WORLDWIDE FLIGHT AND GROUND-BASED EXPOSURE OF COMPOSITE MATERIALS

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INTRODUCTION

The NASA Langley Research Center has had programs underway for the past 12 years to establish a data base on the long-term durability of advanced composite materials for application to aircraft structures. A series of flight service programs are obtaining worldwide service experience with secondary and primary composite components installed on commercial and military transport aircraft and helicopters. Included are spoilers, rudders, elevators, ailerons, fairings, wing boxes, and horizontal stabilizers on transport aircraft, and doors, fairings, tail rotors, vertical fins, and horizontal stabilizers on helicopters. A wide variety of materials, including boron/epoxy, Kevlar/epoxy, graphite/epoxy, and boron/aluminum, are being evaluated. Results of inspection, in-service damage incidents, repair procedures, and residual strength of components removed from service are reported. The effects of environmental exposure of composite materials are reported for up to 10 years of outdoor ground-based exposure. Included are the effects of moisture absorption, ultraviolet radiation, and aircraft fuels and fluids. Residual strength as a function of exposure time is compared with baseline properties. Figure 1 outlines the scope of the flight service and ground-based exposure program reported herein.

Flight service of composite components

- Inspection, damage, and repair
- Residual strength

Environmental effects on composite materials

- Worldwide ground-based outdoor exposure
- Moisture, fuels, fluids, and UV radiation
- Residual strength

Figure 1

FLIGHT SERVICE COMPOSITE COMPONENTS ON TRANSPORT AIRCRAFT

Confidence in the long-term durability of advanced composites is being developed through flight service of numerous composite components on transport aircraft. Emphasis has been on commercial aircraft because of their high utilization rates, exposure to worldwide environmental conditions, and systematic maintenance procedures. The composite components currently being evaluated on transport aircraft are shown in figure 2. Eighteen Kevlar/epoxy fairings have been in service on Lockheed L-1011 aircraft since 1973. In April 1982 eight graphite/epoxy ailerons developed under the NASA Aircraft Energy Efficiency (ACEE) program were installed on four L-1011 aircraft for service evaluation. One hundred and eight B-737 graphite/epoxy spoilers have been in service on six different commercial airlines in worldwide service since 1973. Four B-737 graphite/epoxy horizontal stabilizers were installed on two aircraft in March 1984 for commercial service. Thirteen graphite/epoxy DC-10 upper aft rudders are in service on five commerical airlines and three boron/aluminum aft pylon skins have been in service on DC-10 aircraft since 1975. Ten graphite/epoxy elevators have been in service on B-727 aircraft since 1980. In addition to the commercial aircraft components shown in figure 2, two boron/epoxy reinforced aluminum center-wing boxes have been in service on U.S. Air Force C-130 transport aircraft since 1974. Additional details on the design, development, test, and flight service evaluation of the composite components discussed above are given in references 1 through 7.

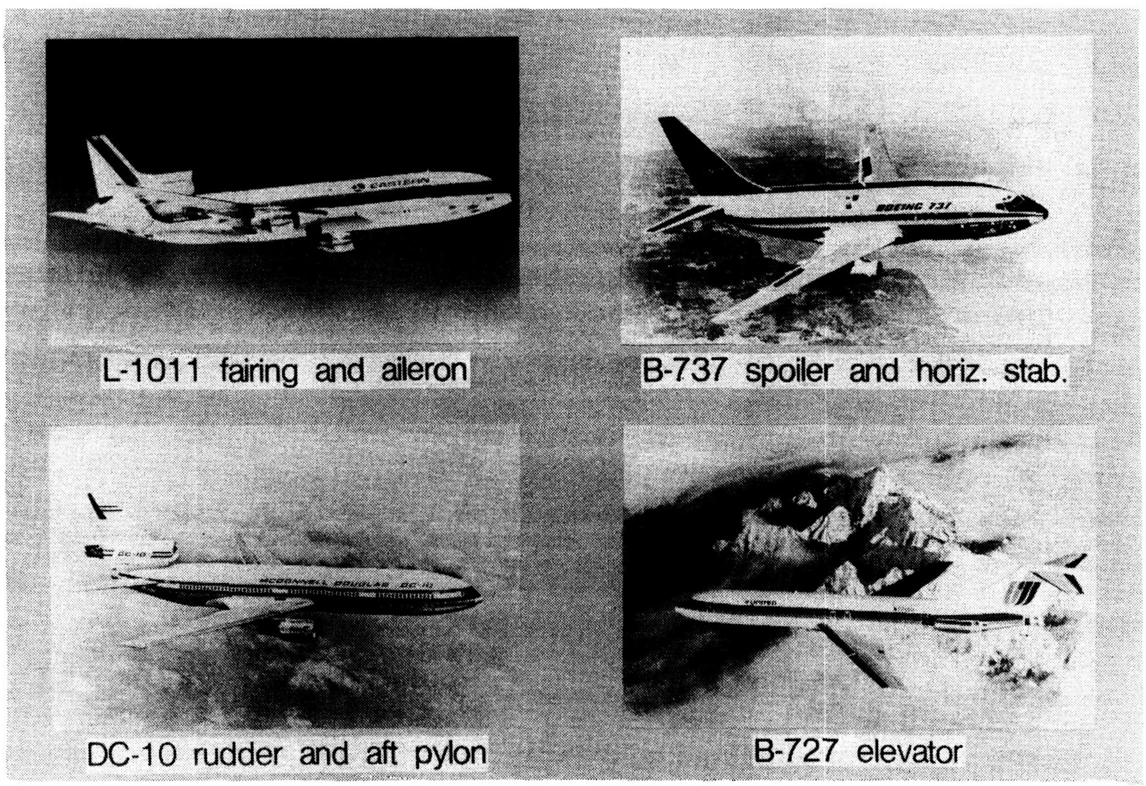

Figure 2

ACEE COMPOSITE COMPONENTS IN FLIGHT SERVICE

As part of the NASA Aircraft Energy Efficiency (ACEE) Program, Boeing, Douglas, and Lockheed have been under NASA contract to design, fabricate, and test large composite structural components. Each of the graphite/epoxy components shown in figure 3 has been certified by the FAA, and flight service evaluation is underway. The four components utilize different design concepts. The B-737 horizontal stabilizers have stringer-reinforced skins, laminated spars, and Nomex honeycomb reinforced ribs. The B-727 elevators are constructed with Nomex honeycomb reinforced laminated skins, the DC-10 rudders are multi-rib stiffened, and the L-1011 aileron skin design features a syntactic-core sandwich with laminated facesheets. An overall mass saving of 24 percent was achieved for the four components when compared to the production aluminum designs. In addition to the components shown in figure 3, Douglas is currently fabricating a graphite/epoxy DC-10 vertical stabilizer for service evaluation.

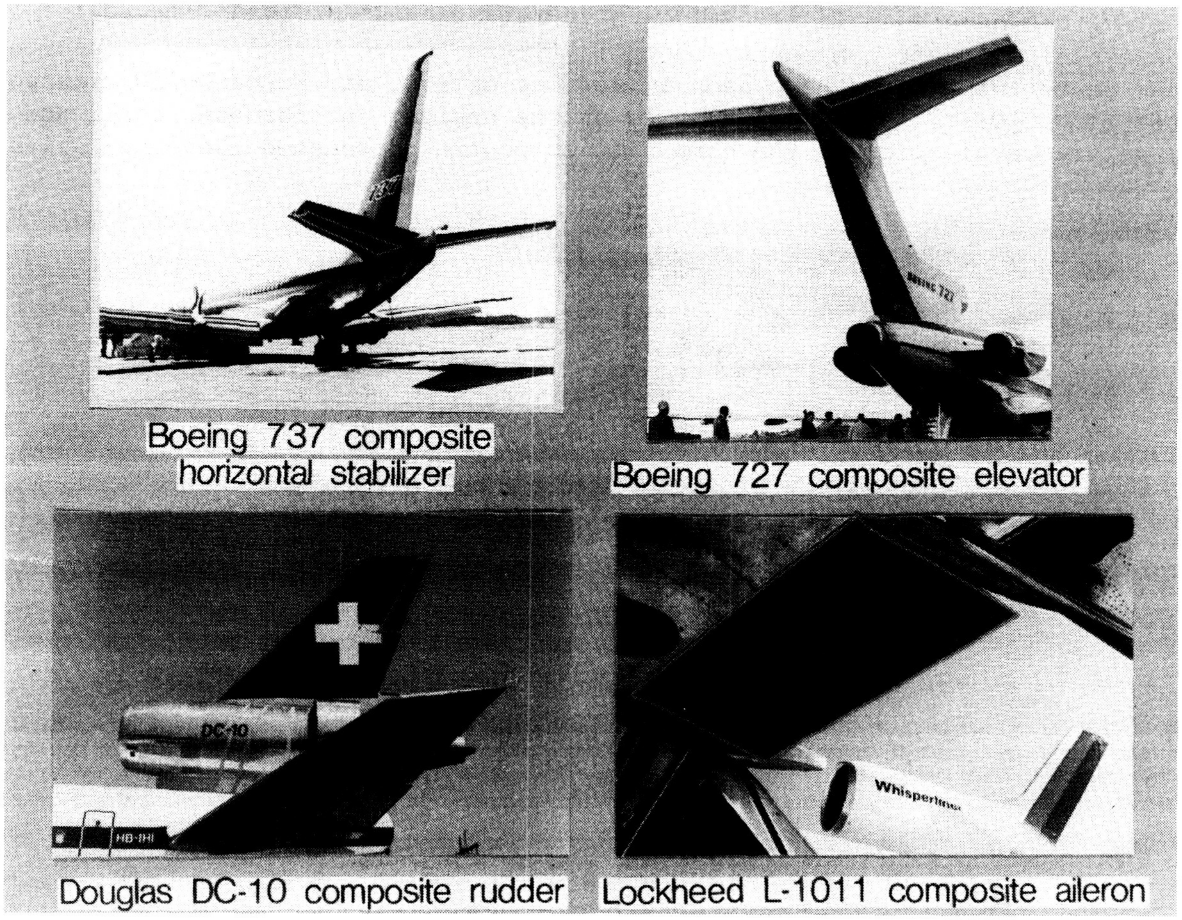

Figure 3

FLIGHT SERVICE COMPOSITE COMPONENTS ON HELICOPTERS

Composite components are being evaluated in service on commercial and military helicopters, as shown in figure 4. Forty shipsets of Kevlar/epoxy doors and fairings and graphite/epoxy vertical fins are being installed on Bell 206L commercial helicopters for 5 to 10 years of service evaluation. The helicopters are operating in diverse environments in Alaska, Canada, U.S. Gulf Coast, and Southwest U.S. Selected components will be removed from service for residual strength testing. Additional details on the Bell 206L program can be found in references 8 and 9. Ten tail rotors and four horizontal stabilizers will be removed from Sikorsky S-76 production helicopters to determine the effects of realistic operational service environments on composite primary helicopter components (ref. 10). Static and fatigue tests will be conducted on the components removed from service and the results will be compared with baseline certification test results. In addition, several hundred composite coupons exposed to the outdoor environment will be tested for comparison with the component test results. A Kevlar/epoxy cargo ramp is being evaluated on a U.S. Marine Corps CH-53D helicopter. The laminated fabric skin may encounter severe handling such as rough runway abrasion and impact. Maintenance characteristics of the Kevlar skin will be compared to those of production aluminum skins.

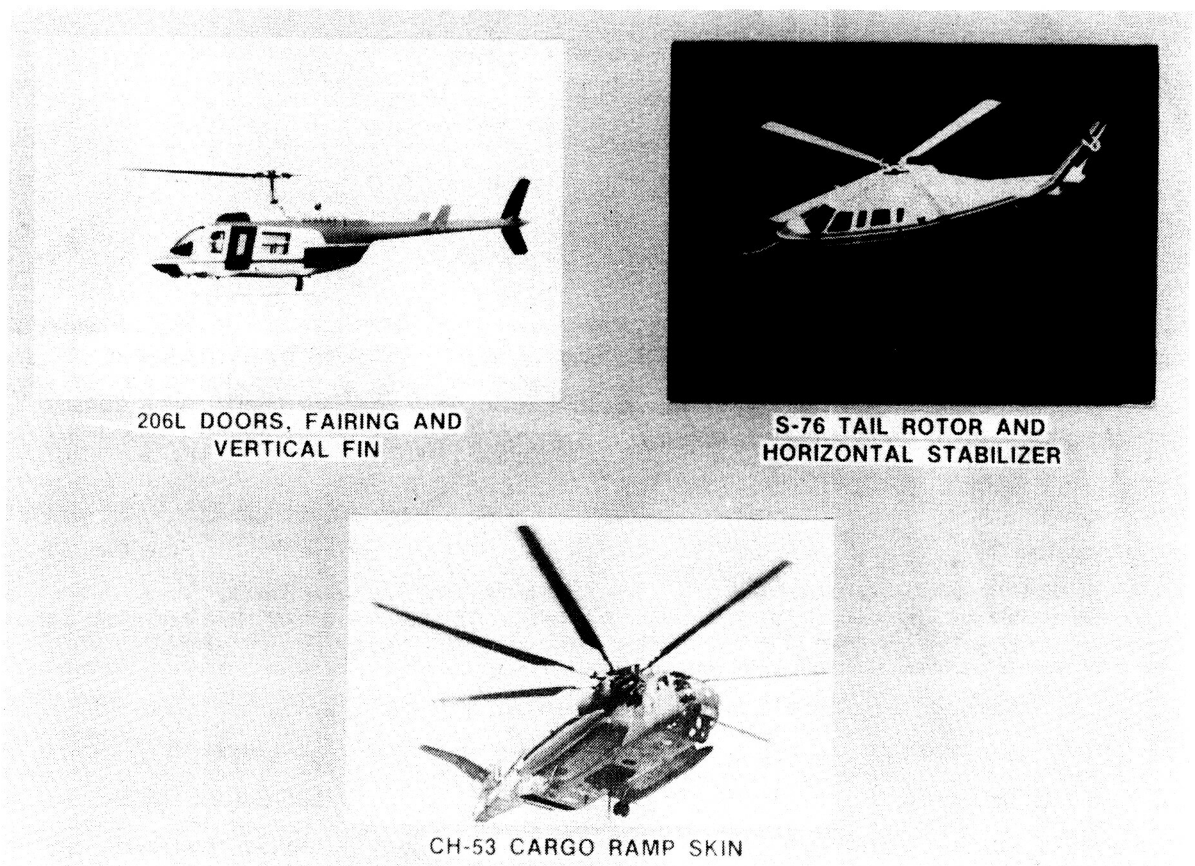

Figure 4

BELL 206L HELICOPTER COMPOSITE COMPONENTS

The four composite components that are being evaluated on the Bell 206L are the forward fairing, litter door, baggage door, and vertical fin, as shown in figure 5. Four different structural design concepts were used in the composite components. The forward fairing is a sandwich structure with a single ply of Kevlar/epoxy fabric co-cured on a polyvinylchloride foam core. The litter door is a hollow section design with Kevlar/epoxy inner and outer skins. Unidirectional Kevlar/epoxy tape is used for local reinforcement at hinges, latches, and in the hat-section stiffeners. The baggage door is constructed with Kevlar/epoxy fabric facesheets and Nomex honeycomb core. Additional reinforcements are added in the latch area and along the edges. The vertical fin is constructed with graphite/epoxy facesheets bonded to a FIBERTRUSS honeycomb core. Composite material coupons are being exposed to outdoor environments at the locations where the flight components are being flown. Tension, compression, and short-beam shear tests are being conducted to establish material degradation as a function of exposure time and location. Strength retention of the materials is being compared with strength retention of components removed from service.

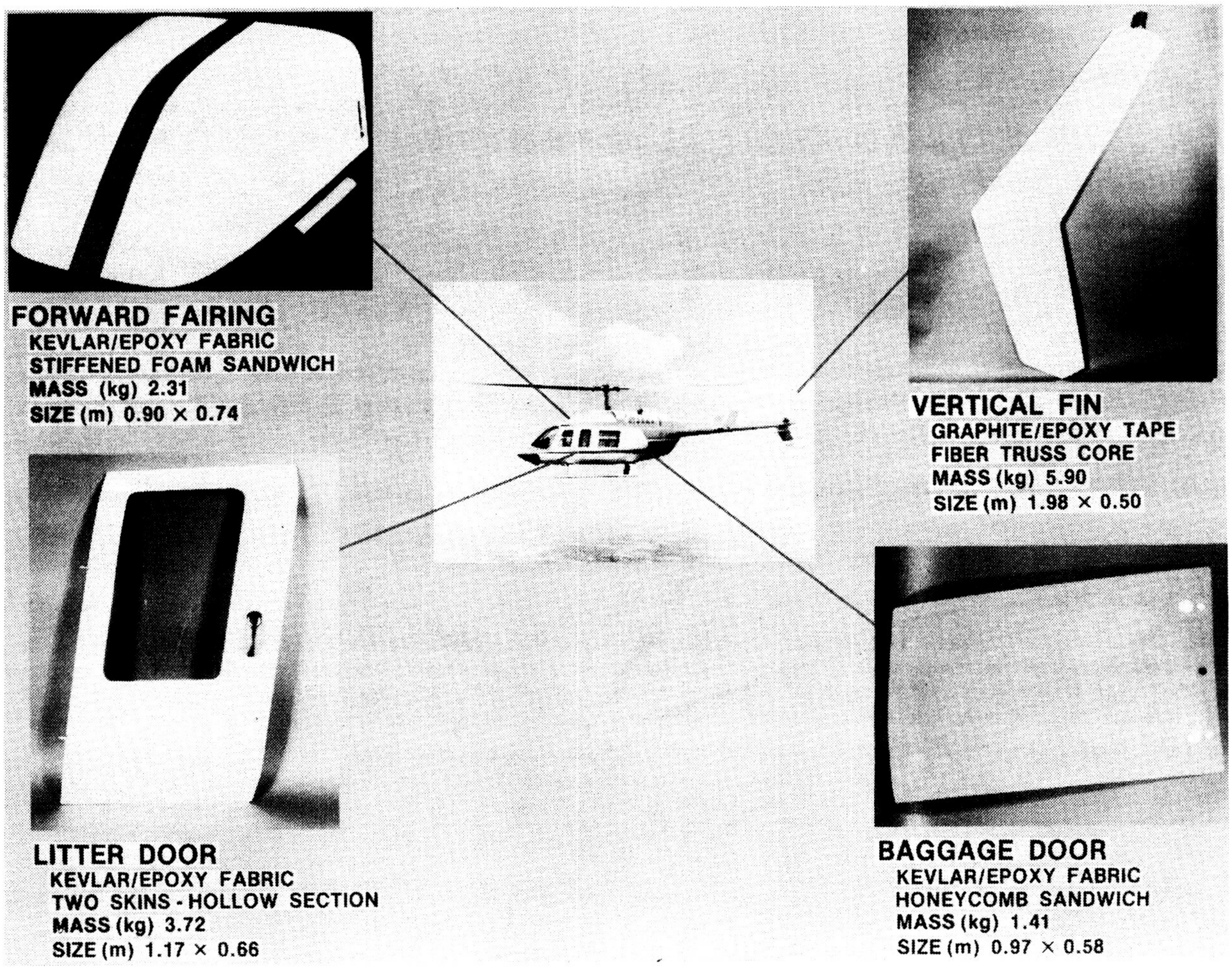

Figure 5

SIKORSKY S-76 HELICOPTER COMPOSITE COMPONENTS

The two composite components that are being evaluated on the Sikorsky S-76 are shown in figure 6. The composite components are baseline designs for the S-76 and are currently in commercial production. The tail rotor has a laminated graphite/epoxy spar with a glass/epoxy skin. The horizontal stabilizer has a Kevlar/epoxy torque tube reinforced with full-depth aluminum honeycomb and graphite/epoxy spar caps, full-depth Nomex honeycomb sandwich core, and Kevlar/epoxy skins. Eight tail rotor spars and two horizontal stabilizers have been removed from helicopters and tested after four years of service. Six of the tail rotor spars were fatigue tested to the same requirements as for FAA certification. Test coupons were cut from the other two spars and tested for residual strength and moisture content. The two horizontal stabilizers were static and fatigue tested, respectively. No significant strength reduction was noted for the spars or stabilizers. Painted composite panels are being exposed to the outdoor environment at Stratford, CT and West Palm Beach, FL. These panels are machined into test coupons to establish materials degradation as a function of exposure time and location. Strength retention results are discussed in a subsequent figure.

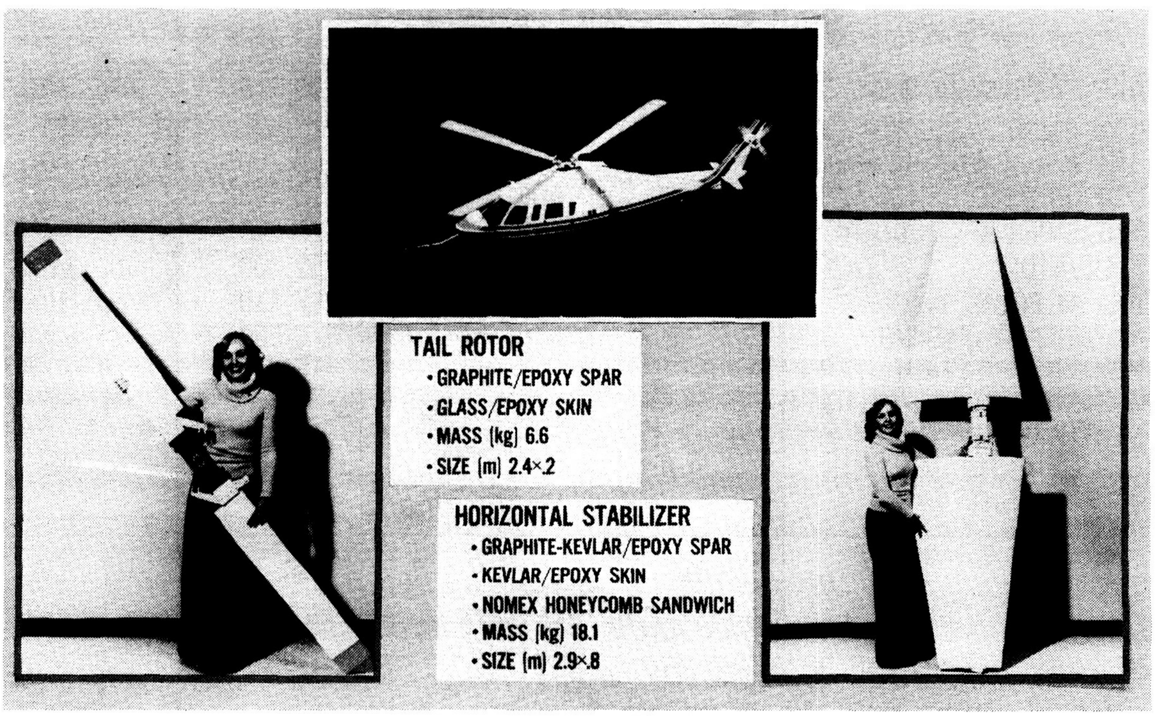

Figure 6

NASA COMPOSITE STRUCTURES FLIGHT SERVICE SUMMARY

Over 300 composite components have been in service with numerous operators, including foreign and domestic airlines, the U.S. Army, the U.S. Marines, and the U.S. Air Force. The NASA Flight Service Program was initiated in 1973 for the components indicated in figure 7. Over 3 million component flight hours have been accumulated with the high-time aircraft having more than 29,000 hours. The 108 graphite/epoxy spoilers installed on B-737 aircraft have accumulated the highest total component flight hours, nearly 2.0 million, during 10 years of service. Over 200,000 total component flight hours have been accumulated on the 206L and S-76 composite helicopter components.

Formal tracking of the L-1011 Kevlar/epoxy fairings under NASA contract was completed in May 1984. The results of the final component inspection conducted by Lockheed-California personnel are presented in reference 1.

AIRCRAFT COMPONENT	TOTAL COMPONENTS	START OF FLIGHT SERVICE	CUMULATIVE FLIGHT HOURS	
			HIGH-TIME AIRCRAFT	TOTAL COMPONENT
L-1011 FAIRING PANELS	18	JANUARY 1973	29,310	480,840
737 SPOILER	108	JULY 1973	29,430	1,996,880
C-130 CENTER WING BOX	2	OCTOBER 1974	6,700	13,300
DC-10 AFT PYLON SKIN	3	AUGUST 1975	24,700	66,700
DC-10 UPPER AFT RUDDER	14*	APRIL 1976	27,600	243,100
727 ELEVATOR	10	MARCH 1980	12,600	108,000
L-1011 AILERON	8	MARCH 1982	7,110	53,110
S-76 TAIL ROTORS AND HORIZONTAL STABILIZERS	14	FEBRUARY 1979	4,200	41,300
206L FAIRING, DOORS, AND VERTICAL FIN	144**	MARCH 1981	3,050	176,000
CH-53 CARGO RAMP SKIN	1	MAY 1981	600	600
737 HORIZONTAL STAB.	4***	MARCH 1984	------	------
GRAND TOTAL	326			3,179,830

* 6 MORE RUDDERS TO BE INSTALLED

** 16 MORE COMPONENTS TO BE INSTALLED

*** 6 MORE STABILIZERS TO BE INSTALLED

APRIL 1984

Figure 7

TYPICAL IN-SERVICE CONDITION OF L-1011 KEVLAR/EPOXY FAIRINGS

During the past 11 years, the Kevlar/epoxy fairings on L-1011 aircraft have been inspected annually to document their condition. The photographs shown in figure 8 indicate various types of damage incurred in service. Minor impact damage from equipment and foreign objects has been noted on several fairings, primarily the honeycomb sandwich wing-to-body fairings. Surface cracks and indentations have been repaired with filler epoxy patches and, in general, the cracks have not propagated with continued service. Paint adherence has been a minor problem, in particular with parts that have been in contact with hydraulic fluid. Frayed fastener holes have been noted in several fairings. This condition is related to nonoptimum drilling and countersinking techniques used during assembly of the fairings in 1972. Several elongated fastener holes have been noted during the annual inspections. This condition is probably related to improper fit and nonuniform fastener load distribution for the fairings. None of the conditions noted above is considered to be major and, in general, the Kevlar/epoxy fairings performed similar to production fiberglass/epoxy fairings.

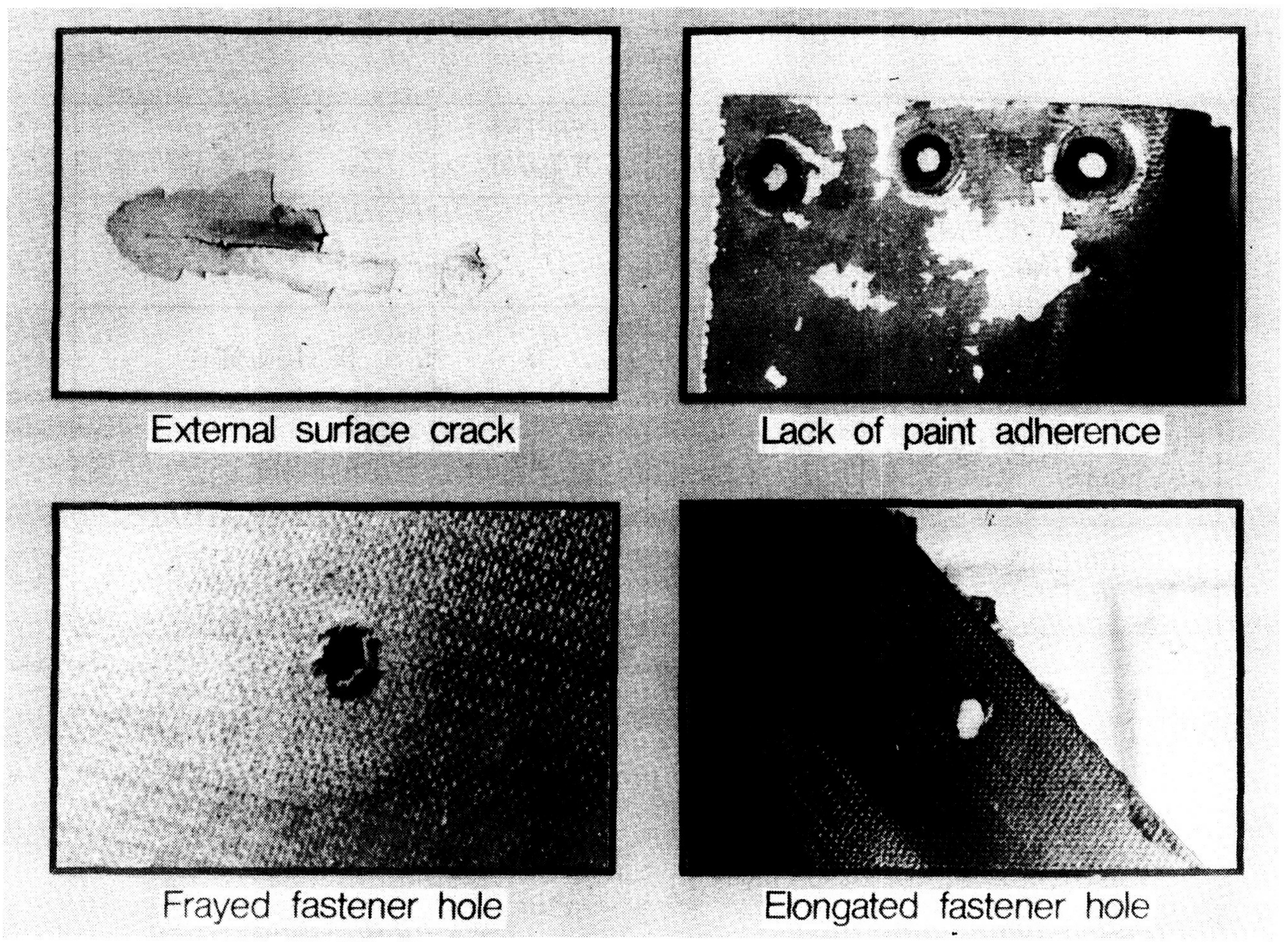

Figure 8

B-737 SPOILER IN-SERVICE DAMAGE AND REPAIR DURING 10 YEARS OF SERVICE

During the first 10 years of flight service, there have been 78 instances in which graphite/epoxy spoilers have received damage in service sufficient to require repair. Typical damage includes skin blisters, corrosion of the aluminum spar and doublers, miscellaneous cuts and dents, and trailing-edge delamination, as shown in figure 9. Over 40 percent of the damage incidents were caused by a design problem wherein actuator rod-end interference caused upper surface skin blisters. The actuator rods have been modified to prevent future damage. One-third of the repairs have been required as a result of corrosion damage to the aluminum spar and doublers. The corrosion initiated at a spar splice and is probably caused by moisture intrusion through a crack in the sealant material coupled with manufacturing defects in the aluminum surface preparation and corrosion protection scheme. There have been 12 incidents of cuts and dents caused by airline use and six trailing-edge delaminations that were apparently caused by normal aircraft maintenance and moisture intrusion. Minor repairs are currently being conducted by the airlines after proper instruction by Boeing. Because of the expense involved, spoilers with major damage are removed from service and retired from the program. Additional details on the spoiler inspection results are reported in reference 3.

PROBLEM	NUMBER OF INCIDENTS	PERCENT OF TOTAL	CAUSE
BLISTER ABOVE CENTER HINGE FITTING	34	44	DESIGN
SPAR AND DOUBLER CORROSION	26	33	DESIGN/MFG.
MISCELLANEOUS CUTS AND DENTS	12	15	AIRLINE USE
TRAILING-EDGE DELAMINATION	6	8	ENVIRONMENT

Figure 9

CORROSION OF B-737 GRAPHITE/EPOXY SPOILERS

Corrosion damage to the B-737 graphite/epoxy spoilers can be characterized by three phases of development (fig. 10). Phase 1 involves corrosion initiation at an aluminum fitting or at the aluminum spar splice. The corrosion is probably initiated by moisture intrusion through cracked paint and sealant material. If the corrosion is not repaired, the damage progresses to phase 2 where moisture is allowed to penetrate under the graphite/epoxy skin along the aluminum C-channel front spar. Normal service loads combined with the moisture contribute to crack initiation and subsequent corrosion between the graphite/epoxy skin and aluminum spar. If the phase 2 corrosion is not repaired, the damage progresses to phase 3 where extensive skin-to-spar separation takes place. The various phases of corrosion damage can result in significant spoiler strength reductions as will be shown in figure 11. There have been no incidents of galvanic corrosion between the graphite/epoxy skins and the aluminum honeycomb substructure. In addition, post-test teardown and core plug samples have not indicated any moisture intrusion into the aluminum honeycomb.

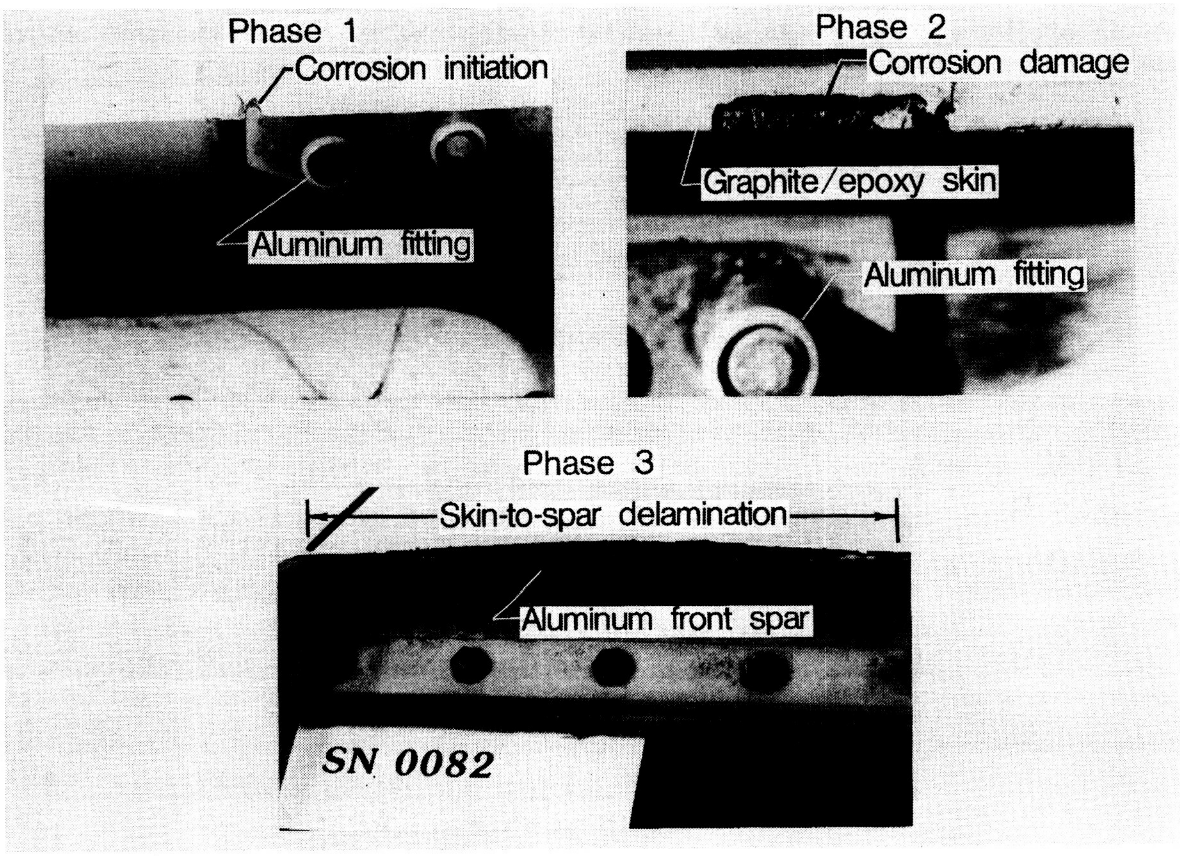

Figure 10

RESIDUAL STRENGTH OF GRAPHITE/EPOXY SPOILERS

Three graphite/epoxy spoilers, one of each material system used in fabricating the spoilers, have been removed from service annually for the past nine years to establish residual strengths. The test results are compared with the strength of 16 new spoilers in figure 11. The strength for each spoiler through six years of service generally falls within the same scatter band as was defined by the strengths of the new spoilers. However, spoilers with significant corrosion damage which were tested after seven and eight years of service, respectively, indicated a 35-percent strength reduction. An additional T300/2544 spoiler with essentially no corrosion damage was tested after seven and one-half years of service to verify that the seven-year strength reduction was in fact related to corrosion damage. Also, three spoilers tested after nine years of service with little or no corrosion damage exhibited strengths equal to the strength of new spoilers with no service hours. In general, spoilers that have been tested after being repaired have not shown any significant strength reduction due to the repairs. The NASA flight-service contract with Boeing has been extended to 15 years. Additional spoiler tests are planned to be conducted after 10, 12, and 15 years of service. Strength retention of the spoilers will be correlated with the size of disbonds that are caused by corrosion damage.

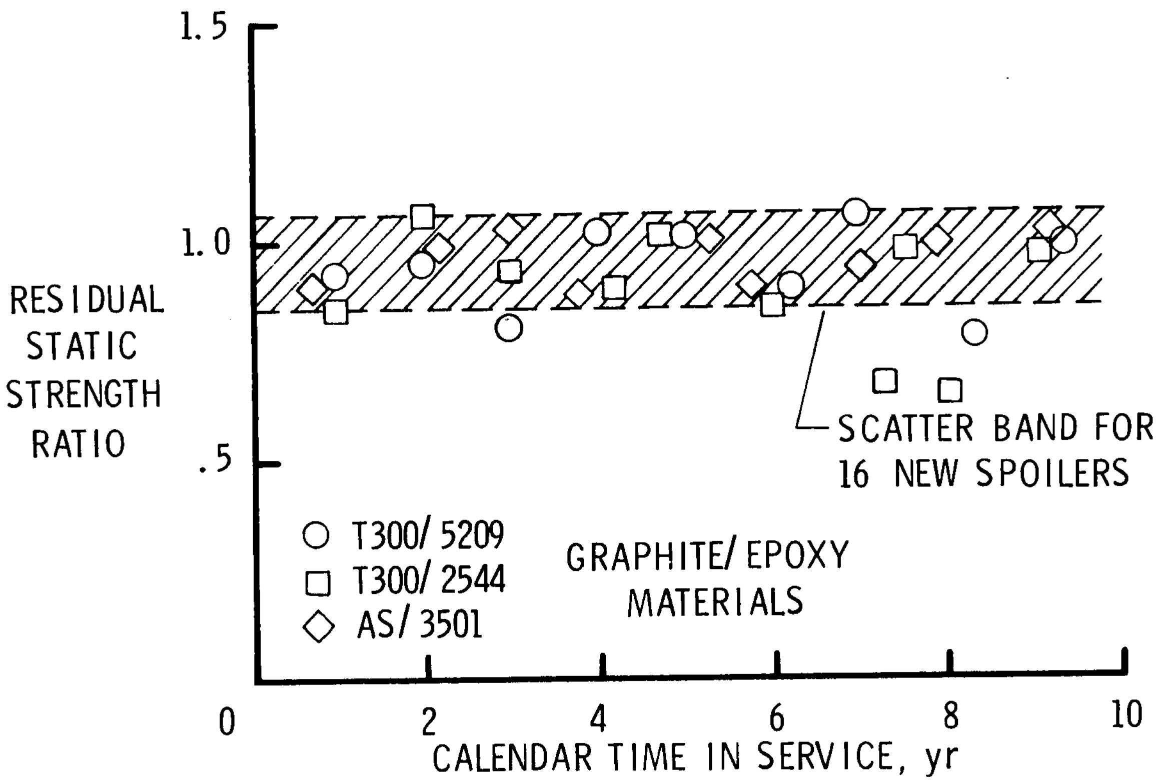

Figure 11

LOAD DEFLECTION RESPONSE OF T300/2544 GRAPHITE/EPOXY SPOILERS FOR B-737 AIRCRAFT

The load deflection respsonse of two T300/2544 graphite/epoxy spoilers tested after eight and nine years, respectively, is compared with a baseline (no service) spoiler in figure 12. The eight-year spoiler with 20,364 flight hours on Piedmont failed at 160 percent of limit load compared to 246 percent limit load for the baseline spoiler. The eight-year spoiler had doubler corrosion and some exfoliation corrosion of the aluminum spar. Note that the eight-year spoiler strength is still above the design ultimate load requirement as indicated in figure 12. The nine-year spoiler with 23,433 flight hours on Piedmont failed at 236 percent of limit load. The nine-year spoiler had some minor corrosion products near the center hinge fitting; however, the corrosion damage was not as severe as for the eight-year spoiler. The stiffness variation between the eight- and nine-year spoilers is typical of other spoilers tested throughout the program. In general, more extensive corrosion causes more skin-to-spar separation and a subsequent reduction in overall spoiler stiffness.

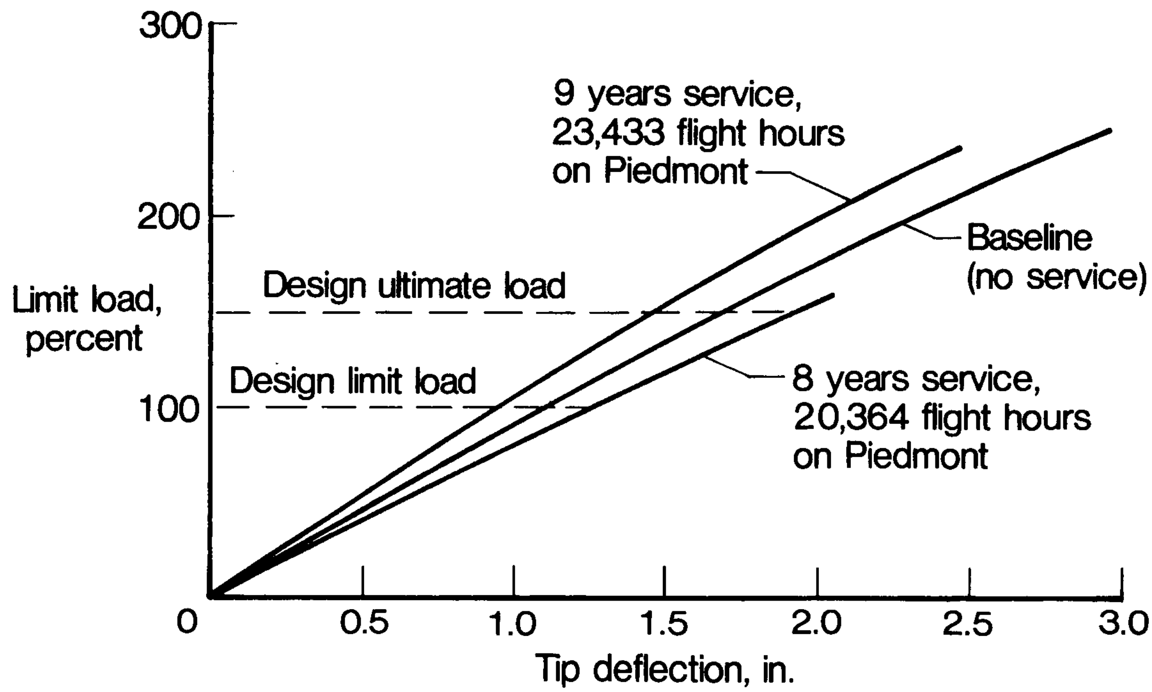

Figure 12

SPOILER MOISTURE LEVELS DETERMINED FROM PLUGS

In addition to structural tests of the spoilers, tests have been conducted to determine absorbed moisture content of the graphite/epoxy skins. The moisture content is determined from plugs cut near the trailing edge as shown in figure 13. The plugs consist of aluminum honeycomb core, two graphite/epoxy facesheets, two layers of epoxy film adhesive, and two exterior coats of polyurethane paint. About 90 percent of the plug mass is in the composite faces, including the paint and adhesive. The moisture content is determined by drying the plugs and recording the mass change. The data shown in figure 13 for plugs removed from three spoilers after nine years of service indicate moisture levels in the graphite/epoxy skins ranging from 0.59 to 0.90 percent for T300/5209, T300/2544, and AS/3501 material systems. The moisture levels for the T300/5209 and AS/3501 systems are similar to moisture levels determined for unpainted material coupons exposed to worldwide outdoor environments. However, the moisture content of 0.90 percent for the T300/2544 plugs is only about one-half the moisture content of the unpainted material coupons. Severe ultraviolet radiation degradation to the T300/2544 unpainted material coupons may explain part of the difference in moisture absorption. Additional results for the material coupons are presented in a subsequent figure.

9 YEARS SERVICE

GRAPHITE/EPOXY	MOISTURE CONTENT PERCENT	AIRLINE
T300/5209	0.59	LUFTHANSA
T300/2544	0.90	PIEDMONT
AS/3501	0.86	PIEDMONT

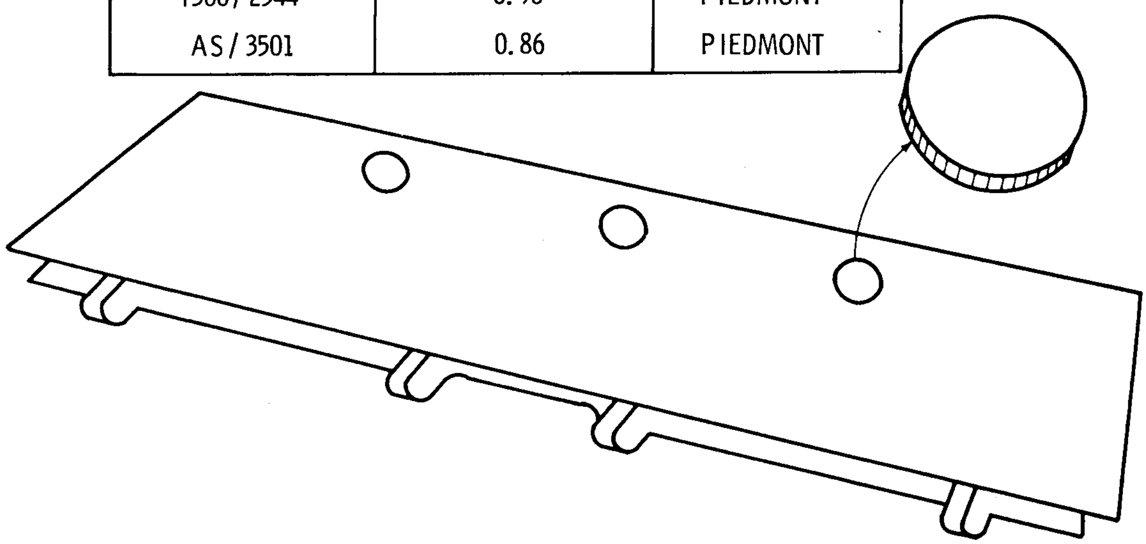

Figure 13

DC-10 GRAPHITE/EPOXY RUDDER DAMAGE

Six DC-10 graphite/epoxy rudders have sustained minor damage since entering into commercial service in 1976. There have been two rudders with minor rib-to-skin disbonds, three rudders with minor lightning strikes, and one rudder sustained rib damage during ground handling while the rudder was off the aircraft. Figure 14 shows photographs of the most severe lightning strike and the rib damage. The lightning damage was localized in an area measuring approximately 0.5 inch by 1.5 inches near the trailing edge of the structural box. Damage was limited to the outer four layers of graphite/epoxy and a room temperature repair was performed in accordance with procedures established at the time the rudders were certified by the FAA. The rib damage was more extensive and a portion of a rib had to be removed and rebuilt. A detailed discussion of the repair procedure is given in reference 11. After completion of the repair, the rudder was returned to the airline for continuation of service.

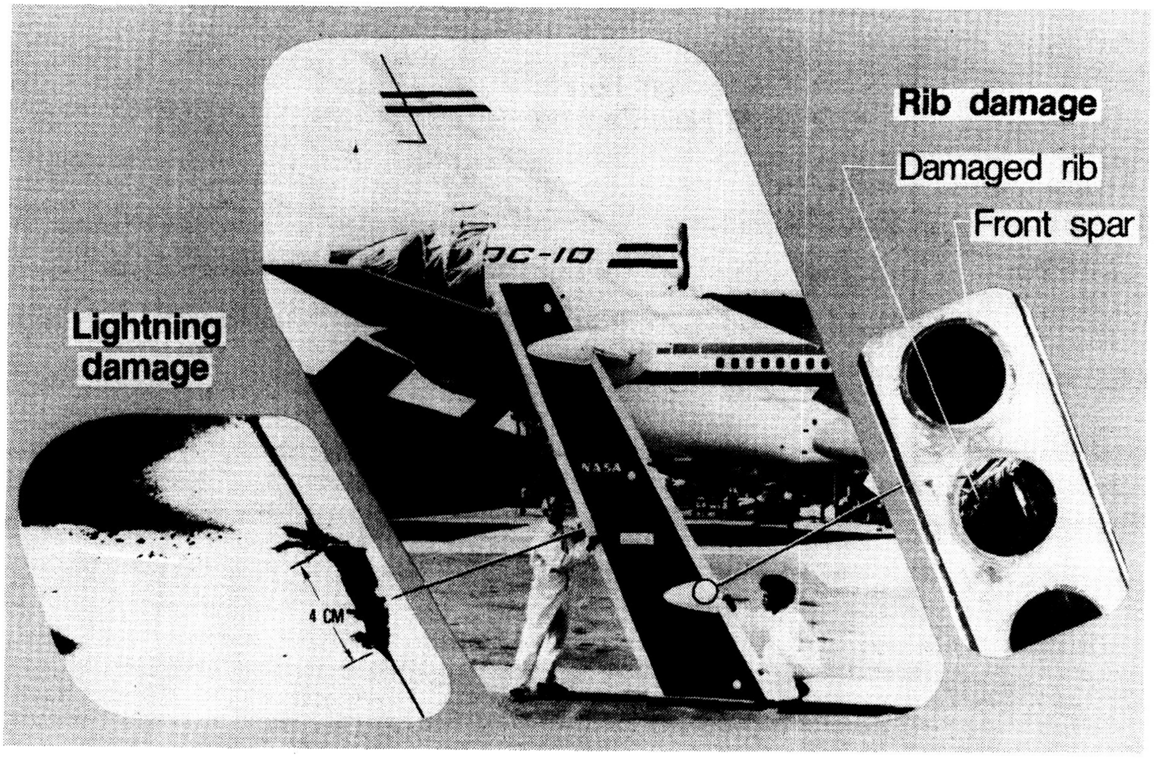

Figure 14

LOAD DEFLECTION RESPONSE OF T300/5208 GRAPHITE/EPOXY RUDDERS
FOR DC-10 AIRCRAFT

A DC-10 graphite/epoxy rudder was removed from service for residual strength testing after 5.7 years and 22,265 flight hours on Air New Zealand. The load deflection response shown in figure 15 indicates that the 5.7-year rudder had an initial stiffness higher than the baseline rudder but the overall response is similar for the two rudders. The baseline and the 5.7-year tests were stopped at approximately 400-percent limit load because of instability of the loading apparatus. Although the rudders are designed by stiffness considerations and only one residual strength test has been conducted, the overall response of the rudder indicates that no degradation has occurred as a result of 22,265 flight hours.

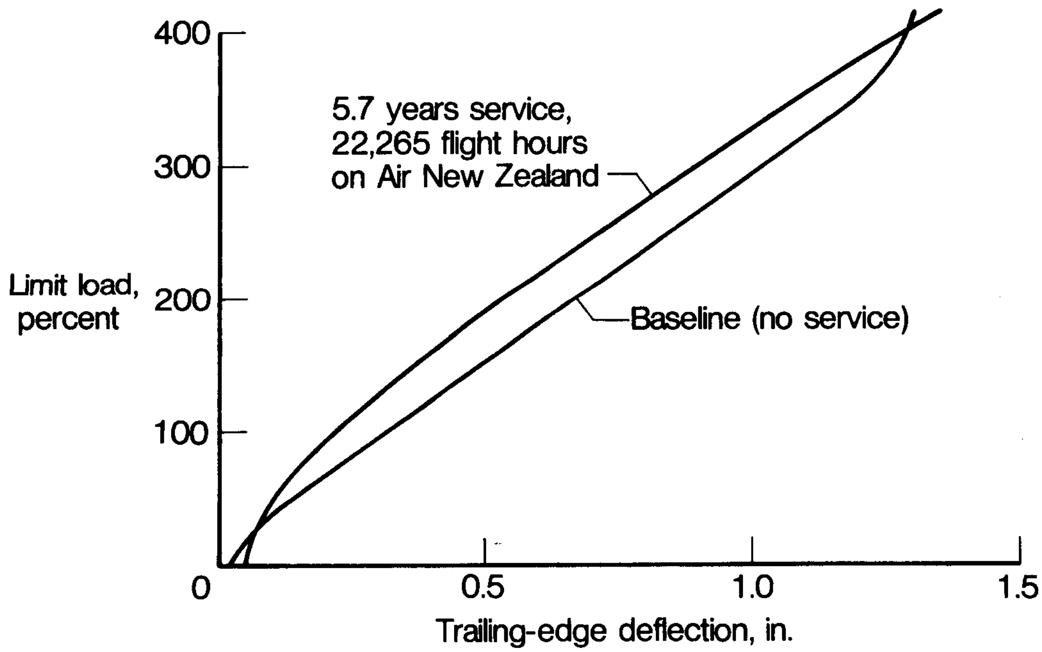

Figure 15

B-727 GRAPHITE/EPOXY ELEVATOR DAMAGE

Since initiation of flight service in 1980, there have been two B-727 graphite/epoxy elevators damaged by minor lightning strikes and two elevators damaged during ground handling. Figure 16 shows typical lightning damage to the trailing edge of an elevator and trailing-edge fracture of another elevator caused by impact from a deicing apparatus while the aircraft was being serviced. Damage from lightning strikes ranged in severity from scorched paint to a minor skin delamination. The most severe damage to an elevator occurred during a ground collision at Portland, Oregon, in 1982. Skin panels were punctured, four holes in the lower surface and one hole in the upper surface, and the lower horizontal flange at the front spar was cut inboard of the outboard hinge. All the elevator repairs were performed by United Airlines maintenance personnel in San Francisco, California. The lightning damage was repaired with epoxy filler and milled glass fibers. The skin punctures were repaired with T300/5208 prepreg fabric and Nomex honeycomb core plugs. The front spar was repaired with a machined titanium doubler, which was mechanically fastened to the lower skin flange of the spar chord.

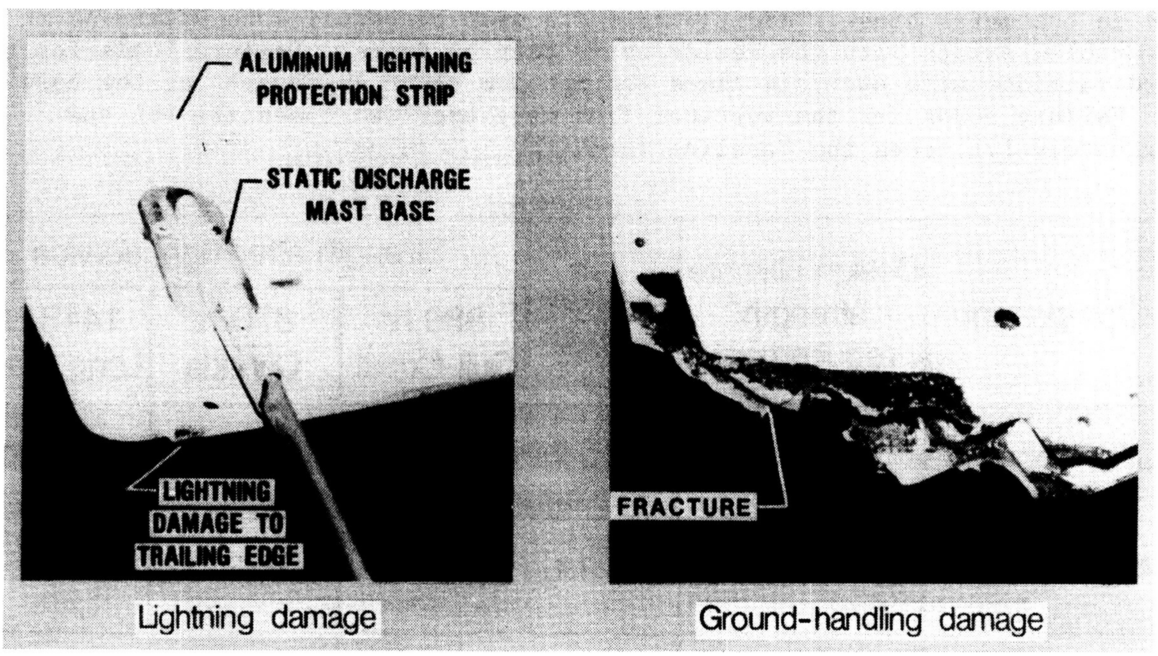

Figure 16

EFFECT OF ONE-YEAR FLIGHT SERVICE ON STRENGTH OF BELL 206L COMPOSITE COMPONENTS

Three sets of Bell 206L composite components have been statically tested after one year of flight service. The components were removed from helicopters flying in the following areas: U.S. Gulf Coast, Canada, and Long Island, NY, and had 880, 870, and 1413 flight hours, respectively, at the time of removal (figure 17). Average failure load for the litter doors was approximately 1.6 times the design ultimate load (DUL) and 85 percent of the baseline average strength. All litter doors failed by the latch pins slipping from the test fixture. The baggage door from the Gulf Coast failed at 1.8 times the DUL and 1.3 times the baseline average strength. The baggage door from Canada failed at 1.08 times the DUL and at 77 percent of the baseline average. The baggage door from Long Island failed at 63 percent of the DUL and 45 percent of the baseline strength. This baggage door failed by a large disbond between the outer skin and the honeycomb core. The lack of an adhesive layer between the outer skin and the honeycomb core could possibly explain the poor bond strength. The other baggage doors (U.S. Gulf Coast and Canada) failed in the metal hinge. Additional tests will be required to determine if a major problem exists with the Kevlar/epoxy baggage doors. Failure loads for the forward fairings were over six times the DUL and about 70 percent of the baseline load. Failure loads for the vertical fins were over two times the DUL and approximately 1.1 times the baseline load.

Component	Design ultimate strength requirement	Baseline strength	Strength after flight service		
			880 hr Gulf Coast	870 hr Canada	1413 hr Long Island
Litter door	634 lb	1215 lb	1009 lb	980 lb	1115 lb
Baggage door	440 lb	613 lb	795 lb	473 lb	275 lb
Forward fairing	0.30 psi	3.13 psi	1.80 psi	2.50 psi	1.80 psi
Vertical fin	1040 lb	2097 lb	2497 lb	2219 lb	2100 lb

Figure 17

EFFECT OF GROUND-BASED EXPOSURE ON STRENGTH OF COMPOSITE MATERIALS USED TO FABRICATE BELL 206L COMPONENTS

The average strength retention ratios for two material systems used in the 206L flight service components are shown in figure 18 after one and three years of outdoor exposure. Three different tests, short-beam shear (SBS), IITRI (Illinois Institute of Technology Research Institute) compression, and tension, were conducted to establish strength as a function of exposure time. The Kevlar/epoxy used in the baggage doors exhibited the lowest strength retention of the three Kevlar/epoxy material systems used in the components. The lowest strength retention, 0.85, was for compression specimens exposed at Ft. Greely, AK, and Toronto, Canada, after one and three years of exposure, repsectively. The specimens exposed for three years in Ft. Greely, AK, will be tested in the summer of 1984. The graphite/epoxy materials used in the vertical fin did not indicate any significant changes in strength after one or three years of exposure at any of the exposure locations indicated in figure 18. Additional tests will be conducted after 5, 7, and 10 years of exposure.

Material-component	Exposure location	Strength retention ratio*					
		1 yr exposure			3 yr exposure		
		SBS	COMP	TEN	SBS	COMP	TEN
Kevlar/ LRF-277 baggage door style 120 fab. (0/90/±45)	Cameron, LA	0.93	0.94	1.03	0.87	0.87	1.04
	Oil platform**	0.90	0.93	0.99	0.90	0.86	1.02
	Hampton, VA	0.97	0.89	1.00	0.90	0.90	1.03
	Toronto, Canada	0.95	0.89	1.04	0.90	0.85	1.05
	Ft. Greely, AK	0.88	0.85	1.02	—	—	—
T-300/E-788 vertical fin (0/±45/0)	Cameron, LA	1.01	1.03	0.97	1.01	0.91	1.01
	Oil platform**	1.02	1.00	0.97	1.04	0.93	1.01
	Hampton, VA	1.02	1.01	1.01	1.04	1.00	1.01
	Toronto, Canada	1.00	1.01	1.08	1.07	0.98	1.02
	Ft. Greely, AK	0.97	1.02	1.00	—	—	—

$$^{*}\text{Strength retention ratio} = \frac{\text{strength (exposed)}}{\text{strength (baseline)}}$$

**Gulf of Mexico

Figure 18

EFFECT OF SERVICE ENVIRONMENT ON S-76 COMPOSITE TAIL ROTOR SPARS

Full-scale fatigue tests have been conducted on six graphite/epoxy S-76 tail rotor spars removed from commercial service and the results are shown in figure 19. Two spars had 25 months and 150 hours of service on a Sikorsky flight test helicopter in West Palm Beach, FL, and four of the spars were removed from helicopters operating in the Lake Charles, LA, area with up to 49 months and 3358 hours of service. The test results are compared to the baseline room temperature dry strength of 10 spars tested for FAA certification. The results indicate that the minimum strength retention is 93 percent of the FAA certification curve shown in figure 19. These results compare well with strength retention factors projected from laboratory-conditioned specimens (ref. 10). Additional tests will be conducted on tail rotor spars with up to eight years of service.

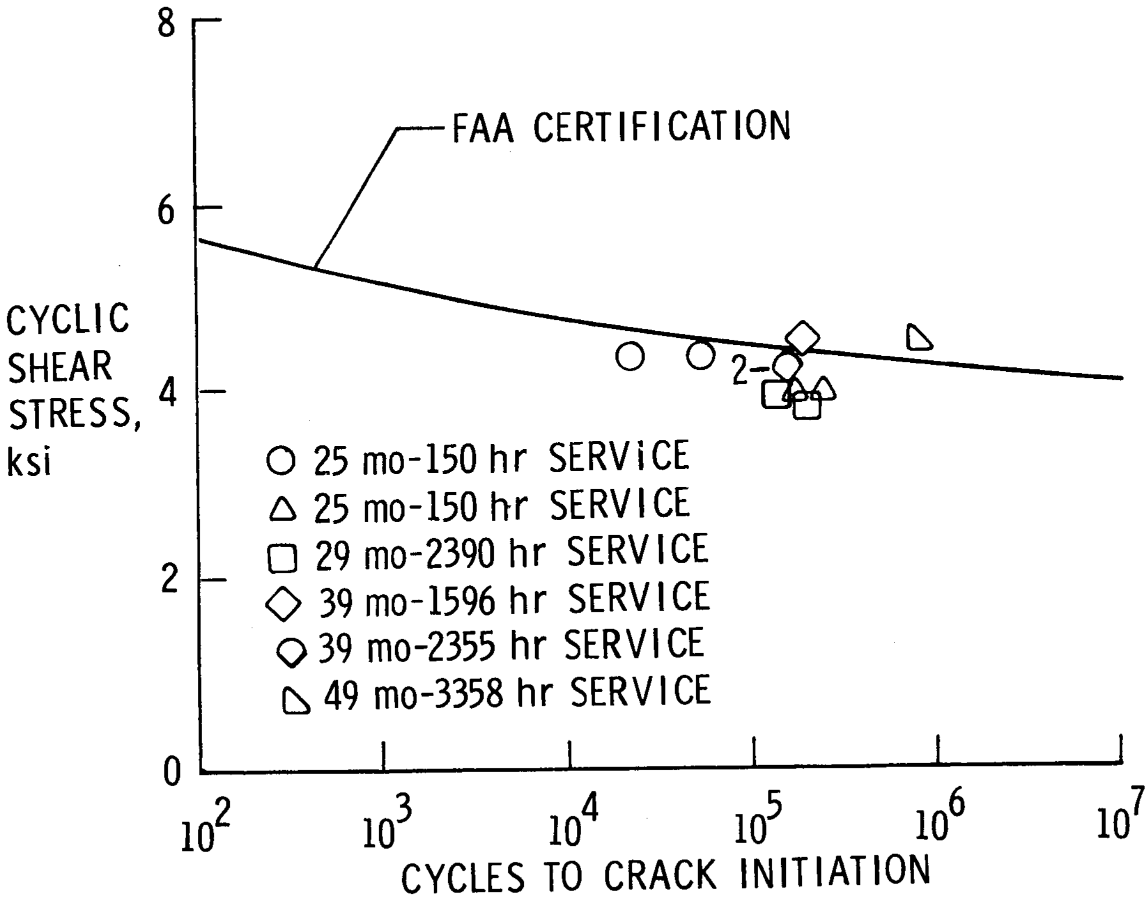

Figure 19

EFFECT OF THREE YEARS GROUND-BASED EXPOSURE ON STRENGTH OF SIKORSKY S-76 COMPOSITE MATERIALS

Results of tests conducted on specimens machined from panels exposed for three years at Stratford, CT, and West Palm Beach, FL, are shown in figure 20. Short-beam shear (SBS), flexure, and tension tests were conducted to establish strength retention factors. The lowest strength retention, 0.78, occurred for the 6-ply graphite/epoxy SBS specimens exposed at West Palm Beach, FL. In addition to strength tests, moisture contents were measured for all the panels after outdoor exposure and the results are shown in figure 20. Laboratory-conditioned specimens were tested during the design phase of the S-76 production program and strength as a function of moisture content was established (ref. 10). The SBS strength for the outdoor exposed specimens closely follows the trend for the laboratory-conditioned specimens. The three-year flexure strength for the outdoor-exposed specimens is slightly higher than the flexure strength for the laboratory conditioned specimens. The moisture content of coupons machined from two spars that had 37 months of service ranged from 0.46 to 0.55 percent. The coupons were removed from the 14-ply thick area of the spars and the results compare well with the 14-ply moisture data presented in figure 20 for three-years exposure at Stratford, CT.

Material	Number of plies	Exposure location	Measured moisture (percent weight)	Strength retention ratio*		
				SBS	Flexure	Tension
Graphite/epoxy	6	Stratford, CT	1.00	0.83	0.79	—
Graphite/epoxy	14		0.48	0.81	1.02	—
Graphite/epoxy	33		0.23	0.87	1.02	—
Kevlar/epoxy	5		1.72	—	—	1.06
Graphite/epoxy	6	W. Palm Beach, FL	1.22	0.78	0.80	—
Graphite/epoxy	33		0.37	0.89	0.98	—
Kevlar/epoxy	5		2.08	—	—	1.07

$$*\text{Strength retention ratio} = \frac{\text{strength (exposed)}}{\text{strength (baseline)}}$$

Figure 20

MOISTURE ABSORPTION OF 6-PLY GRAPHITE/EPOXY PANELS
EXPOSED AT WEST PALM BEACH, FL

A moisture absorption analysis was made for 6-ply graphite/epoxy panels exposed at West Palm Beach, FL (WPB). Average weather bureau data for WPB were used to generate the predicted moisture absorption curve shown in figure 21. The test points shown in figure 21 after two and three years of exposure are the average of four specimens machined from two panels. The test results are in good agreement with the predicted results.

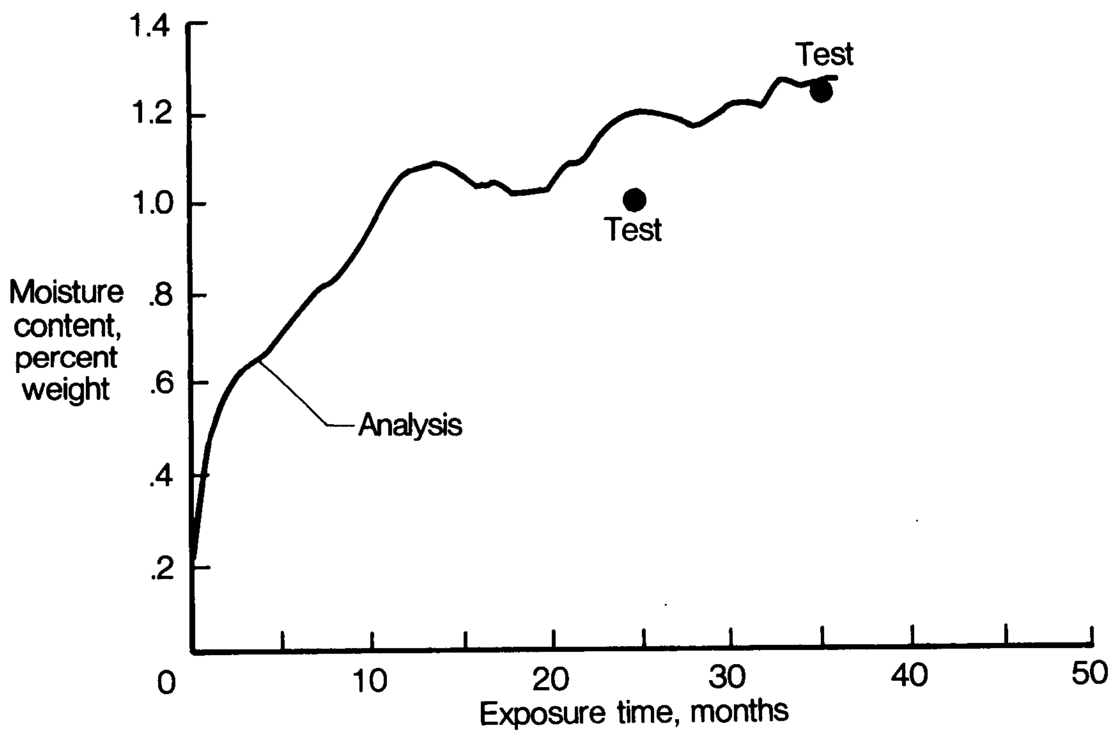

Figure 21

WORLDWIDE ENVIRONMENTAL EXPOSURE OF COMPOSITE MATERIALS USED IN FLIGHT SERVICE PROGRAMS

Concurrent with the flight service evaluation of composite structural components, NASA Langley initiated a program to determine the outdoor environmental effects on composite materials used in fabrication of the flight components (fig. 22). Unstressed short-beam shear, compression, and flexure specimens have been exposed in racks outdoors for 10 years at NASA Langley in Hampton, VA; San Diego, CA; Honolulu, HA; Wellington, New Zealand; São Paulo, Brazil; and Frankfurt, W. Germany. Tension specimens under a sustained load of 25 percent ultimate have been exposed for 10 years at NASA Langley and San Francisco, CA. Residual strength tests have been conducted after 1, 3, 5, 7, and 10 years of exposure and the results are compared with baseline (no exposure) test results. In addition to strength tests, moisture absorption measurements have been made for six different composite material systems.

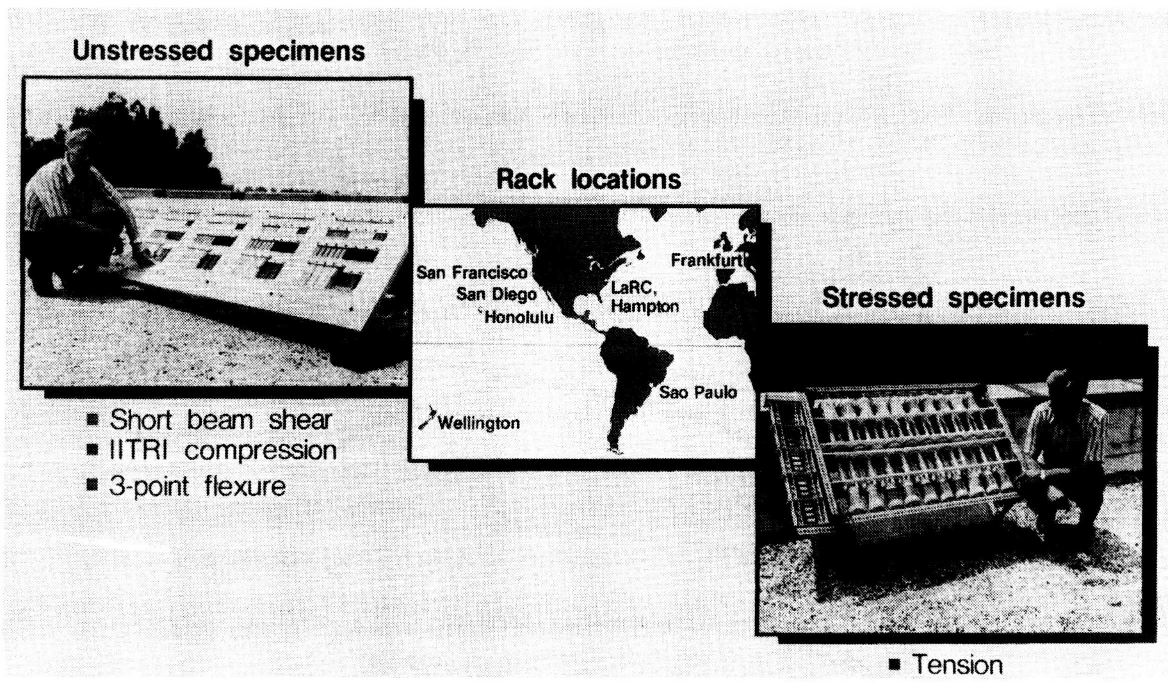

Figure 22

MOISTURE ABSORPTION OF COMPOSITE MATERIALS AFTER WORLDWIDE OUTDOOR EXPOSURE

The moisture contents of four graphite/epoxy and two Kevlar/epoxy material systems after seven years of exposure at six exposure sites are shown in figure 23. The data shown were obtained from flexure coupons that were exposed on outdoor racks located at NASA Langley in Hampton, VA; San Diego, CA; Honolulu, HA; Wellington, New Zealand; São Paulo, Brazil; and Frankfurt, W. Germany. Each data point represents an average value for 18 specimens, three at each of the six exposure locations. The Kevlar/epoxy materials indicate moisture levels above 2.0 percent after seven years of exposure. The T300/2544 graphite/epoxy material indicated a decrease in moisture content from 2.0 percent after five years of exposure to 1.8 percent after seven years of exposure. The reduction may possibly be related to severe ultraviolet degradation of the 2544 epoxy matrix. The AS/3501 graphite/epoxy material appears to have stabilized at about 1.0 percent moisture, although a slight downward trend is noted after seven years of exposure. The T300/5209 and T300/5208 graphite/epoxy materials appear to have stabilized at approximately 0.6 percent moisture. In general, the specimens exposed at São Paulo, Brazil, had the highest moisture content. This result is somewhat expected since the average annual relative humidity is about 80 percent at São Paulo. The specimens exposed for 10 years are currently being dried in an oven to establish moisture content.

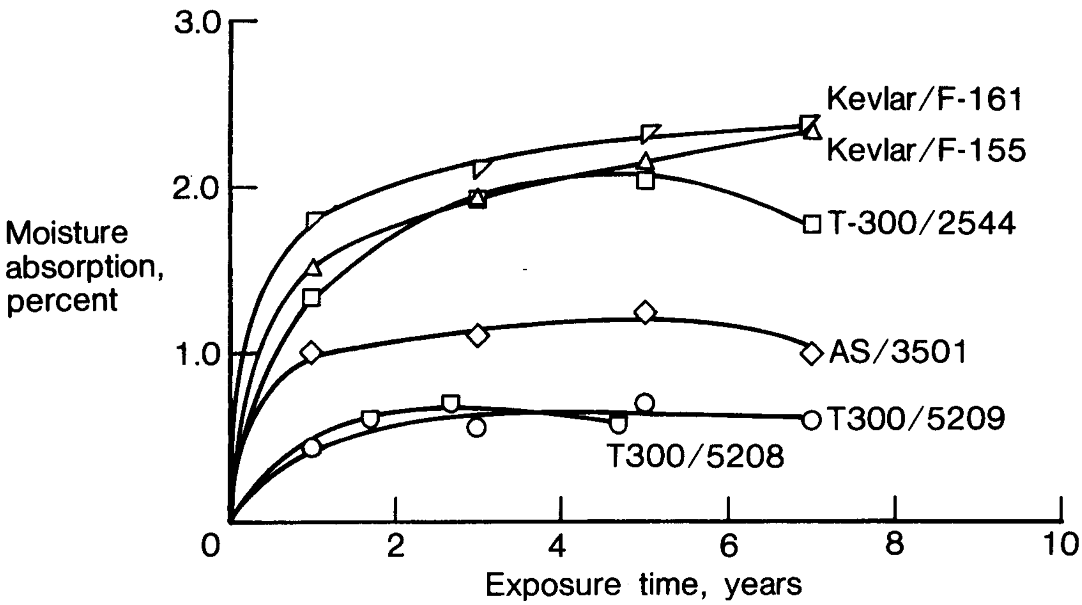

Figure 23

RESIDUAL STRENGTH OF COMPOSITE MATERIALS AFTER WORLDWIDE EXPOSURE

Residual strength data for unpainted graphite/epoxy and Kevlar/epoxy specimens exposed for 10 years at six exposure sites are shown in figure 24. The data points represent a comparison of the average strength value at six exposure sites with the average baseline strength value for that material system. The shaded area represents a plus-or-minus 10-percent scatter in the baseline strength values. Three-point flexure, IITRI compression, and short-beam shear tests were conducted on three replicate specimens after 1, 3, 5, 7, and 10 years of outdoor exposure. Since the T300/5208 material entered the exposure program at a later date, the exposure times are different than for the other five material systems. Also, the 10-year specimens from the Brazil exposure rack were not to be tested until the summer of 1984 because of a later deployment date. Results of the flexure tests indicate that the two Kevlar/epoxy materials and the T300/2544 graphite/epoxy material incurred the largest strength loss after 10 years of exposures. These three materials also had the highest moisture content, approximately 2.0 percent, and the T300/2544 material incurred the most severe surface degradation from ultraviolet radiation. The compression and shear tests indicate a similar trend in that the same three materials show the largest strength reduction after 10 years of exposure. Over the 10-year period the shear and compression specimens show a consistently slightly higher strength reduction than the flexure specimens. This trend indicates that the shear and compression specimens are more sensitive to matrix degradation and moisture than the flexure specimens.

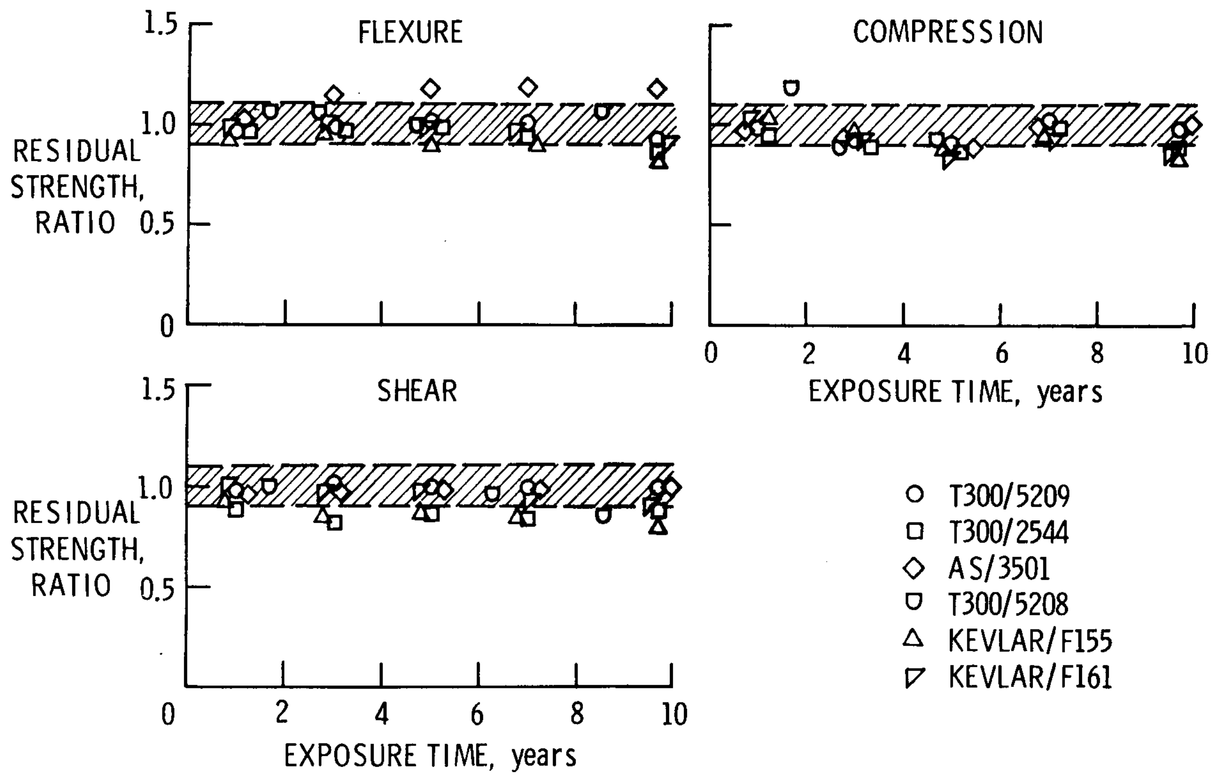

Figure 24

EFFECT OF EXPOSURE LOCATION AND TIME ON COMPRESSION STRENGTH OF COMPOSITE MATERIALS

Compression strength data for three material systems, T300/5209 (250°F cure), Kevlar-49/F-155 (250°F cure), and AS/3501 (350°F cure), are shown in figure 25 to indicate the effect of exposure location. Note that the 10-year Brazil data are not yet available. Each data point is the average of three tests for a particular exposure time and exposure location. Average annual temperature and relative humidity data obtained from the U. S. Air Force indicate that Frankfurt, W. Germany, has the lowest average annual temperature of 49°F and Honolulu, Hawaii, has the highest temperature of 77°F of the six exposure locations. The relative humidity is similar for most of the exposure locations with a range from about 70 percent in Hawaii to about 80 percent in Brazil. The data shown in figure 25 do not indicate any definite trend for the most severe environment. The Kevlar-49/F-155 material shows a consistent compression strength reduction during the 10-year period. A maximum reduction of 27 percent is shown for the specimens exposed in Hawaii. The data for the T300/5209 and AS/3501 materials are somewhat more erratic with the maximum strength reduction occurring after five years of exposure at New Zealand.

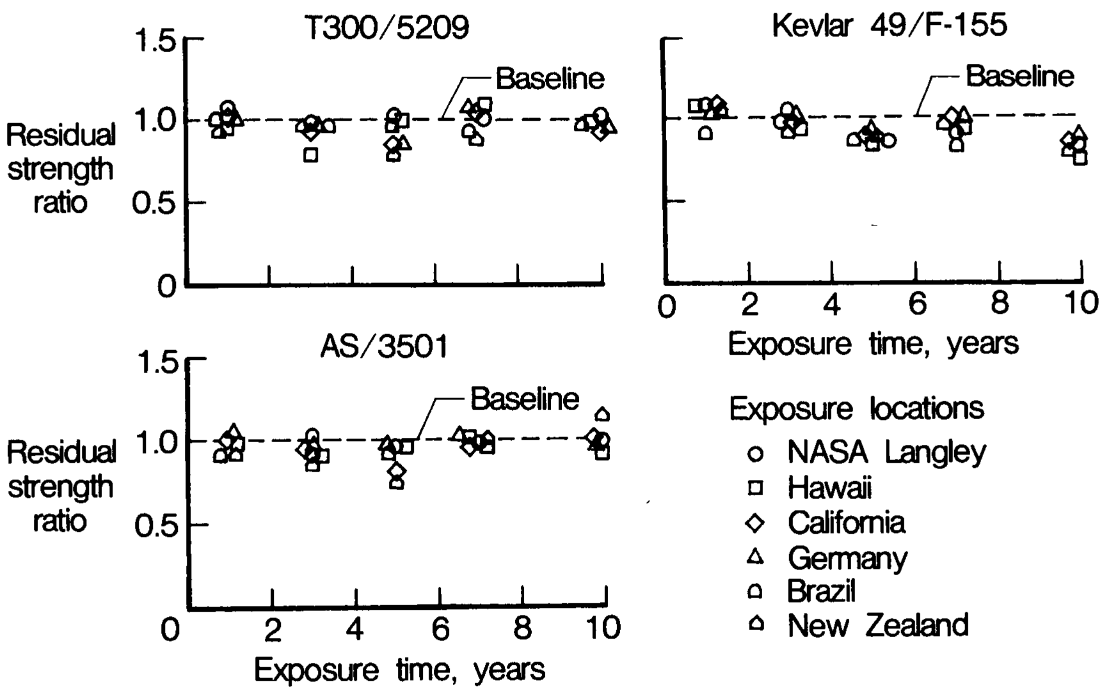

Figure 25

SURFACE DEGRADATION OF UNPAINTED COMPOSITE MATERIALS

Scanning electron micrographs were taken of AS/3501 graphite/epoxy and Kevlar-49/F-155 flexure specimens with no outdoor exposure and seven years of outdoor exposure. The micrographs shown on the left of figure 26 indicate that the surface fibers are coated with resin for the specimens with no outdoor exposure. The micrographs on the right of figure 26 indicate that the surface fibers are exposed due to ultraviolet degradation of the surface layer of epoxy. These micrographs substantiate the need to keep composite aircraft structure painted to prevent utlraviolet radiation damage to composite matrix materials. Controlled laboratory weatherometer test results reported in reference 12 indicated that polyurethane aircraft paint offered substantial protection against ultraviolet degradation.

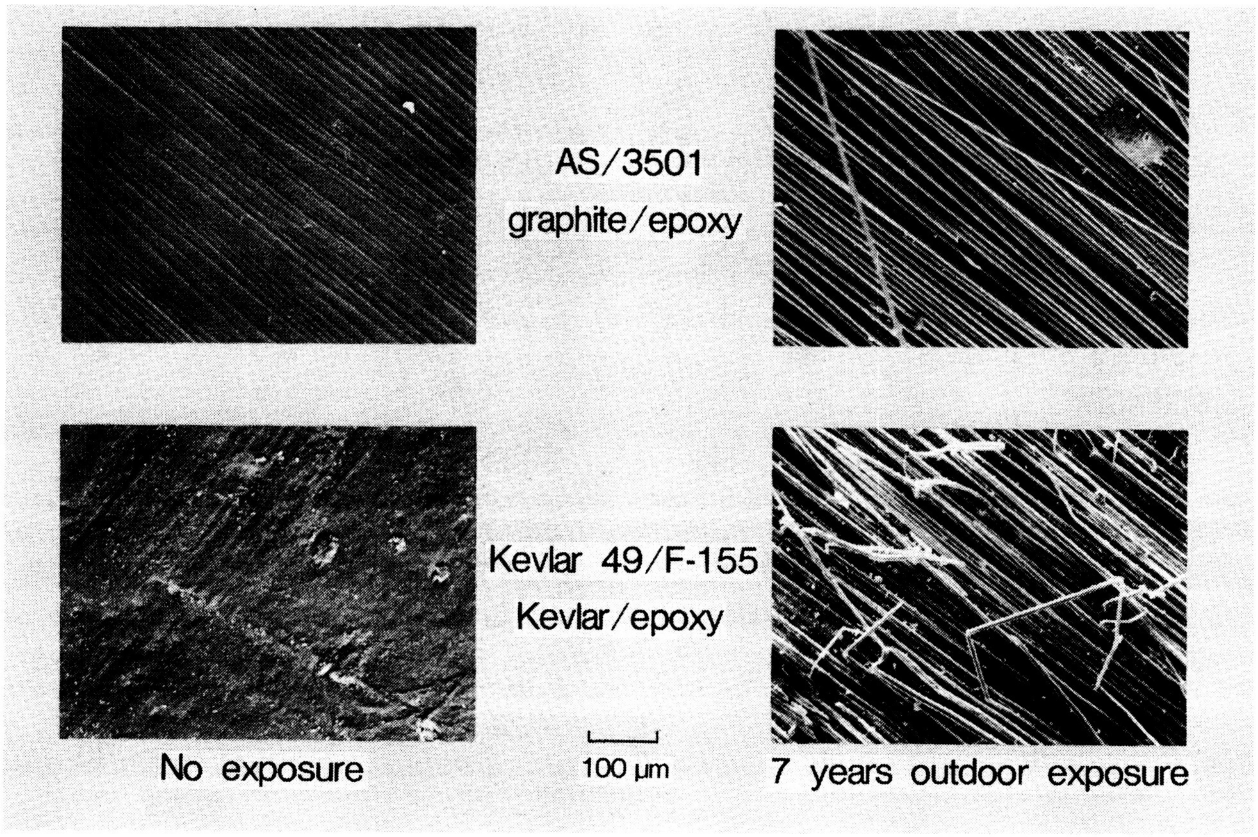

Figure 26

RESIDUAL TENSILE STRENGTH AFTER SUSTAINED-STRESS OUTDOOR EXPOSURES

Effects of sustained-stress during outdoor environmental exposure are being evaluated by exposing tension specimens to 40 percent of ultimate baseline strength. Residual tensile strengths of T300/5208 quasi-isotropic laminated specimens after seven years of outdoor exposure at the Langley Research Center in Hampton, VA, and San Francisco, CA, are shown in figure 27. The residual tensile strength is within the scatter band for the strength of unexposed specimens. Results indicate that the T300/5208 quasi-isotropic tensile specimens were unaffected by either outdoor environment or sustained tensile stress at the two exposure sites indicated. Additional data will be obtained after 10 years of outdoor exposure.

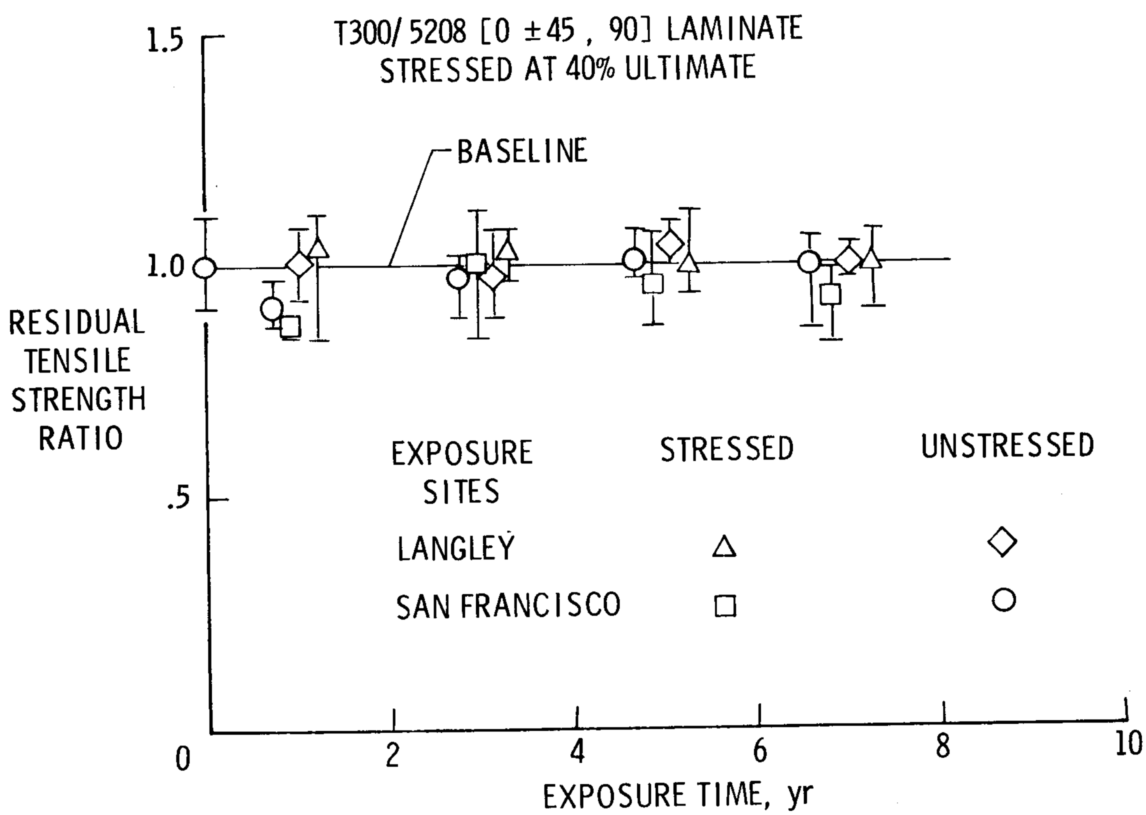

Figure 27

EFFECT OF AIRCRAFT FLUIDS ON COMPOSITE MATERIALS AFTER FIVE YEARS OF EXPOSURE

Although aircraft composite structures are exposed almost continuously to various levels of moisture in the atmosphere, they are frequently exposed to various other fluids used in aircraft such as fuel and hydraulic fluid. The effects of various combinations of these fluids on composite materials have been evaluated after five years of exposure. Specimens were exposed to six different environmental conditions as follows: ambient air, water, JP-4 fuel, Skydrol hydraulic fluid, fuel/water mixture, and fuel/air cycling. The water, JP-4 fuel, and Skydrol were replaced monthly to maintain fresh exposure conditions. Specimens exposed in the fuel/water mixture were positioned with the fuel/water interface at the center of the test specimens. The fuel/air cycling environment consisted of 24 hours of fuel immersion followed by 24 hours of exposure to air. Residual tensile strengths of T300/5208 graphite/epoxy, T300/5209 graphite/epoxy, and Kevlar-49/5209 specimens after strength exposure to the six environments are shown in figure 28. The residual tensile strength of T300/5208 was not degraded by any of the six environments indicated in figure 28. The most degrading environment on the T300/5209 and Kevlar-49/5209 materials was the fuel/water combination. The T300/5209 specimens lost about 11 percent in tensile strength, whereas the Kevlar-49/5209 specimen lost about 25 percent in tensile strength. The ambient air results are consistent with other data obtained from the NASA Langley sponsored ground and flight environmental studies. The tests reported in figure 28 were more severe than actual aircraft flight exposures and the results should represent an upper bound on material property degradation. Additional details on the five-year exposure program, including interlaminar shear test results, can be found in reference 13.

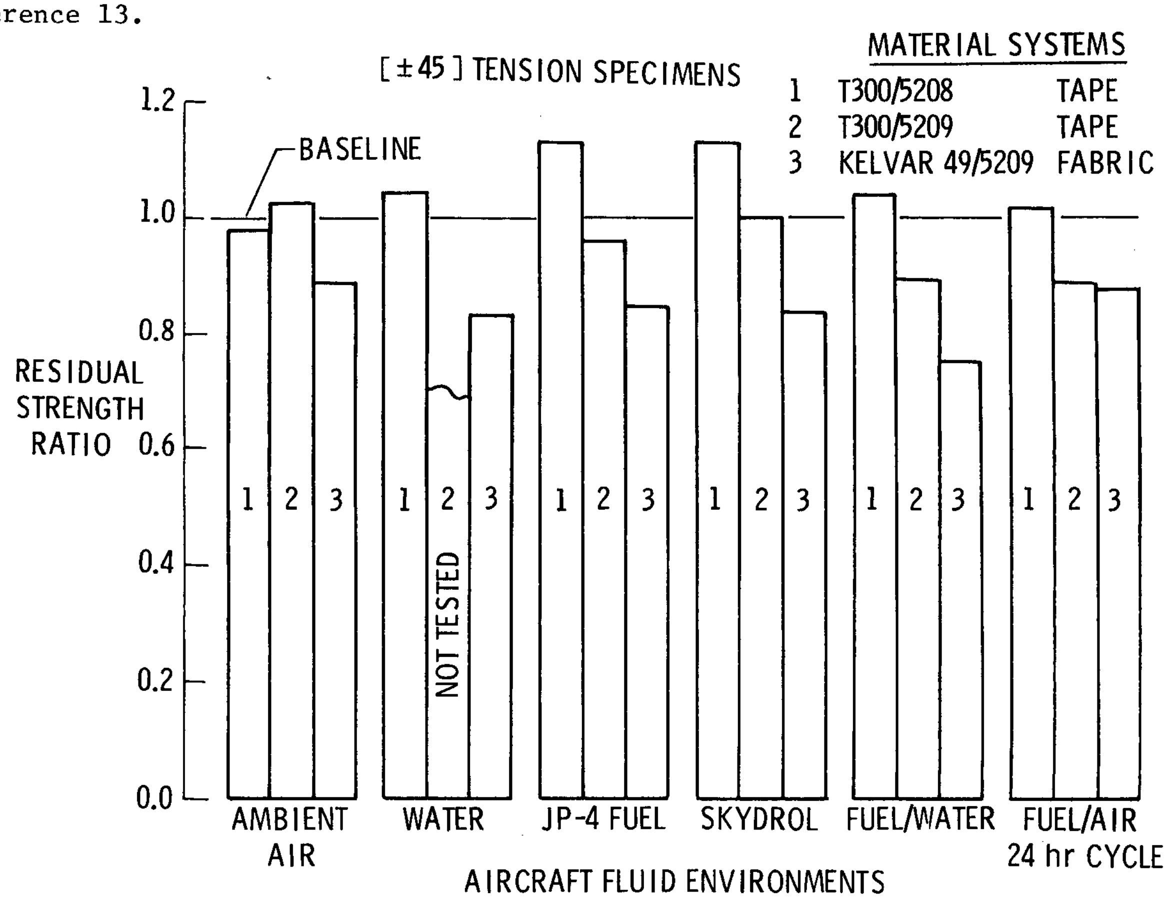

Figure 28

OUTDOOR SUSTAINED-LOAD ENVIRONMENTAL TESTS ON GRAPHITE/EPOXY BOLTED WING SPLICES

Graphite/epoxy panels with bolted joints representative of commercial transport wing splices are being exposed outdoors under a sustained load of 25 percent of the static ultimate to establish the effect of environment on residual strength. The test specimens are installed in loading frames as shown in figure 29. The laminates are approximately 0.50-inch thick and were designed to support a static load of 15,000 pounds/inch. The two configurations that are being tested are 7.5-inch wide T300/5209 graphite/epoxy panels with a double row of fasteners and 8.0-inch wide T300/5208 panels with a single row of fasteners. In addition to sustained-load outdoor exposure for 1, 3, 5, 7, and 10 years, 0.4 lifetimes of spectrum fatigue loads are being applied to the test panels at the end of each year of exposure. Therefore, the 10-year test panel will have 10 years of sustained-load exposure plus an accumulation of four lifetimes of fatigue loading. Test results after 1, 3, and 5 years of exposure are shown in figure 30.

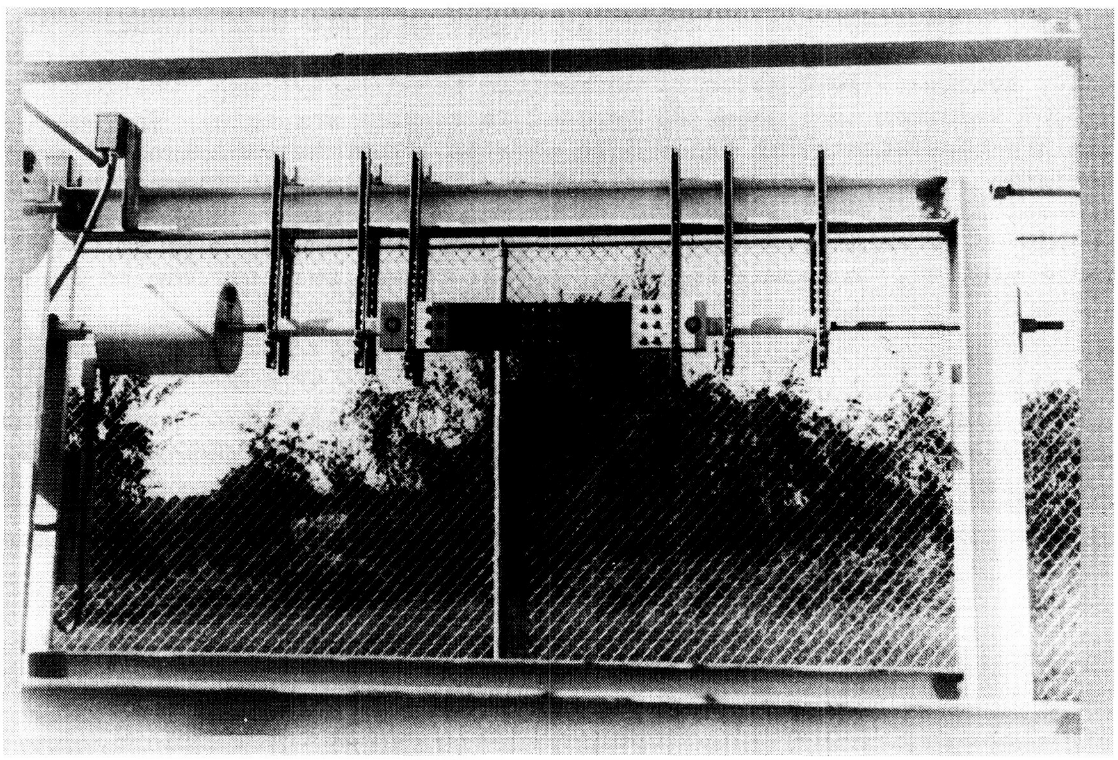

Figure 29

EFFECT OF OUTDOOR EXPOSURE AND LOAD HISTORY ON STRENGTH OF GRAPHITE/EPOXY BOLTED WING SPLICES

Test results for outdoor-exposed graphite/epoxy panels representative of commercial transport bolted wing splices are shown in figure 30. Baseline panels with no outdoor exposure were tested with no fatigue loading and 4.0 lifetimes of fatigue loading. The results shown in figure 30 indicate that the 4.0 lifetimes of fatigue loading did not degrade the strength of the panels. The T300/5209 panel tested after five years of sustained load at 25 percent of static ultimate and an accumulation of 2.0 lifetimes of fatigue loading did not show any significant strength reduction. The five-year T300/5208 panel incurred a 7.5 percent strength reduction. The scatter band for these tests is not known since only one panel is being tested at each test condition, including the baseline. Additional tests are planned after 7 and 10 years of outdoor exposure and additional fatigue loading.

Static strength	Constant load exposure (years) (25% ultimate)	Fatigue loading (lifetimes)	Failure load (kips) Material and joint configuration	
			T300/5209 double row	T300/5208 single row
Baseline	0	0	120.0	117.8
	0	4.0	119.0	119.0
Residual	1	0.4	117.2	113.0
	3	1.2	117.2	110.7
	5	2.0	116.5	109.0
	7	2.8	2/85	N/A
	10	4.0	2/88	3/89

Figure 30

CONCLUDING REMARKS

The NASA Langley Research Center has sponsored design, development, and flight service evaluation of over 300 composite components for transport aircraft and helicopters. Key findings of these programs are summarized in figure 31. Good in-service performance and maintenance experience have been achieved during 10 years and over three million total component flight hours. Boeing 737 graphite/epoxy reinforced aluminum spoilers have incurred design-related corrosion damage and strength reduction up to 35 percent after seven years and approximately 20,000 flight hours of service. Disbonds have been noted between Kevlar/epoxy facesheets and Nomex honeycomb core on a Bell 206L baggage door, and a strength reduction of about 50 percent resulted. Additional tests are required to establish if a problem exists with other baggage doors.

No significant room temperature strength reductions have been noted for several unpainted composite material systems after 10 years of worldwide outdoor exposure. Test results indicate that Kevlar/epoxy composites absorb more moisture than most widely used graphite/epoxy composites. Composite materials must be kept painted with standard aircraft paint to protect the matrix from ultraviolet degradation. Test results for graphite/epoxy panels with bolted joints representative of transport aircraft wing splices did not indicate any significant strength reduction after five years of sustained-load outdoor exposure and accumulated fatigue cycles of 2.0 lifetimes.

Confidence developed through NASA-sponsored programs for service evaluation of transport aircraft and helicopter components, long-term environmental test results, and advanced composite components developed under the ACEE Program has led transport and helicopter manufacturers to make production commitments to selected composite components.

- Good service performance with over 300 composite components during 10 years and three million flight hours

- Corrosion damage to B-737 graphite/epoxy spoilers resulted in 35 percent strength reduction after 7 years service

- No significant strength reduction for composite materials after 10 years outdoor exposure

- Strength of bolted wing splices not affected by fatigue, sustained load, or 5 years outdoor exposure

Figure 31

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