fittings are bolted to the front and rear spars in the center section and are backed up by ribs. Single large-diameter fail-safe pins engage the titanium fittings through the fuselage bulkheads.

Major materials of construction considered consisted of two categories of new and/or improved graphite fibers: high strain (1.8% elongation or greater) and higher modulus [275.8 MPA (40 MSI) or greater with at least 1.5% elongation], in combination with two categories of toughened matrices: toughened thermosets and "engineered thermoplastics". A total of 28 toughened thermoset and nine thermoplastic material systems, summarized in tables II and III, respectively, have been screened for selection and evaluation of the most promising material systems. Grumman's extensive data base and material supplier data were used, in part, to perform the screening. In addition, industry-standard coupon tests were performed to obtain sufficient data where lacking, and to characterize the material systems to permit comparison on a common basis. Four toughened thermoset (IM8/8551-7A, T800/F3900, HITEX45-9B/E7T1-2, and G40-800/F584) and two thermoplastic (T650-42/RADEL-8320 and IM7/APC-II) material systems exhibited an overall balanced improvement in mechanical properties and toughness, and were therefore selected for characterization testing and further consideration for the preliminary design and trade study effort. Two toughened thermosets (IM8/8551-7A and HITEX45-9B/E7T1-2) and one thermoplastic (T650-42/RADEL-8320) were further down selected for battle damage tolerance testing.

TEST OBJECTIVE

The objective of the battle damage tolerance element testing was to demonstrate the ability of the advanced wing cover design concept/material combination to survive a single hit from a 23-mm HEI (with super-quick fuse) while under load without the use of S-Gl/Ep crack-arrestment strips. The intent of the S-Gl/Ep strips is to increase the overall damage tolerance of the design to ballistic impact by isolating the damage and preventing its growth to catastrophic proportions. Inclusion of these strips within the laminate, however, is labor-intensive and adds both cost and weight to the design. Ballistic testing of the toughened thermoset panels (with and without S-Gl/Ep strips) and the thermoplastic panel (without S-Gl/Ep strips) provided a direct comparison of realistic data to evaluate effectiveness of the material/design combination to eliminate the crack-arrestment strips and simplify the overall design.

COMPONENT DESCRIPTION AND DESIGN

The wing cover component, illustrated in figure 2, is a 53.3-cm (21-in.)-wide and 190.5-cm (75-in.)-long discrete cap laminate consisting of two cover-bays and three discrete caps, and is fully representative of

TABLE II. – Candidate Toughened Thermoset Prepregs

FIBER MANUFACTURER	FIBER TYPE	FIBER TENSILE STRENGTH (KSI)	FIBER TENSILE MODULES (MSI)	R6376/CIBA	CYCOM1827/CYAN	XU71787/DOW	F584/HEXCEL	8551/HERCULES	HG9105-2/HYSOL	5745C/NARMCO	E7K8/US POLY	974/FIBERITE	ERLIX 1928/AMOCO	E7T1-2/US POLY	F3900/HEXCEL	AVAILABILITY
BASF/CELION	G-40 -600	600	43.5	√			√			√		√				DEVELOPMENTAL
BASF/CELION	G-40 -700	690	49													DEVELOPMENTAL
BASF/CELION	G-40 -800	820	43.5				√									DEVELOPMENTAL
BASF/CELION	CELION-ST	580	35	√												FULL PRODUCTION
HERCULES	IM6	635	40		√		√	√		√						FULL PRODUCTION
HERCULES	IM7	680	41			√		√								FULL PRODUCTION
HERCULES	IM8	750	45					√								FULL PRODUCTION
HERCULES	AS6	650	35					√								FULL PRODUCTION
HITCO	HITEX-42	600	42							√	√					FULL PRODUCTION
HITCO	HITEX-46	900	46								√			√		FULL PRODUCTION
AMOCO	T-650	650	42										√			FULL PRODUCTION
AMOCO	T-40X	820	41	√			√				√		√			FULL PRODUCTION
HYSOL	IM-S	820	43						√							LTD PRODUCTION QTY
HYSOL	APPOLLO-M	820	53				√		√							LTD PRODUCTION QTY
HEXCEL	T-800	850	42												√	LTD PRODUCTION QTY

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the selected advanced-wing lower-cover design at the one-third semi-span location of the wing outer panel. The component consists of a 0/6/18 (number of plies in the 0-, 90-, and ±45-deg orientations, respectively) basic cover laminate between discrete caps/spar supports, and builds up locally to a 26/6/18 discrete cap laminate. A single row of high-tensile-strength-Kevlar stitches was incorporated through the basic cover laminate (prior to cure) adjacent to both sides of each discrete cap. The rows of stitches were included to provide translaminar reinforcement to arrest delamination growth, if necessary, due to the high operating strain level. The stitches were also an integral part of the overall design approach to address survivability for battle damage tolerance and hydrodynamic ram effects, and were incorporated into the toughened thermoset components for design realism. The spacing between discrete caps/spar supports at this location is 18.7 cm (7.35 in.), and the cover load intensities are 1609 kN/m (9190 lb/in.) axial (Nx), and 128 kN/m

TABLE III. – Candidate Thermoplastic Prepregs

FIBER MANUFACTURER	FIBER TYPE	FIBER TENSILE STRENGTH (KSI)	FIBER TENSILE MODULES (MSI)	APC-2(PEEK)/ICI	PPS(RYTON)PHILLIPS	KII(AVIMID)/DUPONT	PAI(TORLON)/AMOCO	KIII(AVIMID)/DUPONT	RADEL-8320/AMOCO	AVAILABILITY
BASF/CELION	G-40-600	600	43.5		√					DEVELOPMENTAL
HERCULES	IM6	635	40		√	√	√		√	FULL PRODUCTION
HERCULES	AS6	650	35				√		√	FULL PRODUCTION
HYSOL	APPOLLO-M	820	53		√					LIMITED PRODUCTION QTY
AMOCO	T650-42	650	42						√	FULL PRODUCTION

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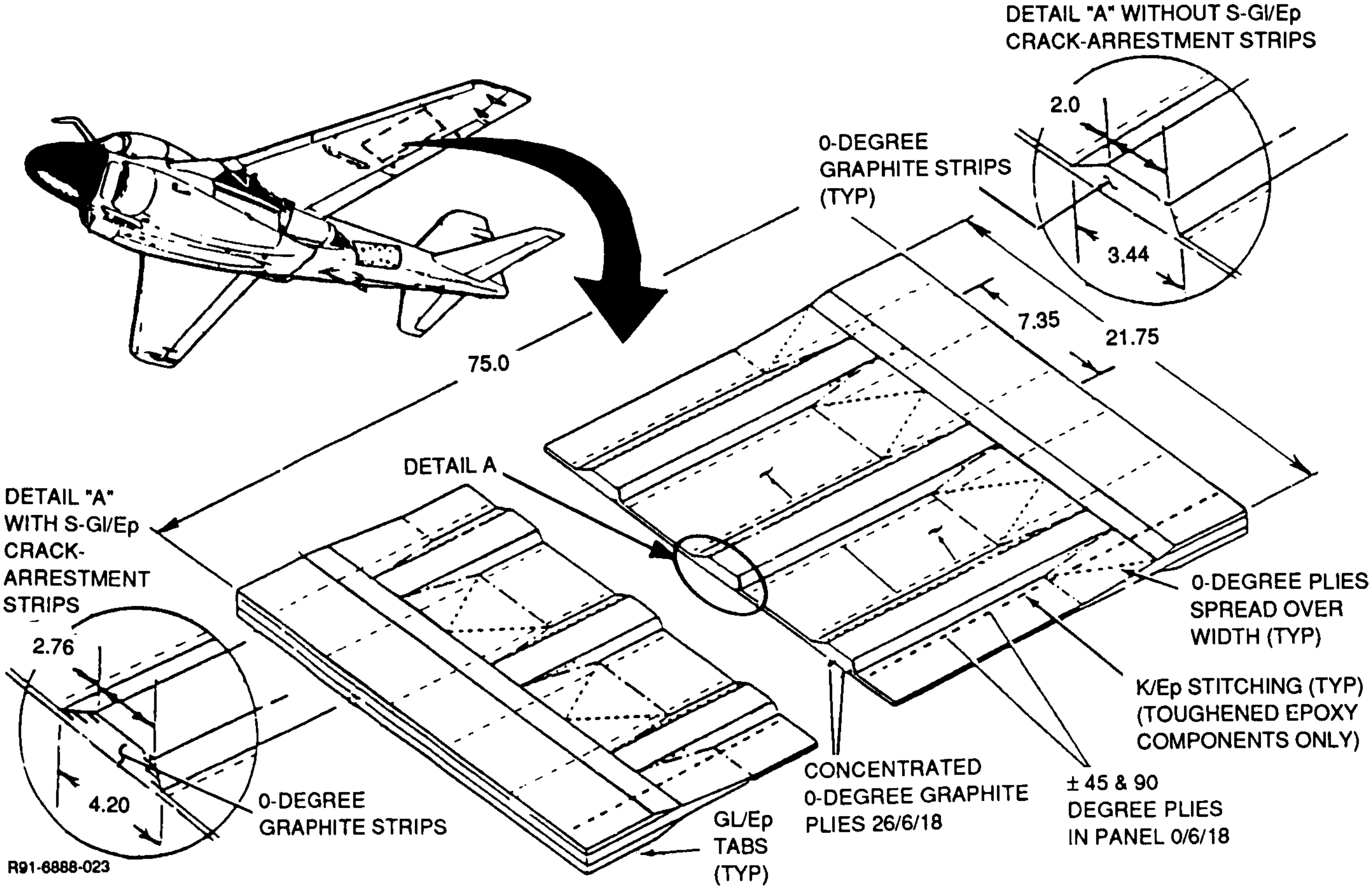


Figure 2 Wing Component Configuration

(731 lb/in.) shear (Nxy). The components were designed to be of sufficient size to provide a realistic demonstration of the survivability of the material/design for the ballistic threat--while under load--and make possible the incorporation of a repair. Detail laminate design, an integral part of the overall structural design process, was performed by extending basic material properties data through classical lamination theory to predict multi-directional laminate behavior. As previously mentioned, laminates representative of the advanced wing cover design contain a high percentage of 0-deg plies or none at all. In either case, careful attention was given to stacking sequence for both the basic-cover and discrete-cap laminates.

Four fiberglass gripper tabs were fabricated as separate details and adhesively bonded to each side of the load introduction areas at both ends of the component.

In preparation for test, the components were drilled and countersunk in the discrete cap areas to accommodate attachment of a simulated substructure support using 0.635-cm (0.25-in.)-diameter Hi-lok fasteners. Steel load introduction gripper plates were bolted to the fiberglass tabs at each end of the component.

SURVIVABILITY TESTING

The cover components were live-fire tested at the USA Ballistic Research Lab, Aberdeen Proving Grounds, MD. The test setup shown in figure 3 consisted of a hydraulic cylinder attached to an adjustable frame, which in turn was attached to the test specimen's gripper plates via single, large-diameter clevis pins at each end. The gripper plates, bolted to each end of the cover component, transfer the tensile load applied by the hydraulic cylinder/adjustable frame combination to the specimen. A tensile load of 400.3 kN (90,000 lb) was applied to attain the required 55% DLL level while subjecting the components to the ballistic hit. The gun used was a 23-mm rifled barrel clamped to a recoil-absorbing mount. It was fired remotely by electrical impulse. The 23-mm projectile was fired at a nominal velocity of 607 m/s (2000 ft/s) into the center of the mid-discrete cap at 0-deg obliquity while the components were loaded in tension to 55% DLL.

TEST RESULTS

All cover components were able to maintain the applied load both during and after the ballistic hit; however, an approximate 10% reduction in applied load was recorded subsequent to the hit, which has been attributed to flexibility in the test setup. The applied load was maintained at this level (48% DLL) for a sufficient length of time after

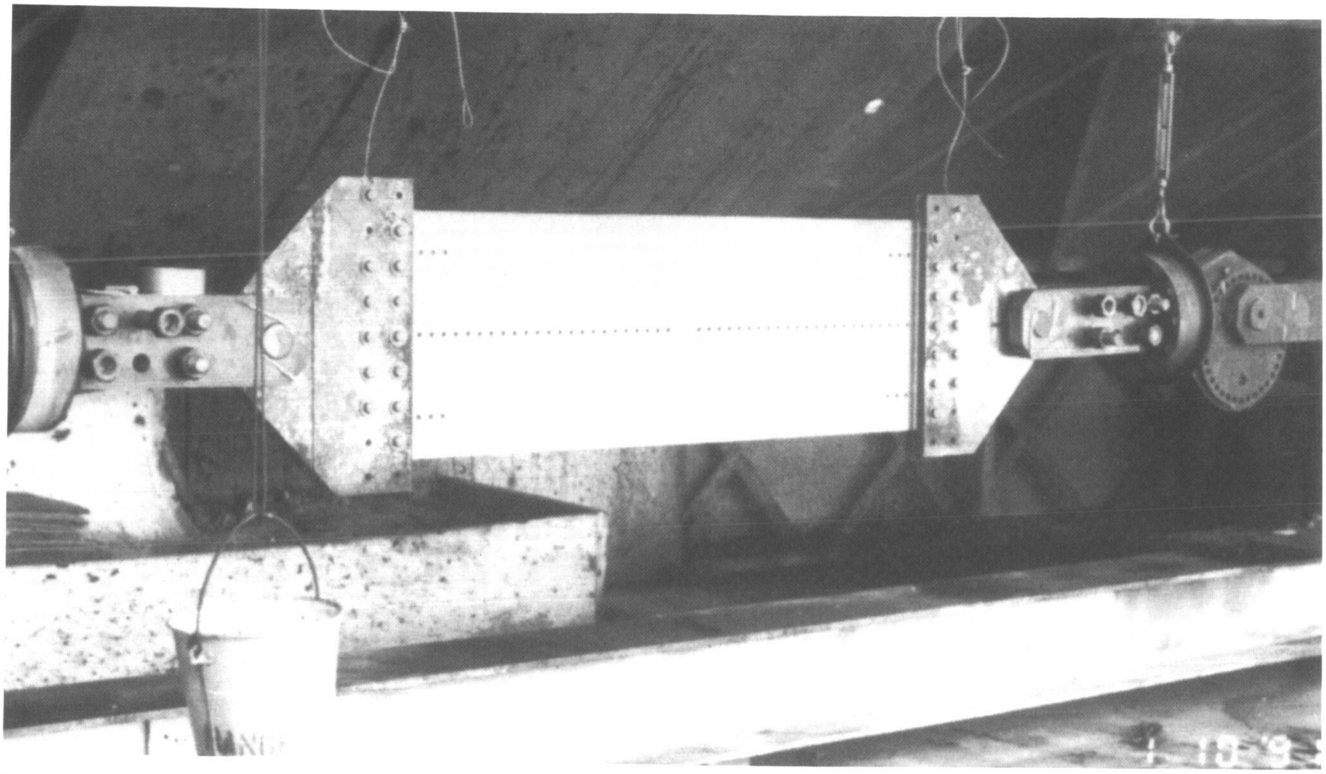


Figure 3 Wing Component Set Up for Test

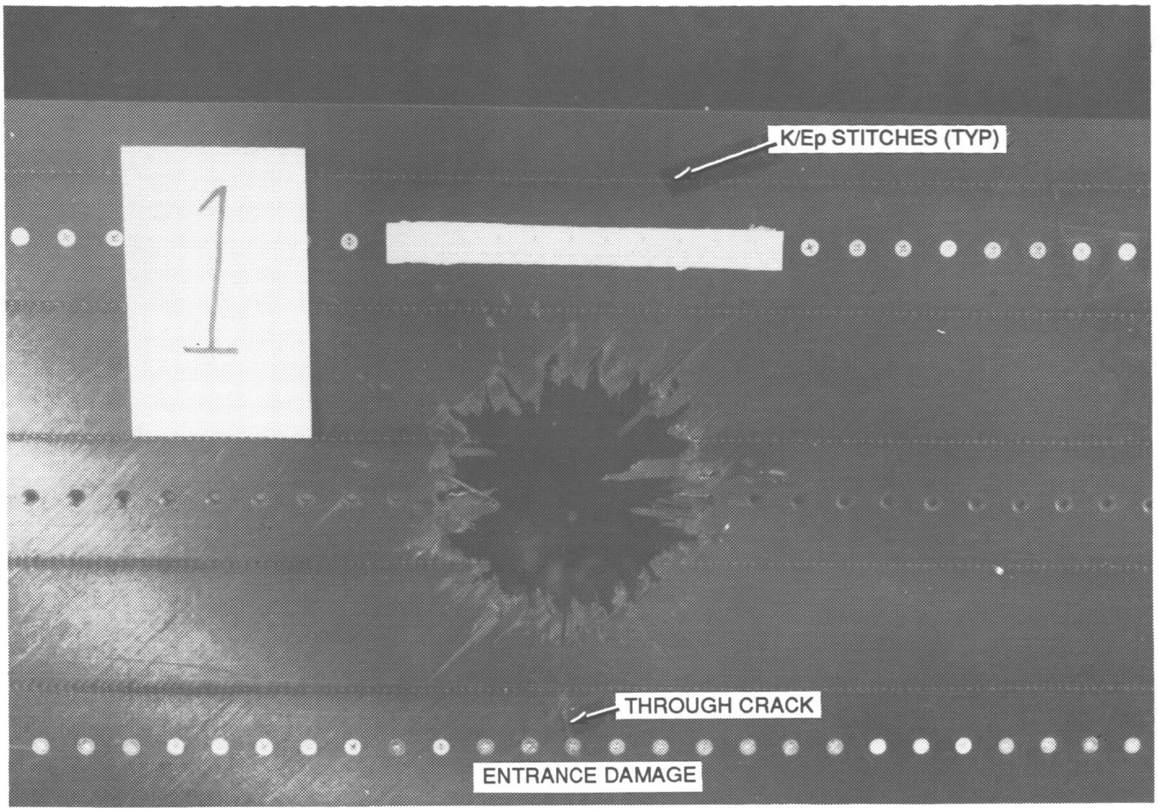
the impact. The following observations, based on visual examinations, were made regarding the damage of each panel subsequent to the ballistic hit.

Panel No. 1 (IM8/8551-7A without crack-arrestment strips)

The round impacted the center of the panel as planned, thus hitting the center of the mid-discrete cap. Upon detonation, it completely severed the cap and blew a jagged hole approximately 22.9 cm (9 in.) in diameter in the panel. Numerous strips of ±45-deg material delaminated and peeled back from the edges of the jagged hole, but were prevented from delaminating further by the rows of Kevlar stitches (see figure 4). However, a crack that originated at the bottom edge of the hole propagated chordwise for approximately 20.3 cm (8 in.), through the row of stitches at the lower adjacent discrete cap, through a bolt hole in the adjacent discrete cap, and then through the second row of stitches on the other side of the discrete cap. The running crack was through the thickness of the specimen from front to back.

Panel No. 2 (HITEX 45-9B/E7T1-2 without crack-arrestment strips)

The entry damage size was similar to panel no. 1 [approximately 22.9-cm (9-in.)-diameter jagged hole] except that only the impacted mid-discrete cap was severed; i.e., no cracks extended from the hole to



ENTRANCE DAMAGE

EXIT DAMAGE

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Figure 4 Panel No. 1 Entrance and Exit Damage

adjacent caps. Exit damage differed from panel no. 1 in that there was more delamination and peeling of surface ±45-deg plies, which stopped at the adjacent rows of stitching. There seemed to be more damage longitudinally, along the cap, than panel no. 1, with more of the cap material peeled back (see figure 5).

Panel No. 3 (IM8/8551-7A with crack-arrestment strips)

The third panel in this series of tests differed from the first two in that it had S-Gl/Ep strips incorporated within the laminate adjacent to both sides of each discrete cap. The entry side damage (see figure 6) is nearly identical to panels no. 1 and 2. However, the exit side damage (also shown in figure 6) extended further spanwise along the length of the panel. The S-Gl/Ep crack-arrestment strips arrested any chordwise growth of damage. However, the S-Gl/Ep crack-arrestment strip adjacent to both sides of the mid-discrete cap were severed (along with the cap) and pulled out of the laminate, thereby pulling loose a section of Gr/Ep material approximately 10.2 cm (4 in.) wide by 22.9 cm (9 in.) long, resulting in more extensive spanwise damage. No through-the-thickness cracks, as seen on panel no. 1, were evident in this specimen.

Panel No. 4 (T650-42/RADEL-8320)

The fourth panel, fabricated from a thermoplastic material without crack-arrestment strips and without Kevlar stitching, responded differently to the ballistic hit than did the three previous toughened thermoset panels. The ballistic projectile impacted the center of the mid-discrete cap as planned. Upon detonation, the ballistic projectile blew a 20.3-cm (8-in.)-diameter jagged hole in the center of the panel. There was minimal ply breakout and surface damage on either the entrance or exit sides (see figure 7). As such, exit side damage was virtually the same as the entrance side damage. Futhermore, the damage was limited to the jagged hole with no through-the-thickness cracks or delaminations extending beyond the hole thus making the component easier to repair. Based on observations at the time of the live-fire test, the resulting damage and overall response of the panel to the ballistic hit was very much like that of aluminum, except that there were no cracks, tears, or permanent deformations evident.

CONCLUSIONS

Conclusions reached as a result of the experimental effort described in this paper have been encouraging. In general, toughened thermoset and thermoplastic materials appear to provide improvements in wing primary structures for future military aircraft to potentially reduce fabrication costs and increase structural efficiency, while providing advantages for

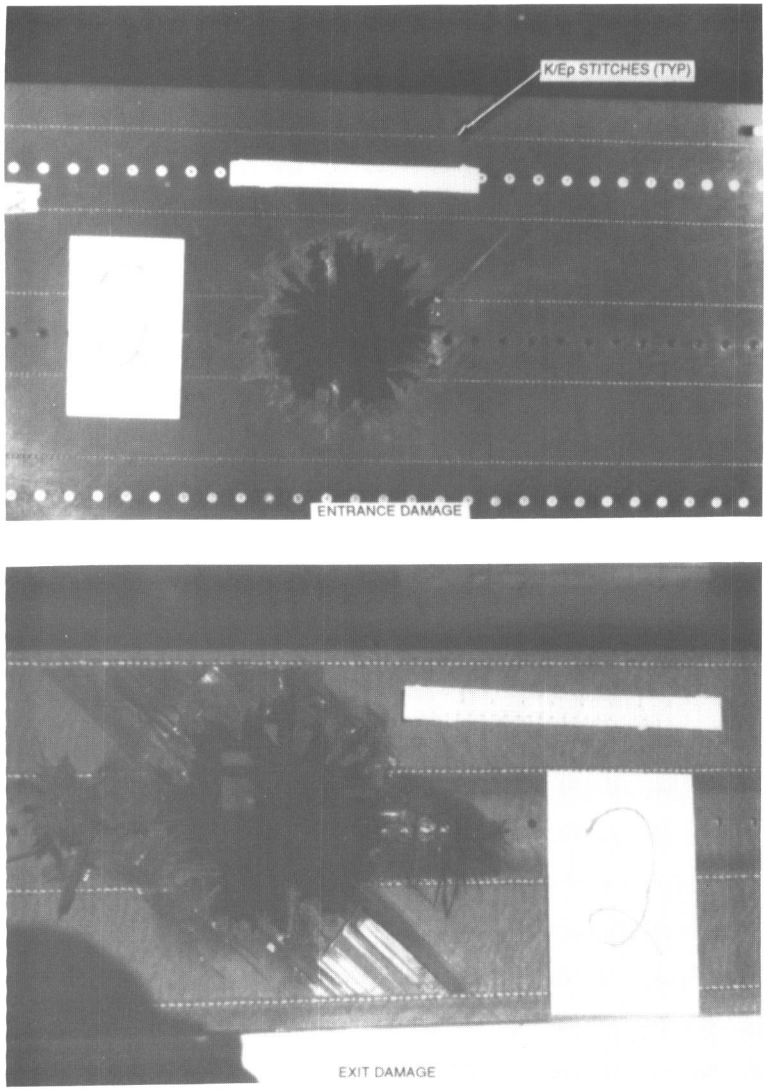

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Figure 5 Panel No. 2 Entrance and Exit Damage

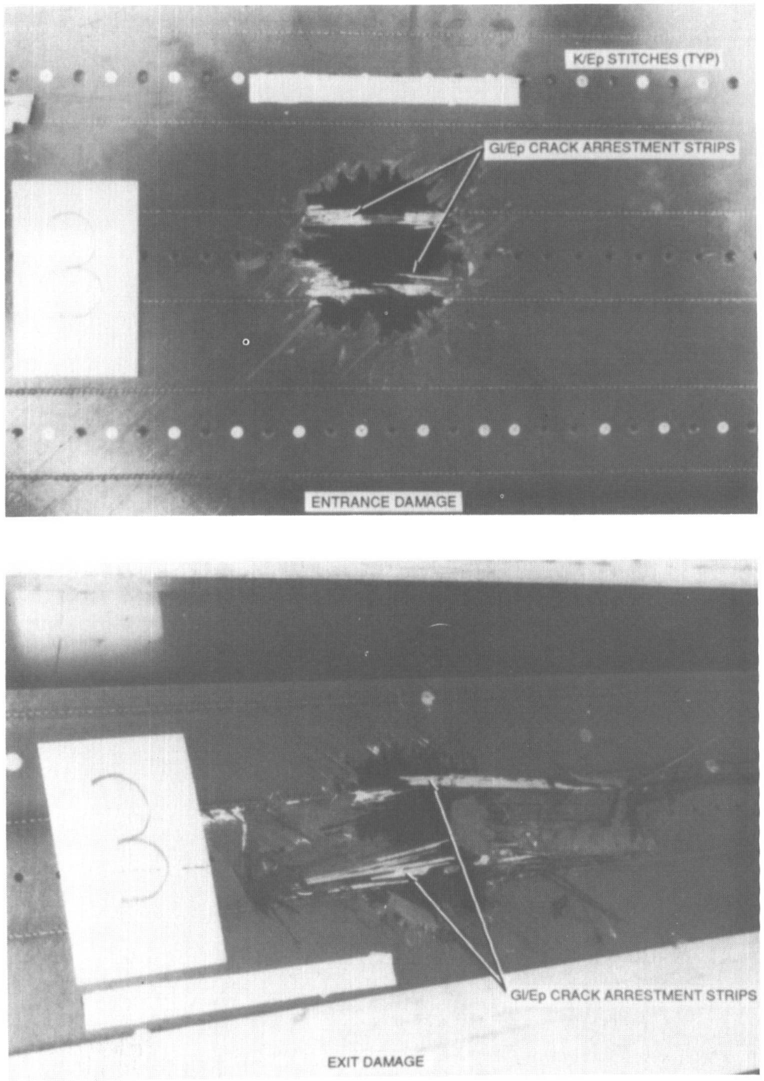

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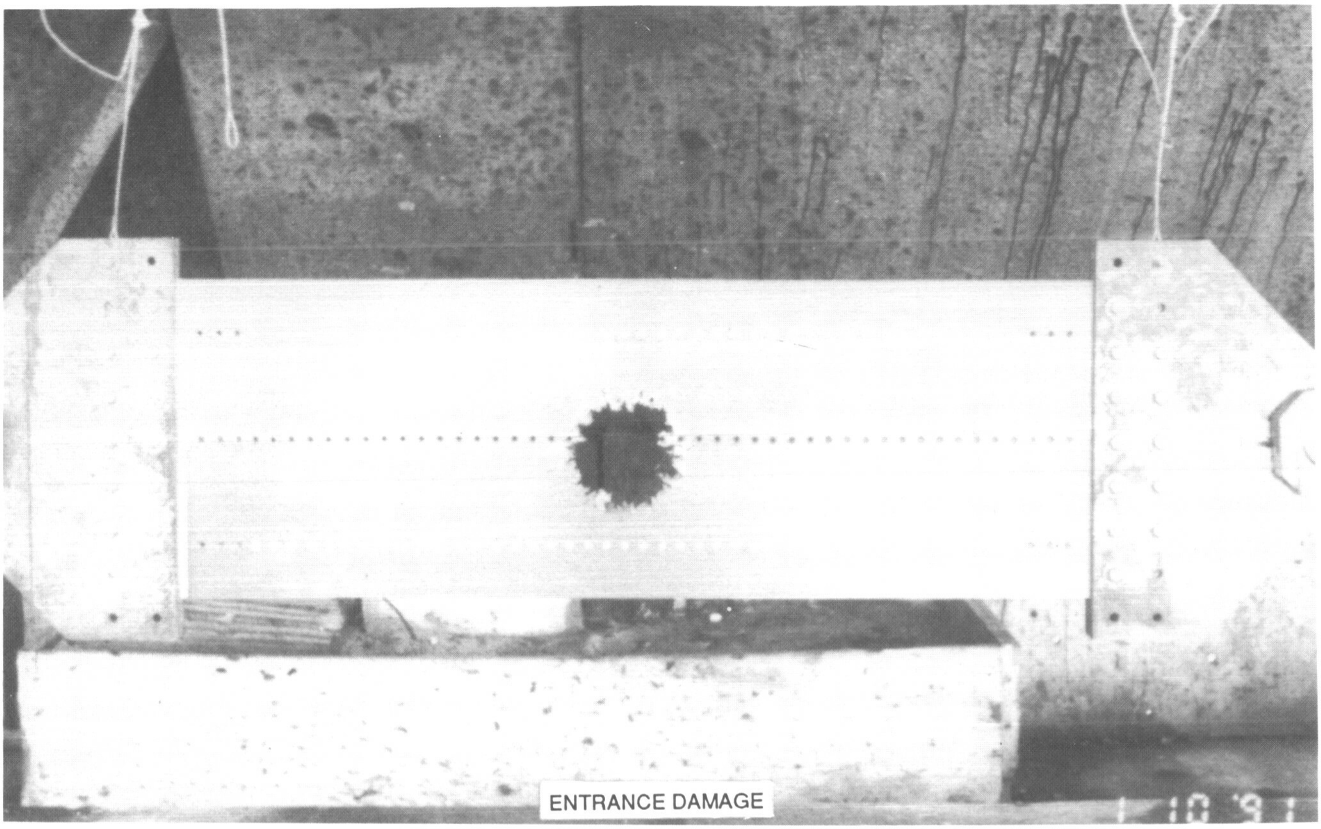
Figure 6 Panel No. 3 Entrance and Exit Damage



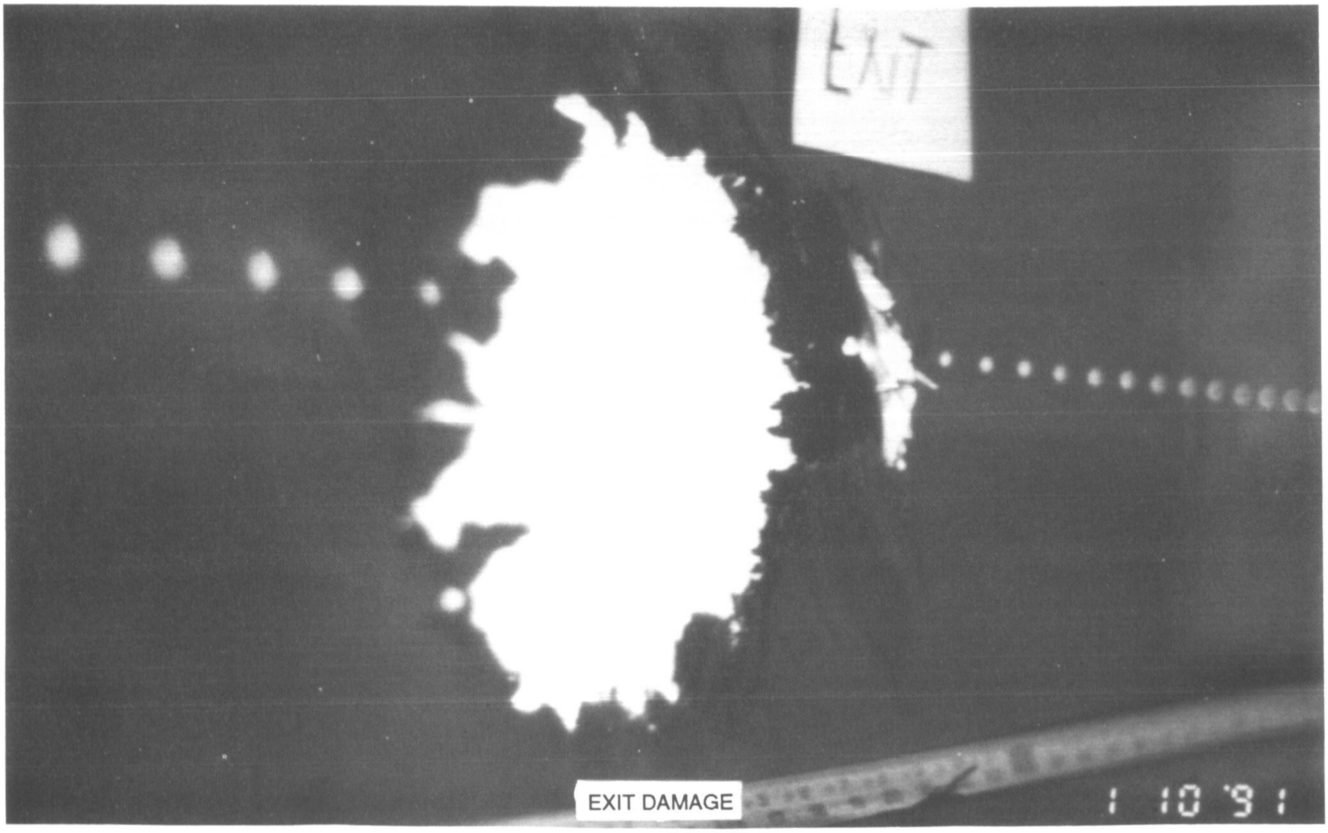


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Figure 7 Panel No. 4 Entrance and Exit Damage

battle damage tolerance and survivability. Specific conclusions based on the live-fire testing are discussed in the following paragraphs.

The IM8/8551-7A (both with and without S-Gl/Ep crack-arrestment strips), HITEX 45-9B/E7T1-2, and T650-42/RADEL-8320 discrete cap cover components survived a single hit from a 23-mm HEI projectile and continued to carry 55% DLL (in tension) during and after the ballistic hit.

Panel no. 1, constructed of IM8/8551-7A (without crack-arrestment strips), suffered the most chordwise damage, which consisted of a through-the-thickness propagating through two rows of stitching and an adjacent discrete cap. However, the surface delamination and peeling was not as severe, resulting in a smaller damage area on the exit side compared with panel no. 3. Panel no. 3, which contained the crack-arrestment strips, showed significant exit side spanwise damage due to the pulling out of the severed crack-arrestment strips peeling back a significant amount of cap material when the round detonated.

Panel no. 2, constructed of HITEX45-9B/E7T1-2 (without crack-arrestment strips), experienced much greater exit side damage, consisting of a great deal of delamination/peeling, but with all chordwise damage arrested by the stitching; no through-the-thickness cracks appeared to propagate beyond the rows of stitches.

Panel no. 4 constructed from the T650-42/RADEL-8320 thermoplastic material system exhibited the least damage of all the panels tested. This damage was limited to a jagged 20.3-cm (8-in.)-diameter hole. The resulting damage and response of the panel to the ballistic hit was very much like that of aluminum, without the tearing, cracking, and permanent deformations indicative of aluminum.

The T650-42/RADEL-8320 panel satisfied the ballistic requirements without the need for translaminar reinforcement (stitching). However, overall suitability for stitch-free delamination failure modes needs to be evaluated.

Discrete cap cover designs, combined with toughened epoxy or thermoplastic matrices, appear to be an efficient approach to satisfy live-fire wing requirements.

Repair of the toughened thermoset and thermoplastic cover components using battle damage repair methods and criteria is being considered.