DURABILITY OF AIRCRAFT COMPOSITE MATERIALS

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INTRODUCTION

Since the early 1970's, the NASA Langley Research Center has had programs under way to develop a data base and establish confidence in the long-term durability of advanced composite materials for 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 and wing boxes on transport aircraft and doors, fairings, tail rotors, vertical fins, and horizontal stabilizers on helicopters. Materials included in the evaluation are boron/epoxy, Kevlar/epoxy, graphite/epoxy and boron/aluminum. Inspection, maintenance, and repair results for the components in service are reported. The effects of long-term exposure to laboratory, flight, and outdoor environmental conditions are reported for various composite materials. Included are effects of moisture absorption, ultraviolet radiation, and aircraft fuels and fluids. Figure 1 summarizes some points of the aircraft composite materials program.

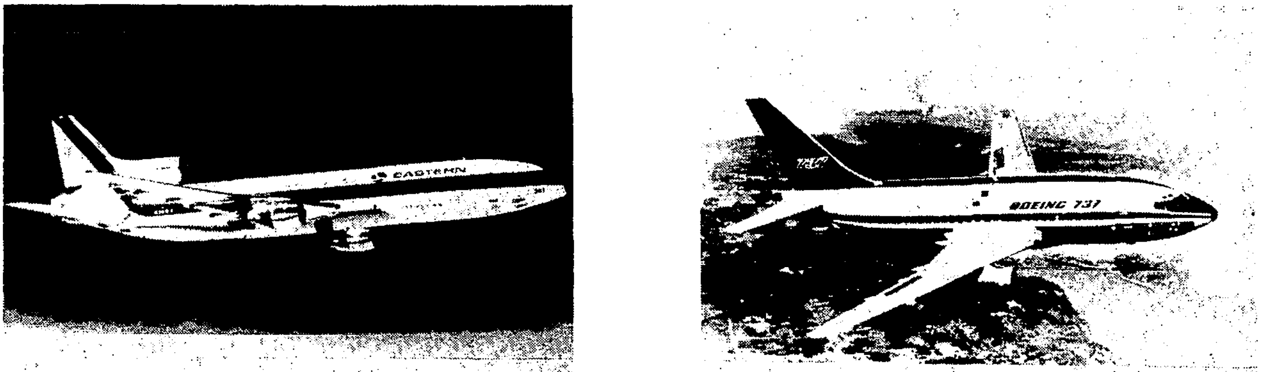
DURABILITY OF AIRCRAFT COMPOSITE MATERIALS

- FLIGHT SERVICE OF COMPOSITE COMPONENTS
  - TRANSPORT AIRCRAFT
  - HELICOPTERS
- ENVIRONMENTAL EFFECTS ON COMPOSITES
  - WORLDWIDE GROUND-BASED OUTDOOR EXPOSURE
  - FLIGHT EXPOSURE OF MATERIAL COUPONS
  - CONTROLLED LABORATORY EXPOSURE

Figure 1

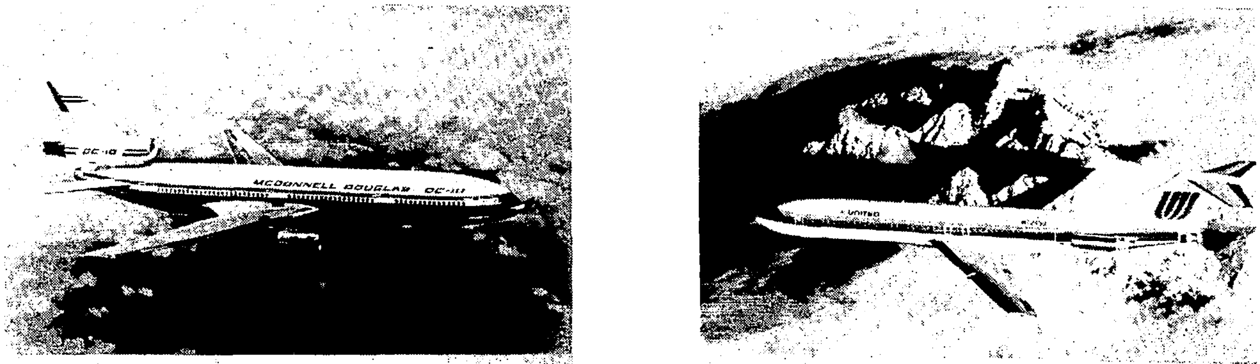
FLIGHT SERVICE COMPOSITE COMPONENTS ON TRANSPORT AIRCRAFT

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 ACEE program were installed on four L-1011 aircraft for service evaluation. One hundred and eight graphite/epoxy spoilers have been in service on six different commercial airlines in worldwide service since 1973. Thirteen graphite/epoxy DC-10 upper aft rudders are in service on five commercial 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.



L-1011 FAIRING AND AILERON

B-737 SPOILER



DC-10 RUDDER AND AFT PYLON

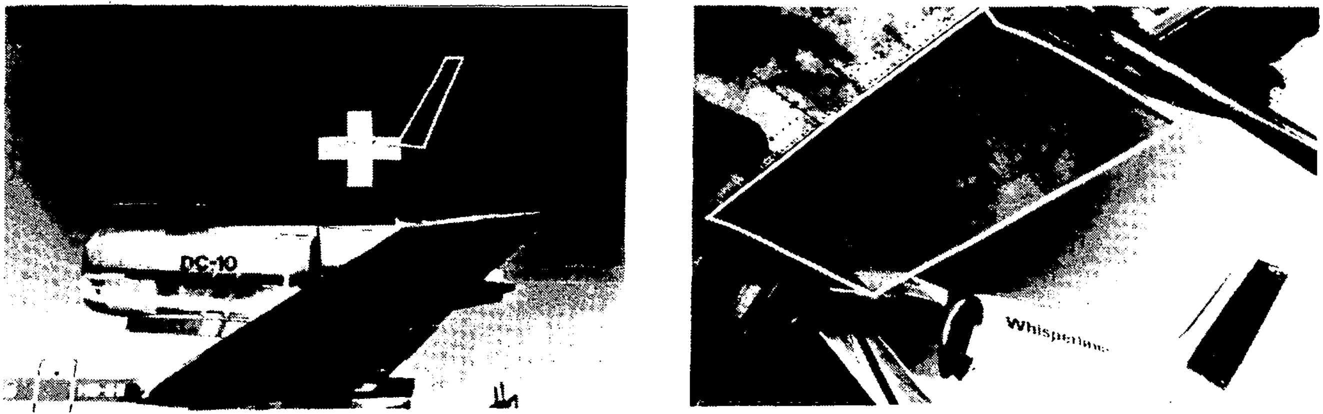
B-727 ELEVATOR

Figure 2

ACEE COMPOSITE SECONDARY STRUCTURES

The three major U.S. commercial transport manufacturers have been under NASA contract to design, fabricate, and test the major secondary composite components shown in figure 3. The components were developed as part of the NASA Aircraft Energy Efficiency (ACEE) Program. Each of the components has been certified by the FAA and flight service evaluation is under way. The three components utilize different design concepts. The graphite/epoxy rudders are multi-rib stiffened, the elevators are constructed with graphite/epoxy skins and Nomex honeycomb sandwich, and the aileron design features a syntactic-core sandwich with graphite/epoxy facesheets. An overall mass saving of 25 percent was achieved for the three components when compared to the production aluminum designs.

BOEING 727 COMPOSITE ELEVATOR



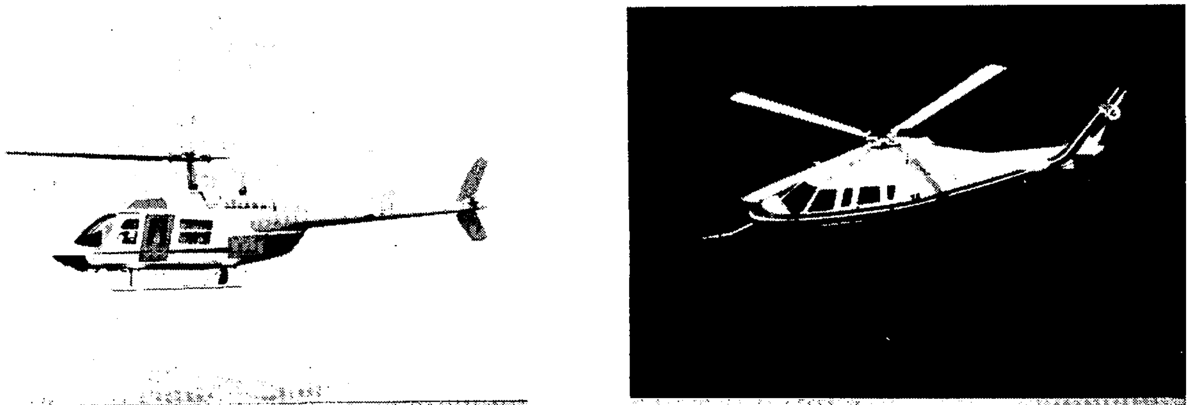
DOUGLAS DC-10 COMPOSITE RUDDER

LOCKHEED L-1011 COMPOSITE AILERON

Figure 3

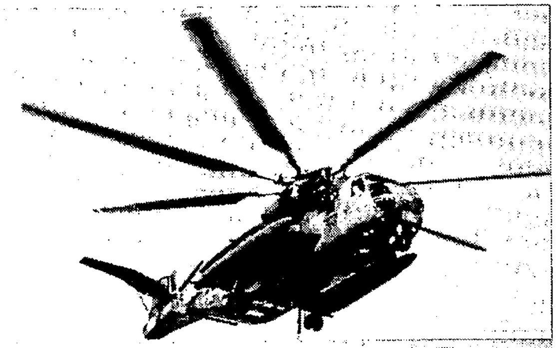
FLIGHT SERVICE COMPOSITE COMPONENTS ON HELICOPTERS

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, and the U.S. Gulf Coast. Selected components will be removed from service for residual strength testing. Ten tail rotors and four horizontal stabilizers will be removed from S-76 production helicopters to determine the effects of realistic operational service environments on composite primary helicopter components. 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 skin 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 with those of production aluminum skin.



206L DOORS, FAIRING AND VERTICAL FIN

S-76 TAIL ROTOR AND HORIZONTAL STABILIZER



CH-53 CARGO RAMP SKIN

Figure 4

BELL 206L HELICOPTER COMPOSITE COMPONENTS

The four composite components that are being evaluated on the Bell 206L are shown in figure 5. Four different structural design concepts are 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 vertical fin is constructed with graphite/epoxy facesheets bonded to a Fibertruss honeycomb core. The litter door is constructed with Kevlar/epoxy fabric and has local reinforcement at load introduction points (hinges and latch assembly). The litter door is a hollow section with inner and outer skins and unidirectional Kevlar/epoxy tape is used in the post area 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 area of the latch and along the edges.

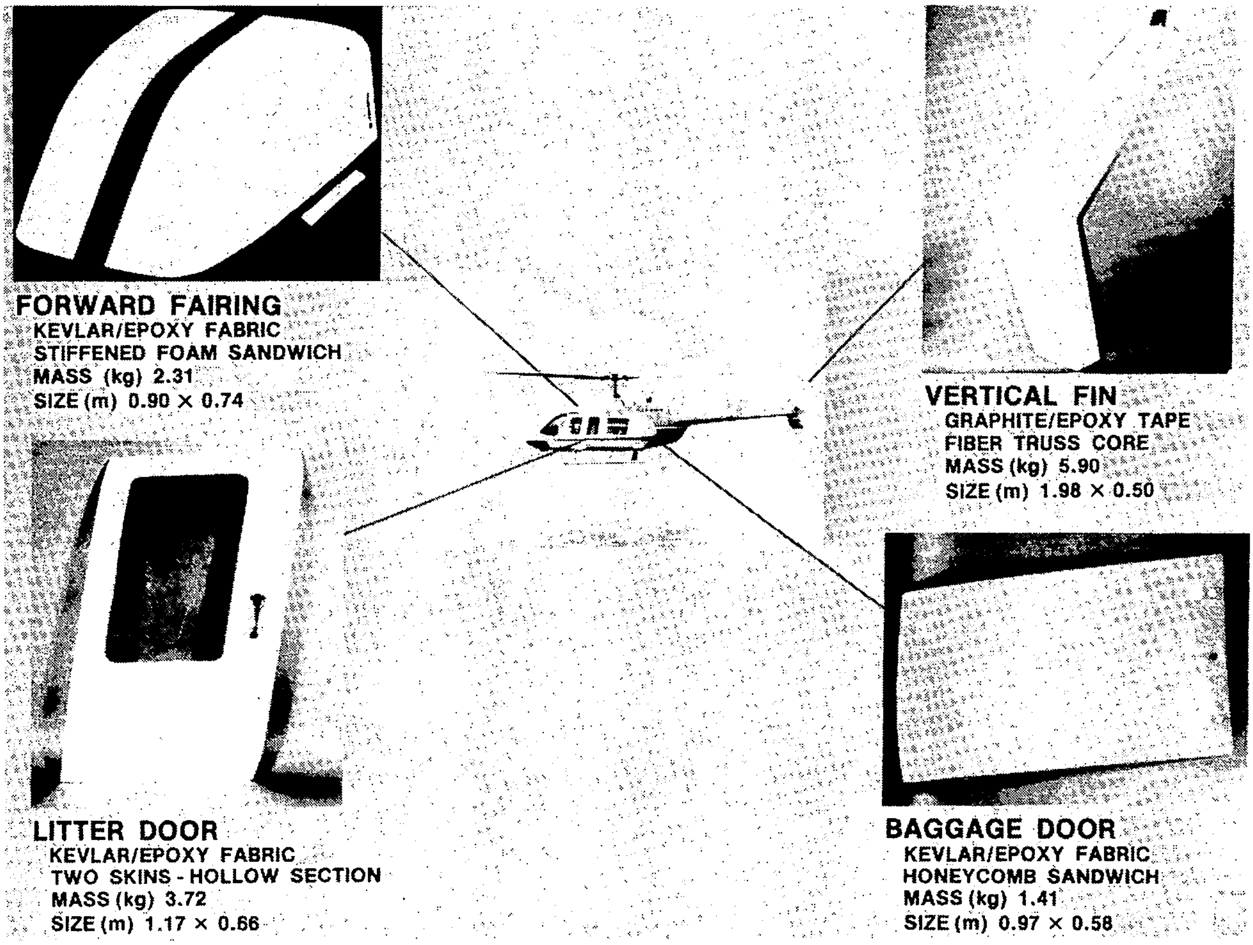


Figure 5

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 with graphite/epoxy spar caps, full-depth Nomex honeycomb sandwich core, and Kevlar/epoxy skins. Components have been removed from helicopters and tested after 2 years of service. In addition, small coupons exposed to the outdoor environment were tested and results were compared to baseline values. No significant reduction in either component or coupon strengths was noted. Measured moisture levels were similar to results obtained from other environmental effects programs sponsored by NASA Langley.

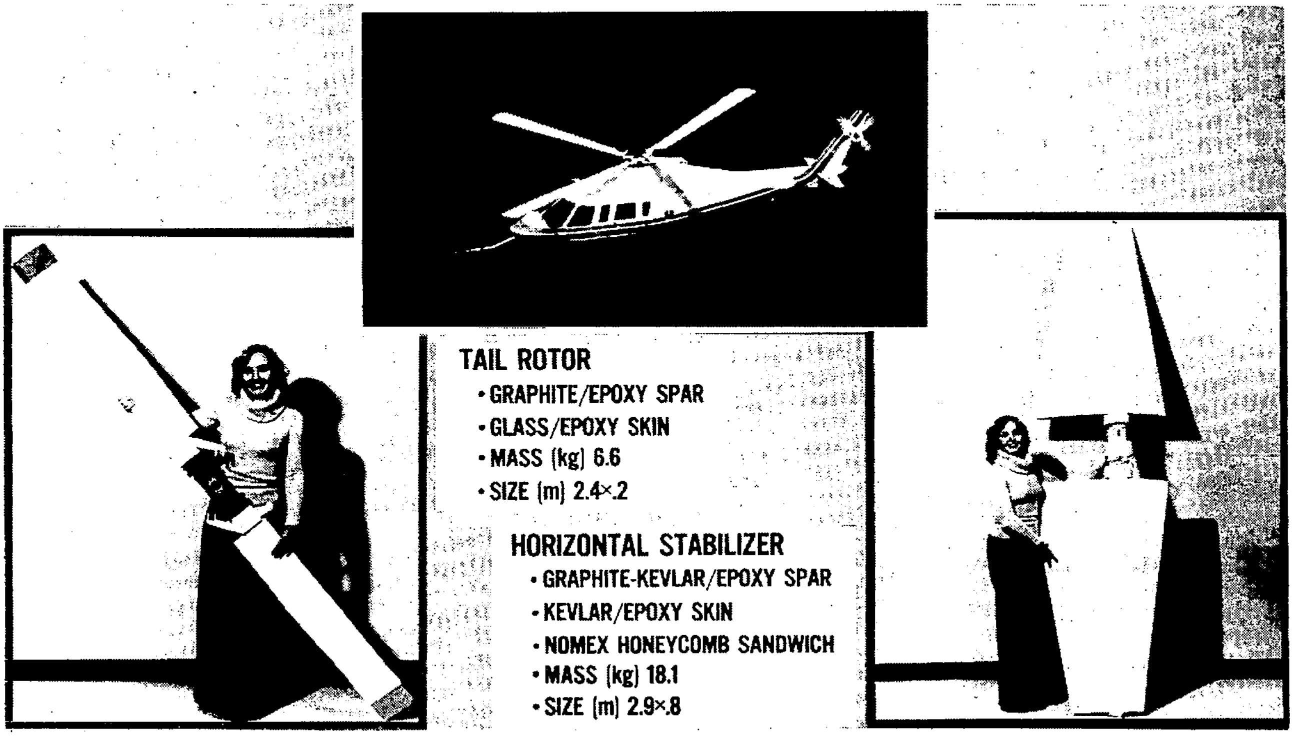


Figure 6

NASA COMPOSITE STRUCTURES FLIGHT SERVICE SUMMARY

A total of 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 2.5 million component flight hours have been accumulated with the high-time aircraft having more than 24,000 hours. Some of the graphite/epoxy DC-10 upper aft rudders have been accumulating flight service time at a rate of over 300 hours per month during the past 6 years. The 108 graphite/epoxy spoilers installed on B-737 aircraft have accumulated the highest total component flight hours, over 1.7 million, during 9 years of service. Over 66,000 total component flight hours have been accumulated on the 206L and S-76 composite helicopter components.

AIRCRAFT COMPONENT	TOTAL COMPONENTS	START OF FLIGHT SERVICE	CUMULATIVE FLIGHT HOURS	
			HIGH TIME AIRCRAFT	TOTAL COMPONENT
L-1011 FAIRING PANELS	18	JANUARY 1973	23 130	409 590
737 SPOILER	108	JULY 1973	24 290	1 712 470
C-130 CENTER WING BOX	2	OCTOBER 1974	6 080	12 100
DC-10 AFT PYLON SKIN	3	AUGUST 1975	19 240	55 810
DC-10 UPPER AFT RUDDER	13*	APRIL 1976	22 420	186 970
727 ELEVATOR	10	MARCH 1980	7 180	65 630
L-1011 AILERON	8	MARCH 1982	1 180	7 210
S-76 TAIL ROTORS AND HORIZONTAL STABILIZERS	14	FEBRUARY 1979	3 670	32 070
206L FAIRING, DOORS, AND VERTICAL FIN	124**	MARCH 1981	900	34 000
GRAND TOTAL	300			2 515 850

JUNE 1982

* 7 MORE RUDDERS TO BE INSTALLED
**36 MORE COMPONENTS TO BE INSTALLED

Figure 7

RESIDUAL STRENGTH OF GRAPHITE/EPOXY SPOILERS

The large number of spoilers with graphite/epoxy skins allows planned retrievals from flight service without seriously impairing the total exposure. Six spoilers, which include two of each of three material systems used in fabricating the spoilers, are selected at random for removal from service annually. The six spoilers are shipped to Boeing for ultrasonic inspection. Three of the spoilers are returned to service after inspection and three are tested to failure to compare residual strengths with the strength of 16 new spoilers that were tested early in the program. Tests have been completed on all three graphite/epoxy systems after 6 years of service and the seventh-year test has been completed on a spoiler constructed with T300/5209. Results of tests conducted to date are shown in figure 8.

The strengths for the individual spoilers generally fall within the same scatter band as was defined by strengths of the new spoilers. The results indicate essentially no degradation in strength after the 7-year period of service for the materials indicated. In addition, stiffness measurements for the graphite/epoxy spoilers indicate essentially no reduction in stiffness as a result of 7 years of service exposure.

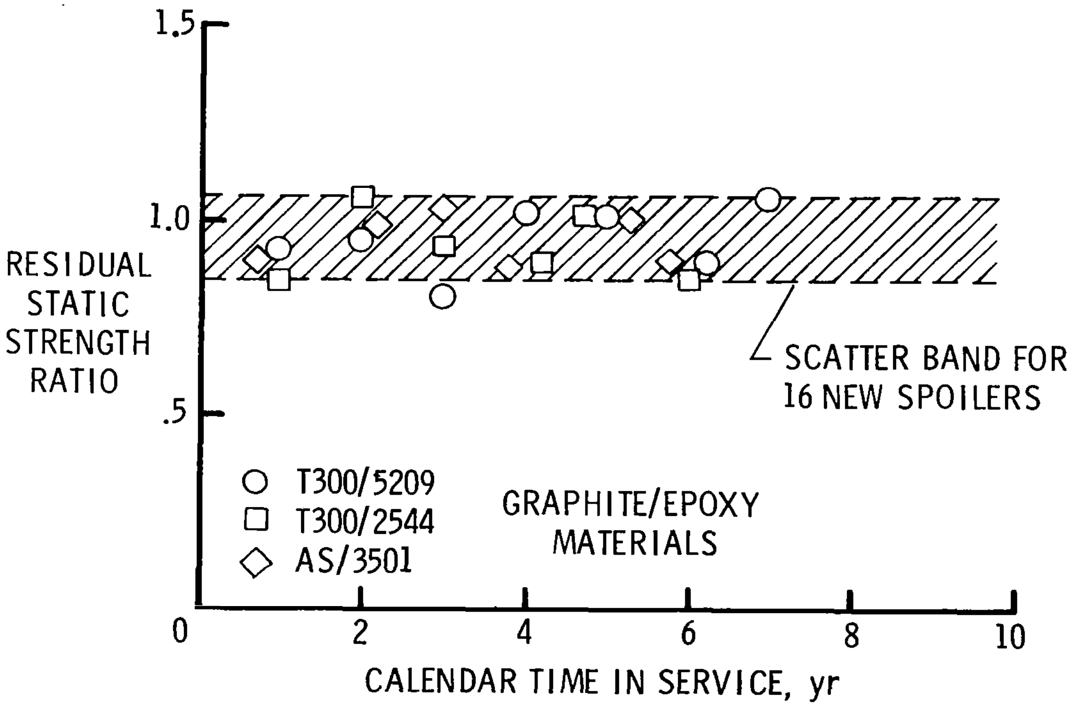


Figure 8

NASA COMPOSITE COMPONENT INSPECTION AND MAINTENANCE RESULTS

The composite components in the NASA Flight Service Evaluation Program are being inspected at periodic intervals to check for damage, defects, or repairs that may occur during normal aircraft operation. The composite components are being inspected by the aircraft operators and manufacturers, and in some cases both visual and ultrasonic inspection methods are being used, as indicated in figure 9.

The Kevlar/epoxy fairings on the L-1011 aircraft have incurred minor impact damage from equipment and foreign objects. Fiber fraying and fastener hole elongations have been noted on all the fairings but no repair has been required. The B-737 graphite/epoxy spoilers have encountered several types of minor damage or defects. Included are spar and doubler corrosion, cuts and dents, and delaminations. Some repairs are being prepared by the airlines but most repairs have been done at Boeing. One of the boron/aluminum aft pylon skins on the DC-10 aircraft was removed from service because of surface corrosion. This corrosion is believed to have been caused by improper surface preparation during panel fabrication.

Minor rib-to-skin disbonds have been detected on two DC-10 rudders. Also, three rudders have encountered minor lightning strikes and one rudder was damaged during ground handling. Minor lightning strikes have also been discovered on two graphite/epoxy elevators. One elevator has been damaged by ground handling. Overall, excellent performance has been achieved with the NASA flight service composite components.

COMPONENT	INSPECTION INTERVAL, months	INSPECTION METHODS	STATUS
L-1011 FAIRING PANELS	12	VISUAL	MINOR IMPACT DAMAGE, FIBER FRAYING AND HOLE ELONGATIONS
737 SPOILER	12	VISUAL ULTRASONIC	INFREQUENT MINOR DAMAGE REPAIRED AT BOEING
DC-10 AFT PYLON SKIN	12	VISUAL	ONE SKIN PANEL REMOVED DUE TO CORROSION
DC-10 UPPER AFT RUDDER	3, 12	VISUAL ULTRASONIC	MINOR RIB-TO-SKIN DISBOND ON TWO RUDDERS; MINOR LIGHTNING STRIKE ON THREE RUDDERS; GROUND HANDLING DAMAGE ON ONE RUDDER
727 ELEVATOR	13	VISUAL	MINOR LIGHTNING STRIKE ON TWO ELEVATORS; GROUND HANDLING DAMAGE ON ONE ELEVATOR

Figure 9

B-737 SPOILER IN-SERVICE DAMAGE AND REPAIR

During the first nine years of flight service there have been 67 instances in which graphite/epoxy spoilers have received damage in service sufficient to require repairs. Typical damage includes graphite/epoxy skin blisters, trailing-edge delamination, miscellaneous cuts and dents, and corrosion of the aluminum spar and doublers, as shown in figure 10. Over one-half 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. Nineteen repairs have been required as a result of corrosion damage to the aluminum spar and aluminum doublers. The corrosion initiates 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 schemes. Bondline fatigue in the spar splice area probably contributes to crack initiation and subsequent corrosion. There have been no incidents of galvanic corrosion between the graphite/epoxy skins and the aluminum honeycomb substructure. There have been ten incidents of cuts and dents caused by airline use and four trailing-edge delaminations that were apparently caused by normal aircraft maintenance and moisture intrusion.

Overall, excellent in-service performance has been achieved with the graphite/epoxy spoilers. Several of the airline maintenance executives have expressed the opinion that significantly fewer problems have been experienced with the graphite/epoxy spoilers compared to production aluminum spoilers.

PROBLEM	NUMBER OF INCIDENTS	PERCENT OF TOTAL	CAUSE
BLISTER ABOVE CENTER HINGE FITTING	34	51	DESIGN
SPAR AND DOUBLER CORROSION	19	28	DESIGN/MFG.
MISCELLANEOUS CUTS AND DENTS	10	15	AIRLINE USE
TRAILING-EDGE DELAMINATION	4	6	ENVIRONMENT

Figure 10

DC-10 COMPOSITE RUDDER LIGHTNING DAMAGE

Three of the graphite/epoxy upper aft rudders flying on DC-10 aircraft have sustained minor lightning strikes. The rudder that encountered the most severe strike is shown in figure 11. The damage was localized in an area measuring approximately 1.3 cm by 4.0 cm near the trailing edge of the structural box. The paint layer and four of the outer layers of the graphite/epoxy were removed by the lightning strike. Dry graphite fibers around the edge of the damaged region suggested that the epoxy resin had been vaporized by intense heat generated by the lightning strike. Repair of the rudder was performed in accordance with repair procedures established at the time the graphite/epoxy rudders were certified by the FAA. The repair consisted of a fiberglass cloth patch and a room temperature curing epoxy adhesive. The other two rudders were repaired in a similar manner using either fiberglass or graphite cloth. All three repairs were performed by airlines maintenance personnel and the aircraft resumed scheduled airline service.

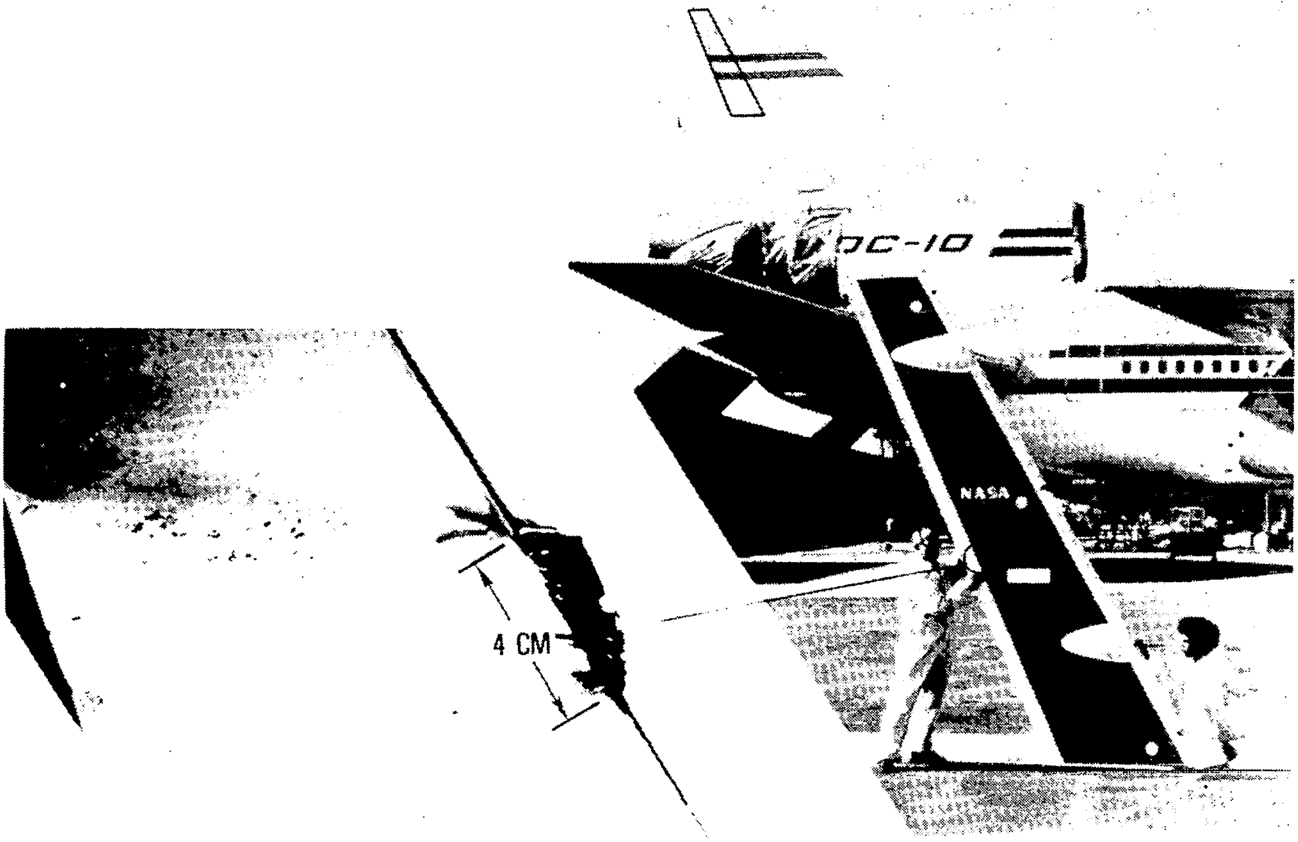


Figure 11

ENVIRONMENTAL EFFECTS ON LONG-TERM DURABILITY OF COMPOSITE MATERIALS FOR COMMERCIAL AIRCRAFT

Concurrent with the flight evaluation of structural composite components, NASA initiated programs to determine the outdoor ground, flight, and controlled laboratory environmental effects on composite materials, as shown in figure 12. Included are effects of moisture absorption, ultraviolet radiation, aircraft fuels and fluids, and sustained tensile stress. Specimens configured for various mechanical property tests are exposed to real-time environmental conditions on aircraft in scheduled airline service and at various ground stations around the world. Composite specimens are also exposed to controlled laboratory environments including temperature, relative humidity, and simulated ultraviolet radiation. The tests, involving more than 17,000 composite specimens, are scheduled to run for up to 10 years. The results of these tests will be correlated to provide a broad data base for environmental effects on composite materials.

- GROUND EXPOSURE – 10 YEARS AT AIRPORTS
- FLIGHT EXPOSURE – 10 YEARS ON AIRPLANES
- LABORATORY EXPOSURE – CONTROLLED CONDITIONS
- CORRELATE AND ANALYZE RESULTS

Figure 12

WORLD-WIDE ENVIRONMENTAL EXPOSURE OF COMPOSITE MATERIALS

Composite test specimens are being exposed to outdoor environmental conditions at the ground station locations shown in figure 13. Specimens are mounted on racks and positioned on building rooftops where they are exposed to ambient environmental conditions. Test specimens are configured for interlaminar shear, flexure, compression and tension tests. Stressed and unstressed tension specimens are being exposed to assess the effects of sustained tensile load. Some specimens are unpainted to evaluate the effects of weathering on unprotected resin matrix materials, while other specimens are painted to evaluate protection afforded by standard aircraft paint. The materials being evaluated include several different graphite/epoxy and Kevlar/epoxy systems. Specimens are removed from the racks at intervals of 1, 2, 3, 5, 7, and 10 years to evaluate mass and mechanical property changes.

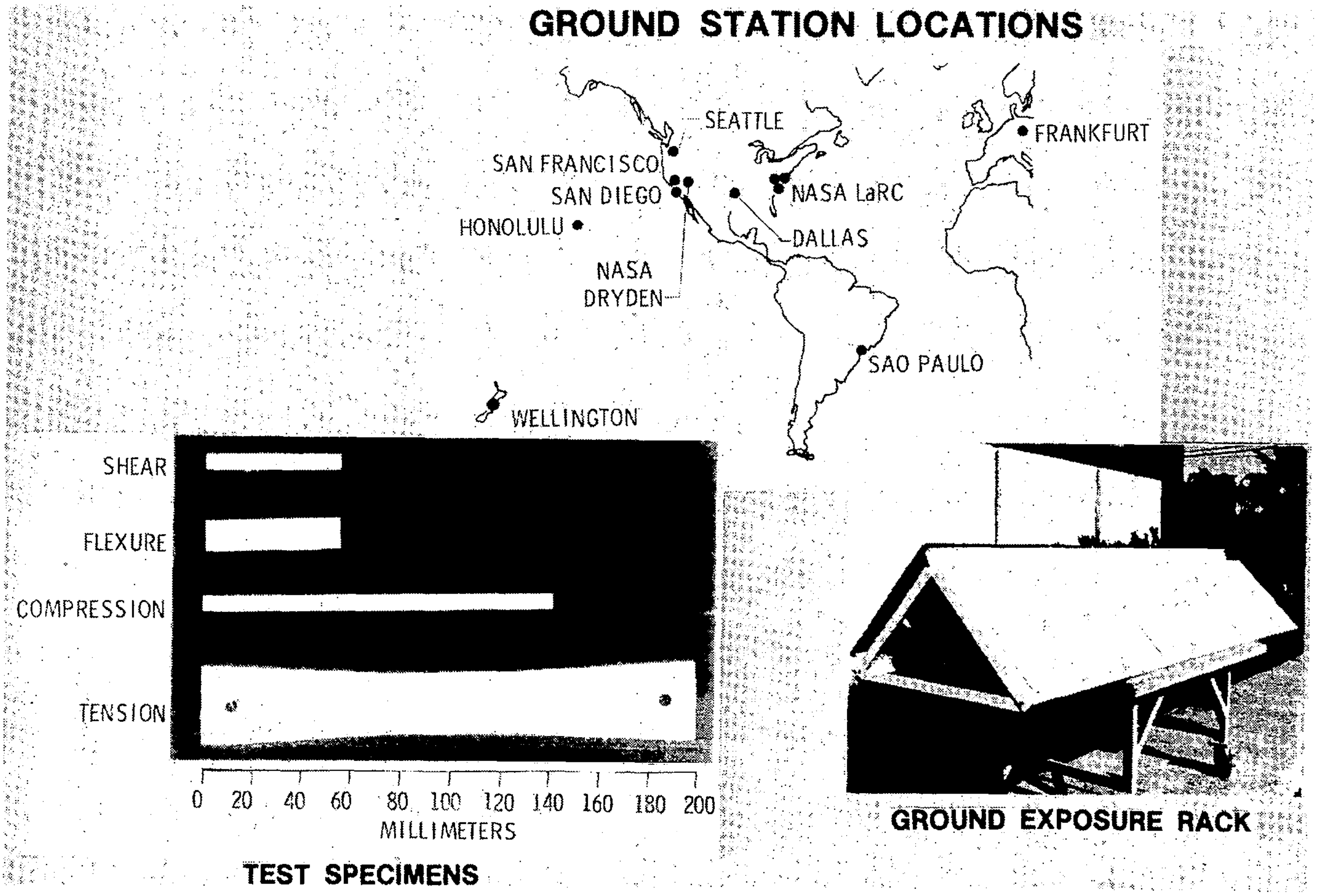


Figure 13

MOISTURE ABSORPTION DURING GROUND EXPOSURE

The moisture contents of four graphite/epoxy and two Kevlar/epoxy material systems after 5 years of exposure at six exposure sites are shown in figure 14. The data shown were obtained from flexure specimens that were exposed on outdoor racks located at Hampton, Virginia; San Diego, California; Sao Paulo, Brazil; Wellington, New Zealand; Honolulu, Hawaii; and Frankfurt, Germany. Each point plotted represents an average value for eighteen specimens, three at each of the six locations. The graphite/epoxy materials have stabilized after 5 years but the Kevlar/epoxy materials are apparently still gaining a slight amount of moisture. The Kevlar/epoxy materials and T300/2544 have moisture levels of about 2 percent. AS/3501 graphite/epoxy has a moisture content of about 1 percent, while both T300/5209 and T300/5208 graphite/epoxy have moisture contents of about 0.5 percent. The low value in the 5 year scatter band, in all cases, represents specimens exposed in Frankfurt, Germany; the high value for all material systems except T300/5209 represents specimens exposed in Sao Paulo, Brazil. Additional moisture absorption data will be obtained after 7 and 10 years of outdoor exposure.

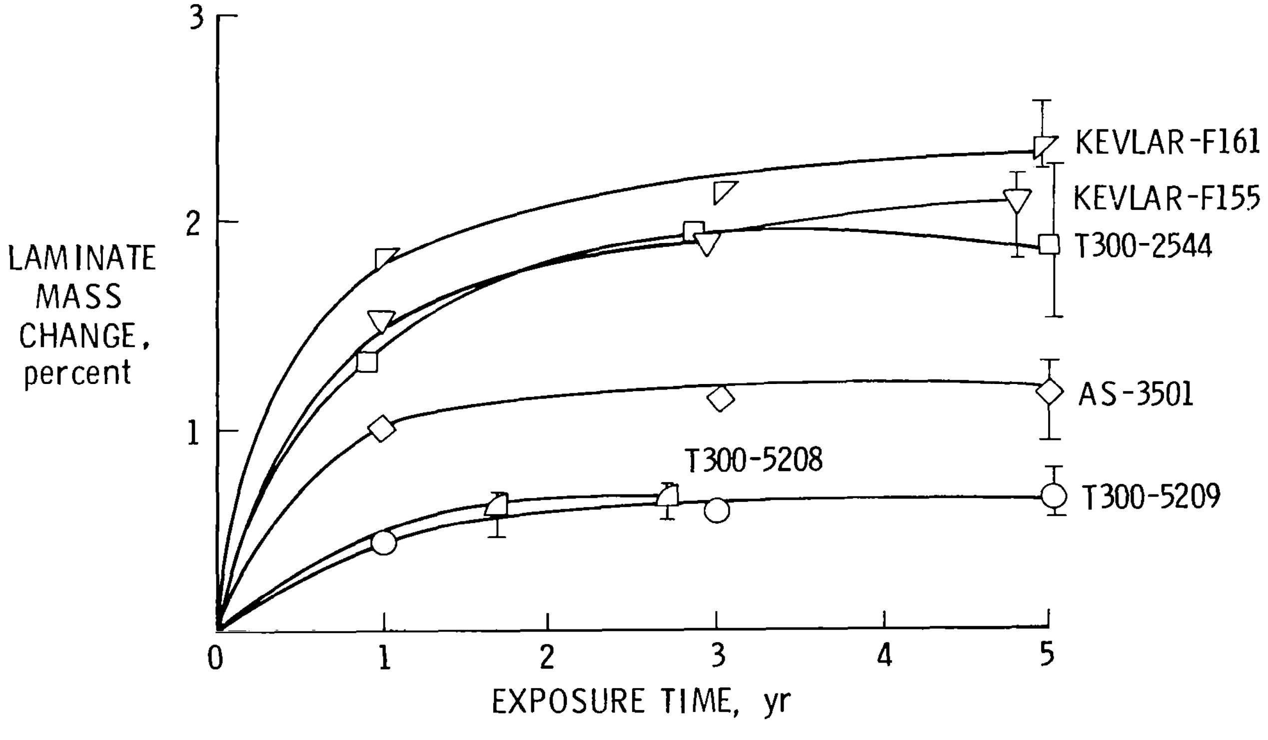


Figure 14

RESIDUAL STRENGTH OF COMPOSITE MATERIALS AFTER WORLDWIDE OUTDOOR EXPOSURE

Data obtained to date on specimens from four graphite/epoxy and two Kevlar/epoxy systems are shown in figure 15. The data points represent a comparison of the average strength values 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. Results of flexure tests indicate little or no degradation in strength over the 7-year exposure period. Compression strengths indicate a slight downward trend, but are still close to the baseline values after 7 years. Short beam shear strength is apparently influenced more by outdoor environmental exposure. The shear strengths for the T300/2544 graphite/epoxy and Kevlar/F-155 systems have dropped below the scatter band of the baseline test results. All the results presented in figure 15 are for unpainted specimens and several of the materials show evidence of surface deterioration due to solar radiation exposure. It is expected that the flexure strength will start to degrade as more matrix resin is leached away and more surface fibers become free. The data obtained to date confirm that the short beam shear strength tests are more sensitive to variations in matrix properties than the flexure or compression tests. One additional set of test specimens remains to be tested after 10 years of outdoor exposure.

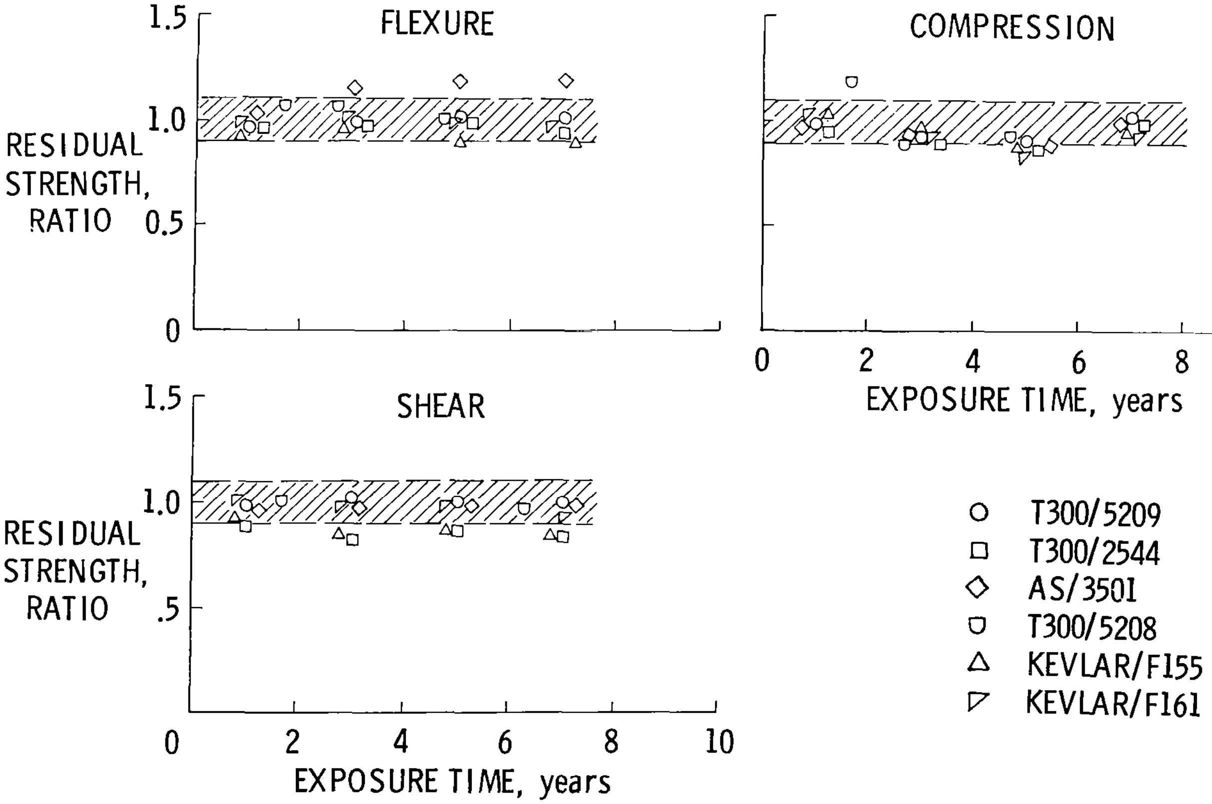


Figure 15

RESIDUAL TENSILE STRENGTH AFTER SUSTAINED STRESS OUTDOOR EXPOSURES

Effects of sustained stress during outdoor environmental exposure are evaluated by exposing tension specimens to 40 percent of ultimate baseline strength. Residual tensile strengths of T300/5208 quasi-isotropic laminated specimens after 7 years of outdoor exposure at the Langley Research Center and San Francisco are shown in figure 16. 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.

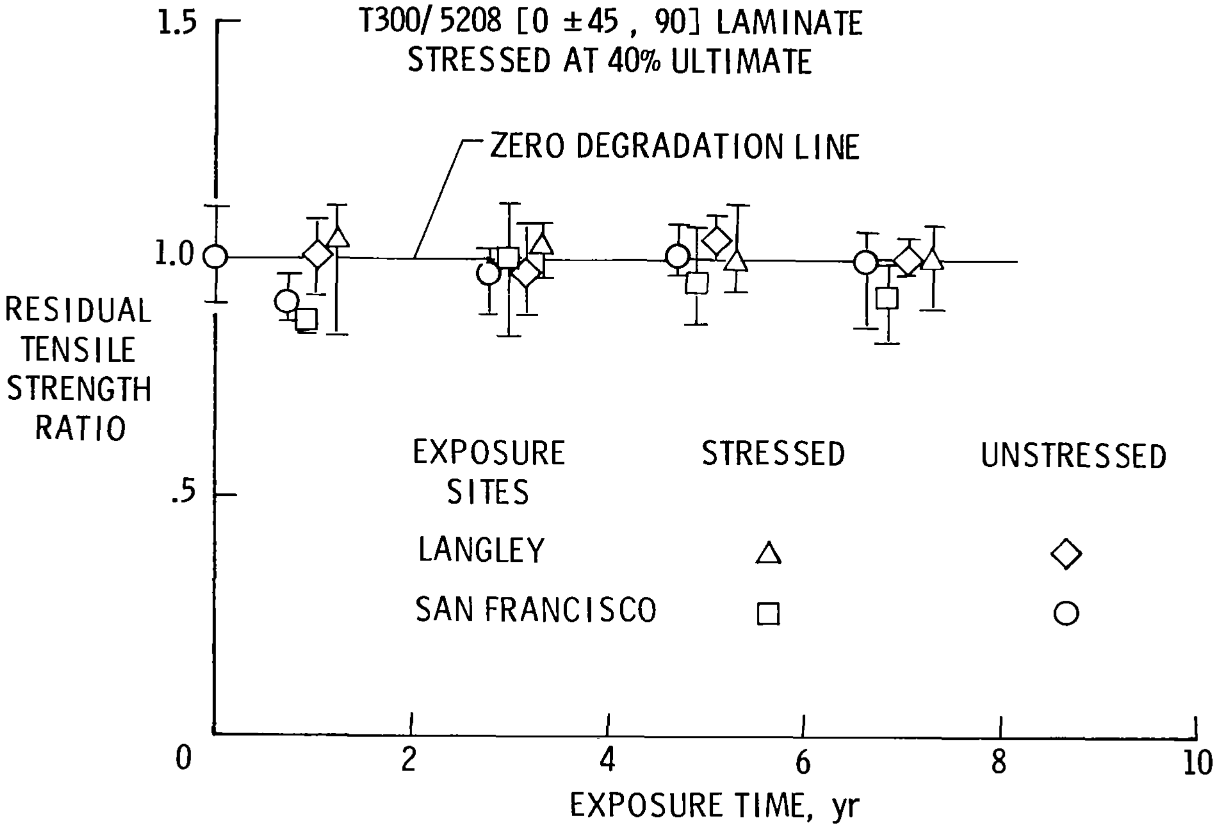


Figure 16

EFFECT OF AIRCRAFT FLUIDS ON COMPOSITE MATERIALS AFTER 5 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 5 years of exposure. Specimens were exposed to six different environmental conditions as follows: ambient air, water, JP-4 fuel, Skydrol, 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, T330/5209 graphite/epoxy, and Kevlar 49/5209 specimens after exposure to the six environments are shown in figure 17. The residual tensile strength of T300/5208 was not degraded by any of the six environments indicated in figure 17. 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 specimens 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 17 were more severe than actual aircraft flight exposures and the results should represent an upper bound on material property degradation.

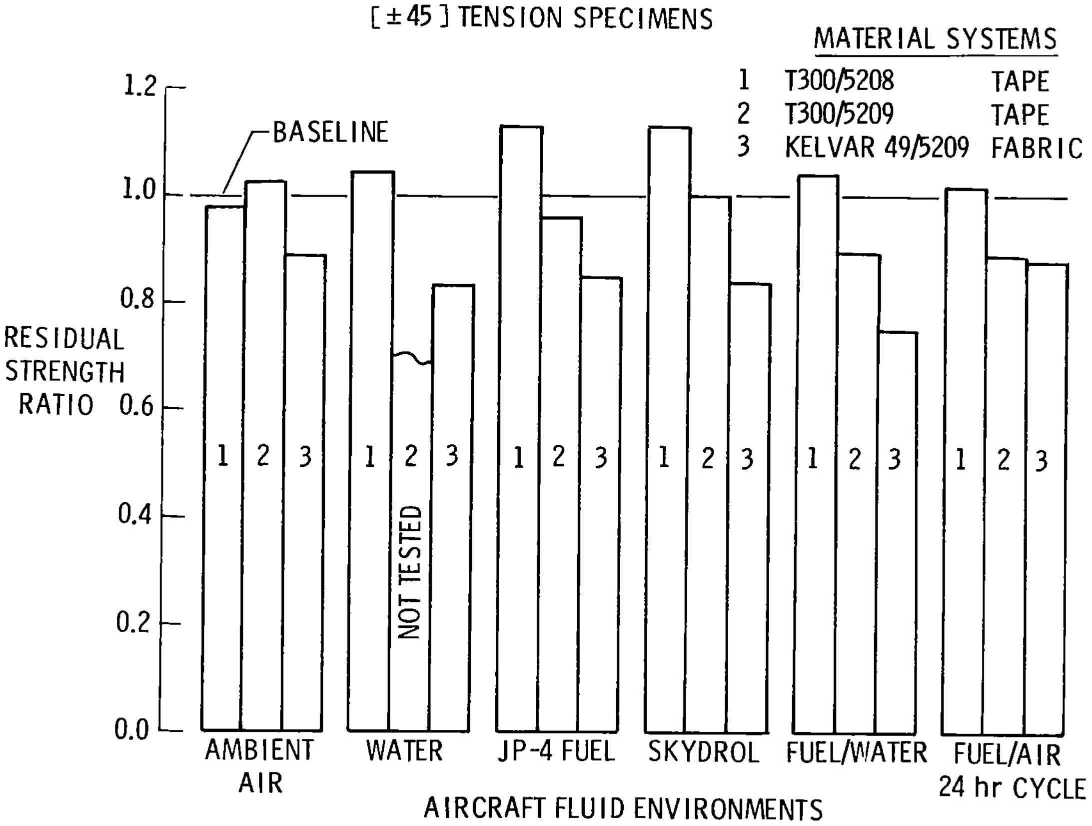
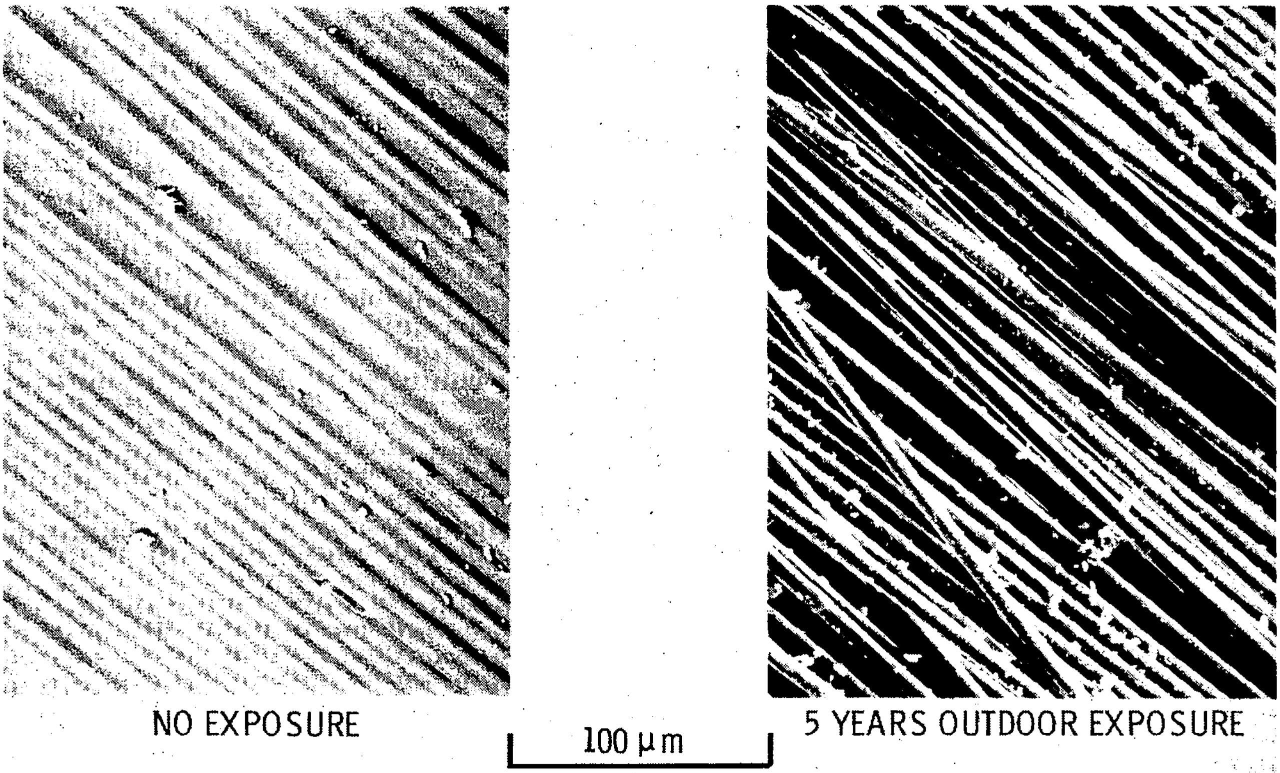


Figure 17

SURFACE DEGRADATION OF AS/3501 GRAPHITE/EPOXY

Scanning electron micrographs were taken of AS/3501 graphite/epoxy flexure specimens with no outdoor exposure and after 5 years of outdoor exposure. The micrograph shown on the left of figure 18 indicates that all the surface fibers are coated with resin for the specimen with no outdoor exposure. The micrograph shown on the right of figure 18 indicates that the surface fibers are no longer coated with resin after 5 years of outdoor exposure. The 5 years of weathering has removed the outer layer of resin and bare graphite fibers are visible.

As with controlled laboratory weatherometer results, these micrographs substantiate the need to keep graphite/epoxy composite aircraft structures painted to prevent ultraviolet radiation damage to composite matrix materials.


NO EXPOSURE

5 YEARS OUTDOOR EXPOSURE

Figure 18

CONCLUDING REMARKS

The NASA Langley Research Center has sponsored design, development, and flight service evaluation of 300 composite aircraft components. Excellent in-service performance and maintenance experience have been achieved during 9 years and over 2.5 million hours of flight service. No significant degradation has been observed in residual strength of composite components or environmental exposure specimens after 7 years of service or exposure. Results obtained to date indicate that composite surfaces must be painted with standard aircraft polyurethane paint to protect the matrix from ultraviolet degradation. Test results also indicate that Kevlar/epoxy composites absorb more moisture than most widely used graphite/epoxy composites and a larger reduction in residual strength results for the Kevlar composite systems. Additional details on the programs discussed herein can be found in references 1 through 8.

Confidence developed through NASA-sponsored service evaluation, environmental testing, and advanced composite component development programs has led commercial transport and helicopter manufacturers to make production commitments to selected composite components (fig. 19).

- EXCELLENT IN-SERVICE PERFORMANCE AND MAINTENANCE EXPERIENCE HAVE BEEN ACHIEVED WITH OVER 300 COMPOSITE COMPONENTS DURING 9 YEARS AND OVER 2.5 MILLION HOURS OF FLIGHT SERVICE

- NO SIGNIFICANT DEGRADATION HAS BEEN OBSERVED IN RESIDUAL STRENGTH OF COMPOSITE COMPONENTS OR ENVIRONMENTAL EXPOSURE SPECIMENS AFTER 7 YEARS OF SERVICE OR EXPOSURE

- CONFIDENCE DEVELOPED THROUGH NASA SERVICE EVALUATION, ENVIRONMENTAL TESTING, AND ADVANCED COMPOSITE COMPONENT DEVELOPMENT PROGRAMS HAS LED COMMERCIAL TRANSPORT AND HELICOPTER MANUFACTURERS TO MAKE PRODUCTION COMMITMENTS TO SELECTED COMPOSITE COMPONENTS

Figure 19

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