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SERVICE EVALUATION OF AIRCRAFT COMPOSITE STRUCTURAL COMPONENTS

by William A. Brooks, Jr.
and Marvin B. Dow

Langley Research Center
Hampton, Virginia

TECHNICAL PAPER presented at the Fifth National SAMPE Technical Conference, Kiamesha Lake, New York, October 9-11, 1973

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Abstract

The advantages of the use of composite materials in structural applications have been identified in numerous engineering studies. Technology development programs are underway to correct known deficiencies and to provide needed improvements. However, in the final analysis, flight service programs are necessary to develop broader acceptance of, and confidence in, any new class of materials such as composites. Such flight programs, initiated by NASA Langley Research Center, will be reviewed in the proposed paper. These programs, which include the selectively reinforced metal and the all-composite concepts applied to both secondary and primary aircraft structural components, will be described and current status will be indicated.

1. INTRODUCTION

Because of great potential benefits, in the last decade a large amount of resources have been expended on the development of technology associated with composite structural materials. The NASA Langley Research Center has been involved in this activity, concentrating primarily on the application of composites to aircraft structural components. The main thrust of Langley's program is toward flight service programs.

Langley's composite flight service programs are in keeping with one of the major recommendations, resulting from the recent Project Recast deliberations, that government agencies should sponsor "fly and try" programs on primary and secondary (or not critical to flight safety) composite structural components. The objective of the recommended action is to increase the producer's and user's confidence in composite structures, to broaden the base of experience, and to obtain meaningful manufacturing data by producing enough components of a given type to require the use of pilot production practices. These benefits are expected to be derived from Langley's flight service programs.

A major deficiency in composites technology is the lack of a data base for predicting life cycle costs. Data are lacking in the areas of operations, maintenance, reliability, inspectability, and repairability. Appropriate flight service programs, such as those sponsored by Langley, are the most meaningful way to obtain the required data, although the return is on a somewhat long-range basis.

L-9024

The NASA Langley Research Center at present has many flight service programs underway or in the advanced planning stages. A summary of these flight service programs is given in Table I. These programs involve both primary and secondary structural components. In addition, the degree of composite utilization varies from the reinforcement of conventional metallic components with composites, to the substitution of composites for metal, and to redesigning the component specifically for composite utilization. The purpose of this paper is to review the programs in sufficient depth to indicate the totality of activity. Technical details beyond the scope of this paper are given in suitable references identified herein.

2. LOCKHEED C-130 CENTER WING BOX

The NASA Langley Research Center's early research on composites dealt with the concept of selectively reinforcing metal structures with composites. During this period, a unique opportunity for the application of this concept to aircraft structures developed when the C-130 transport fleet was retrofitted with strengthened center wing boxes. These aircraft had experienced a rapid accumulation of fatigue damage as the result of exposure to severe flight environments in Southeast Asia.

The standard retrofit involved the installation of strengthened aluminum center wing boxes in these aircraft, shown in Figure 1. However, a study[1] performed for NASA indicated that about 350 pounds of uniaxial boron/epoxy bonded to the skins and stiffeners of the wing box would reduce the stress levels and thus increase the fatigue life as much as the aluminum retrofit design, but with a 10% weight saving. The joint NASA/U.S. Air Force C-130 composite flight service program evolved from that study.

Some of the details are shown in Figure 2. Laminated strips of uniaxial boron/epoxy with the required number of plies are bonded to the inner surface of the skin panels under each stringer and to each hat-section stringer on the enclosed crown surface. The area ratio of boron/epoxy to aluminum is nominally 1 to 4. This ratio was selected on the basis of four criteria: weight reduction, equivalent ultimate strength, equivalent damage tolerance, and equivalent fatigue endurance. An additional requirement is the wing box must sustain 100% of the design limit load without the benefit of composite reinforcement.

One of the most significant development activities was associated with residual thermal stresses produced when the boron/epoxy laminates were bonded to the aluminum structure at an elevated temperature. Due to the difference in the thermal expansion characteristics of aluminum and boron/epoxy, significant residual stresses and warping were induced at temperatures different from the bonding temperature. Because the potential weight reduction afforded by use of the composite was jeopardized, it was necessary to reduce these residual stresses. The result was the development of the "cool tool" bonding concept which constrained expansion of the aluminum parts during the bonding process. In this concept, the tool is thermally insulated from the parts to be bonded and heat is supplied by an electric blanket arrangement, rather than by an autoclave.

The composite laminates are stepped out at the junctions with the outboard metal wing boxes and at access holes by progressively stopping individual plies. Fasteners are used at the ends of the laminates to prevent peeling, thus providing more reliable joints. As the sketch in Figure 2 shows, adequate bearing surface is provided in the fastener penetration areas by titanium doublers which are inserted and integrally bonded into the laminates.

This composite flight service program, which is the largest funded by NASA, involves the fabrication of three wing boxes: one for ground testing and two for installation in aircraft that will be flown in regular Air Force service. The wing box for ground testing will be statically tested to limit load, fatigue tested to four lifetimes (40,000 simulated flight hours), and then statically tested to determine the residual strength.

The advanced development and detailed design phases have been completed, with results reported in References (2), (3), and (4). Fabrication is underway and testing is expected to start in December 1973 with the flight service phase beginning in August 1974. The present arrangement is to fly the wing boxes for 3 years with detailed inspections being scheduled to coincide with regularly phased aircraft inspections. If no technical problems exist, NASA will likely negotiate for an option to continue flight service beyond the initial 3 years.

3. SIKORSKY CH-54B HELICOPTER TAIL CONE

Another flight service program utilizing composite reinforced metal structures involves the Sikorsky CH-54B (Fig. 3). During developmental testing, the original CH-54B airframe was found to be in resonance for certain combinations of cable sling length and load, resulting in an undesirable dynamic condition in the tail cone. The production fix was to provide thicker top and bottom skins for the aluminum tail cone, which is approximately 3 by 4 by 15 feet in size.

A preliminary analysis indicated that uniaxial strips of boron/epoxy bonded to the tail cone stiffeners would provide the extra stiffness needed to prevent resonance and would result in a 14% weight saving. NASA Langley and the U.S. Army Air Mobility R & D Laboratory jointly sponsored a contract with Sikorsky to design, fabricate, and place into flight service a tail cone embodying the reinforced stringer concept. The details of the program are given in References (5) and (6).

The general criteria were that the stiffness of the composite-reinforced tail cone had to be the same as that of the modified production tail cone and that manufacturing changes had to be minimal. In addition, the design static strength requirement had to be satisfied by the metal structure without composite reinforcement. Thus, the composite provided the additional increment of stiffness needed to satisfy the dynamic requirements.

Some of the details are shown in Figure 4. Five of the top stringers and seven of the bottom stringers of the tail cone were reinforced by boron/epoxy laminates as shown by the sketch. The laminates (0.75 by 0.25 inch) contained 50 plies of uniaxial boron/epoxy. Use of the laminates permitted skin gage reductions from 0.140 inch in the modified aluminum production version to 0.040 inch in some sections of the reinforced tail cone.

Bonding laminates to the aluminum stringers at elevated temperature resulted in residual stresses and warpage. However, the warpage could be easily removed by applying hand pressure. Furthermore, the residual stresses were not as critical as in the C-130 program because the tail cone is rather lightly loaded.

In this case, composites were used to meet a stiffness requirement only and, therefore, it was possible to terminate the composite before reaching joint areas. This was done by tapering the laminate by dropping plies. The critical aspect of this approach was keeping the shear stress induced in the bond at an acceptable level. The concept employed was to use a 2-inch-long fiberglass insert, consisting of two plies of 0^{o} fiberglass/epoxy, at the beginning of a tapered joint. This had the effect of reducing the stiffness of the laminate, thereby reducing the peak shear stresses to 50% of the peak stresses in a tapered joint without the fiberglass insert.

The composite-reinforced tail cone was installed in a U.S. Army helicopter and has been in service since March 1972.

4. LOCKHEED L-1011 EXTERNAL FAIRINGS

In many past applications, the concept of substituting composites for a metal detail of a conventional structure has been employed. However, in a Lockheed program, sponsored by Langley, composites are substituted for composites to obtain longtime flight service experience with the relatively new PRD-49/epoxy material. The components involved are the external fairing panels on the L-1011 transport shown in Figure 5.

The particular panels involved are a wing-to-fuselage fairing, a wing-to-fuselage fillet, and a center-engine fairing which were produced by making a ply-for-ply substitution of the PRD-49 for the fiberglass material used in normal production panels.

The individual panels are shown in Figure 6. The largest panel is a 60- by 67-inch wing-to-fuselage fairing panel which has a slight single curvature. The panel is constructed from a Nomex honeycomb core with three-ply PRD-49 face sheets. The wing-to-body fillet is a solid PRD-49/epoxy laminate construction with a thickness of 0.090 inch tapering to 0.030 inch thick edge closeouts. The center-engine fairing is approximately triangular in shape with maximum dimensions of 30 by 73 inches. This panel is also of Nomex honeycomb construction with three-ply PRD-49 face sheets.

The lower density of PRD-49 results in significant weight savings when this material is substituted for fiberglass on a ply-for-ply basis. The simple replacement of fiberglass with PRD-49 on a ply-for-ply basis in a shipset of these panels (three left, three right) results in a saving of 27% of the weight of corresponding fiberglass panels.

One of the most troublesome areas in this program was the machining of the PRD-49 panels. Tooling used for cutting, trimming, drilling, and countersinking fiberglass panels was not adequate for the PRD-49 panels. Tool life was drastically reduced and machined surfaces were badly frayed. Therefore, special tools were developed. Details of the tooling and other aspects of the program are given in Reference (7).

Three shipsets of these panels (18 panels) have been installed on three L-1011 aircraft, one from each of three airlines. Flight service began in January 1973 and will continue for 5 years.

5. BOEING 737 SPOILERS

In a company-funded development program, the Boeing Company conducted a study of using composite spoilers on the 737 aircraft at the locations shown in Figure 7. There are three spoilers on each side and, although functionally important, the spoilers are not critical to the safety of the aircraft.

Subsequently, the Boeing Company designed, certified, and installed two graphite/epoxy skinned spoilers on a commercial 737 for flight evaluation. A composite spoiler (22 by 52 inches) is shown in Figure 8 and some of the details are shown in Figure 9. The aluminum production skin was replaced with cross-plied graphite/epoxy and the aluminum end ribs were replaced with fiberglass/epoxy ribs. The aluminum hinge fittings, spar, and the aluminum honeycomb core are the same as used in the production spoilers. Use of composites in the spoiler resulted in a 15% weight saving.

NASA Langley elected to build on this start and create a more comprehensive ground and flight-test program. One objective was to manufacture a large number of spoilers so that needed data on manufacturing costs could be obtained. Also, the availability of a large number of spoilers allows for flight service with five airlines with world-wide route structures. Thus, environmental exposures will be varied and service experience with inspection and maintenance can be gained by several airlines.

In the first phase of the NASA Langley program, 114 spoilers will be manufactured from three selected graphite/epoxy material systems. Generic type-A graphite was specified as having the properties to provide stiffness comparable to the aluminum production design and a low materials cost. (The spoiler is a stiffness critical component. The composite spoilers are slightly stiffer than the aluminum spoiler and failed at 240% to 290% of design limit load compared to 210% for the aluminum spoiler.)

A total of 108 spoilers will be supplied to the airlines in sets of four for installation on 27 aircraft. The nominal period of flight service is 5 years. Periodically during the 5 years, spoilers will be removed and tested for possible deterioration resulting from environmental exposure. In addition, comparisons will be made from results from concurrent ground-based environmental exposures to determine the reliability of ground testing.

The second phase of the program involves the development of advanced composite spoilers. The objective of this phase is to make the maximum possible effective use of composites in the spoiler. Possibilities being considered are chopped-fiber molded parts to replace the hinge fittings and spar, a Nomex or PRD-49 honeycomb core to replace the aluminum honeycomb, and other types of advanced filaments to replace the graphite used in the first phase. Ten advanced composite spoilers will be produced for 5-year flight service.

One of the most significant problems encountered during the early stages of this program involved the graphite/epoxy materials. The suppliers' recommended cure cycles did not produce laminates which met specifications and new cycles had to be developed. Furthermore, the quality of the prepreg tape was not satisfactory in many instances. Considerable effort was expended to obtain prepreg tape with quality measurably better than that available at the start of this program. Results obtained should be beneficial to future composites production programs.

Minor problems were encountered in establishing the manufacturing sequences. These were resolved and the final assembly sequence is shown in Figure 10. First, the metal details (hinge fittings and leading-edge channels) and the fiberglass end ribs are assembled. The machined honeycomb core is then bonded to the frame. The layed-up and cured skins are then bonded to the frame and honeycomb and finish details are added. At this time, all spoilers except the advanced versions have been fabricated and delivered.

6. LOCKHEED YF-12 WING PANELS

The NASA Advanced Supersonic Technology program includes activities related to the development of advanced materials and structural concepts for supersonic aircraft. One aspect of this multi-faceted program is the manufacturing development and flight qualification of selected concepts. As a focal point to this activity, a joint NASA Langley/NASA Flight Research Center/U.S. Air Force flight service program has been developed using the YF-12 aircraft shown in Figure 11 as the test vehicle.

Figure 11 shows the location of three panels which have been selected for replacement with advanced panel concepts. These panels, which are essentially flat and located in the dry bay areas of the wing, include both primary and secondary structures. The composite panels are designed to meet the load envelope of the original panels at both room temperature and flight temperatures. Ground-test exposures of the composite panels to 10,000 hours with simulated flight conditions are planned in addition to the flight tests.

As shown in Figure 12, each panel has a different critical loading. Panel 1 is a rectangular primary structural panel (16 by 28 inches), located aft of the main landing gear, and is critical for shear loads. Panel 2 is a rectangular secondary structural panel (26 by 40 inches), located over the main landing gear well, and is critical for pressure loads. Panel 3 is a trapezoidal primary structural panel (28 inch spanwise width, 14 and 21 inch parallel sides), located just forward of the wing rear beam and has a critical tension loading.

Some of the structural concepts being considered for this program are shown in Figure 13. Both skin-stringer and sandwich panels will be investigated and the composite materials are boron/aluminum and graphite/polyimide. At this time, it appears that a boron/aluminum concept designed for the conditions of panel 1 will be the initial selection for development and flight testing. Other concepts will be included as permitted by available funding.

7. DOUGLAS DC-10 RUDDER

The DC-10 rudder program will be the first of the NASA Langley programs in which a commercial aircraft component is extensively redesigned for composite applications. The rudder (one segment of the four-segment rudder on the DC-10) is identified as the upper aft rudder and is located as shown in Figure 14. The configuration of the 38- by 158-inch upper aft rudder, in the aluminum production version, is shown in Figure 15.

The Douglas Aircraft Company is performing the initial work required to certify composite rudders for flight service on DC-10 transports. With the Douglas work as a starting point, the NASA Langley program will provide for the design, manufacture, ground test, and flight-service evaluation of composite rudders. Early studies by Douglas showed that a 40% weight reduction could be achieved with a composite rudder. However, in the NASA Langley program both structural configurations and manufacturing methods will be emphasized so that the selected design achieves significant weight savings, but at relatively low cost. The design goal is to make the composite rudder cost competitive with the present aluminum rudders.

The components of one concept for a composite upper aft rudder are shown in Figure 16. With the exception of aluminum hinge fittings and lightning protection straps, this concept consists entirely of graphite/epoxy and fiberglass. In addition to the lightning protection identified in Figure 16, the upper aft rudder, because of its location on the DC-10, will require a lightning protection system on the skin of the composite rudder. The requirement to provide lightning protection for the composite material is another distinct difference between the DC-10 rudder program and the Boeing 737 spoiler program.

Present plans for the program are to manufacture about 19 composite upper aft rudders in Douglas production facilities. Manufacturing this number of rudders should provide good definition of the fabrication costs and the cost learning curve. Of the 19 rudders, one will be used for ground tests and 18 will be used in flight service evaluations.

Six each of the composite rudders will be supplied to three airlines for installation on DC-10 aircraft in regular airline service. The nominal period of flight service will be 5 years. The rudders will be regularly inspected by the airlines and, periodically during the 5 years, rudders will be removed for comprehensive inspections and tests to investigate possible deterioration due to environmental exposure and flight loads.

8. LOCKHEED L-1011 AILERON

One of the most recent considerations for a flight service program is the aileron of the Lockheed L-1011 as shown in Figure 17. As is the case for the DC-10 rudder, the aileron is sufficiently large (48 by 96 inches; see Fig. 18) and complex to permit the examination of alternate structural configurations and fabrication processes. Furthermore, the severity of the environment, which includes acoustical loading, engine exhaust contaminants, and foreign object damage, is a rigorous test for a composite aileron.

At present, NASA Langley is committed to an engineering design study with the goal of defining a composite aileron that is lighter and cheaper than the aluminum production version. An example of a possible configuration is shown in Figure 19. To be noted is the use of PRD-49 to lessen the possibility of impact damage. The composite configuration shown has fewer internal members than the aluminum version. This is due in part to the use of a honeycomb sandwich skin but also to the better properties of the composite materials.

A composite L-1011 aileron is a strong contender for inclusion in the NASA Langley flight service programs. However, whether or not this project proceeds to flight service is dependent on the results of the design study and the existence of budgetary constraints.

9. SUMMARY AND STATUS OF THE NASA LANGLEY FLIGHT SERVICE PROGRAMS

To supplement the general description of the NASA Langley flight service program, a summary is presented in Table II. This table identifies the number of complete structural components being fabricated in each program, for both ground and flight testing. Two of the programs, the 737 spoiler program and the YF-12 panel program, are associated with a large amount of ground testing of full-scale components.

Approximately 25 production composite 737 spoilers will be tested to determine the variability in properties and performance when loaded. One objective is to ascertain if there is a correlation between the variable materials properties and the performance of the complete component.

In the case of the YF-12 program, ground testing of flight-qualified panels will be greatly more extensive than the flight testing. The present plan includes eight panels that will be tested in a variety of load, temperature, and pressure conditions to investigate thermal aging, thermal cycling, and the overall response to simulated flight conditions.

Closely coupled to the flight service testing, but not indicated by Table II, is the testing of many hundreds of small specimens. The tests, most of which will be conducted at Langley, are to obtain complete determination of materials properties and the effect of environmental exposure. Periodically, the results of these tests will be compared with results obtained from specimens taken from removed flight service components. These test results and comparisons should yield valuable information regarding possible composite degradation.

Typically, those programs which involve the use of military aircraft will not accumulate a large number of component flight hours. However, those programs based on the use of commercial aircraft will produce a large number of flight hours. This aspect of the programs is most attractive as the possibility of obtaining ample and meaningful maintenance data is certainly enhanced.

Finally, the estimated start of flight service is shown for each program. Flight service has already begun on three of the programs (the CH-54 tail cone, the L-1011 fairing panels, and the 737 spoilers). Two of the remaining programs (C-130 wing box and YF-12 panels) have the planned start of flight service in the last half of calendar year 1974. The DC-10 program will start flight service in 1975. The last program, the L-1011 aileron, is not yet sufficiently advanced to make judgments concerning flight service.

10. CONCLUDING REMAKRS

A review of the NASA Langley Research Center programs for the service evaluation of aircraft composite structural components has been given. The objective of these programs is to promote the acceptance of composites for structural applications by increasing the user's confidence and by providing service data which is much needed to determine life-cycle costs. In addition, a few of the programs involve a sufficiently large number of components to develop good manufacturing cost data.

A recognized deficiency in the present flight service programs is lack of sufficient utilization of composite components in primary aircraft structures. Opportunities exist for implementing such programs; however, the associated costs are high. When budgetary constraints permit, the NASA Langley Research Center plans to implement appropriate activity in flight service evaluation of composites in primary aircraft structures.

Finally, it is becoming increasingly clear that all composites technology programs, whether they include flight service or not, should emphasize the acquisition costs of the composite components as well as the total life-cycle costs. The development of technology that allows a composite component to be pricewise competitive with its all-metal counterpart is an attractive addition to the challenge of showing benefits by considering total life-cycle costs of composite structures. Indeed, it may be advisable to sacrifice some of potential weight saving of composites to approach the cost competitive situation. Of course, the extent of this trade off depends on the relative significance of acquisition costs, weight, and the in-service costs of composites for the particular application of concern.

11. REFERENCES

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TABLE 1. NASA LANGLEY COMPOSITES FLIGHT SERVICE PROGRAMS

PROGRAM DESCRIPTION	DESIGN CONCEPT	MATERIAL
C-130 CENTER WING BOX	COMPOSITE REINFORCED METAL	BORON/EPOXY
CH-54 B TAIL CONE	COMPOSITE REINFORCED METAL	BORON/EPOXY
737 SPOILER	COMPOSITE SUBSTITUTION	GRAPHITE/EPOXY AND CHOPPED FIBER MOLDINGS
L-1011 FAIRING PANELS	COMPOSITE SUBSTITUTION	PRD-49/EPOXY
YF-12 PANELS	ALL COMPOSITE REDESIGN	BORON/ALUMINUM AND GRAPHITE/ POLYIMIDE
DC-10 UPPER AFT RUDDER	ALL COMPOSITE REDESIGN	GRAPHITE/EPOXY
L-1011 AILERON*	ALL COMPOSITE REDESIGN	PRD-49, GRAPHITE/ EPOXY

*AT PRESENT, DESIGN STUDY ONLY

TABLE 2. SUMMARY OF COMPONENTS, NUMBER OF AIRCRAFT, AND COMPONENT FLIGHT SERVICE HOURS FOR THE NASA LANGLEY FLIGHT SERVICE PROGRAMS

PROGRAM DESCRIPTION	NUMBER OF COMPONENTS		NUMBER OF AIRCRAFT INVOLVED	ESTIMATED COMPONENT FLIGHT SERVICE HOURS	START OF FLIGHT SERVICE
	GROUND	FLIGHT			
CH-54B TAIL CONE	1	1	1	400	MARCH 1972
C-130 CENTER WING BOX	1	2	2	4800	AUGUST 1974
737 SPOILERS	32	118	27	1632000	JULY 1973
L-1011 FAIRING PANELS	1	18	3	270000	JANUARY 1973
YF-12 PANELS:					
B/AL	9	1	1	50	LATE 1974
G/PI	9	1	1	50	LATE 1975
DC-10 RUDDER	1	18	18	261 000	JANUARY 1975
L-1011 AILERON*	-	-	-	-	-

* AT PRESENT, DESIGN STUDY ONLY

Figure 1. C-130 composite reinforced wing box.

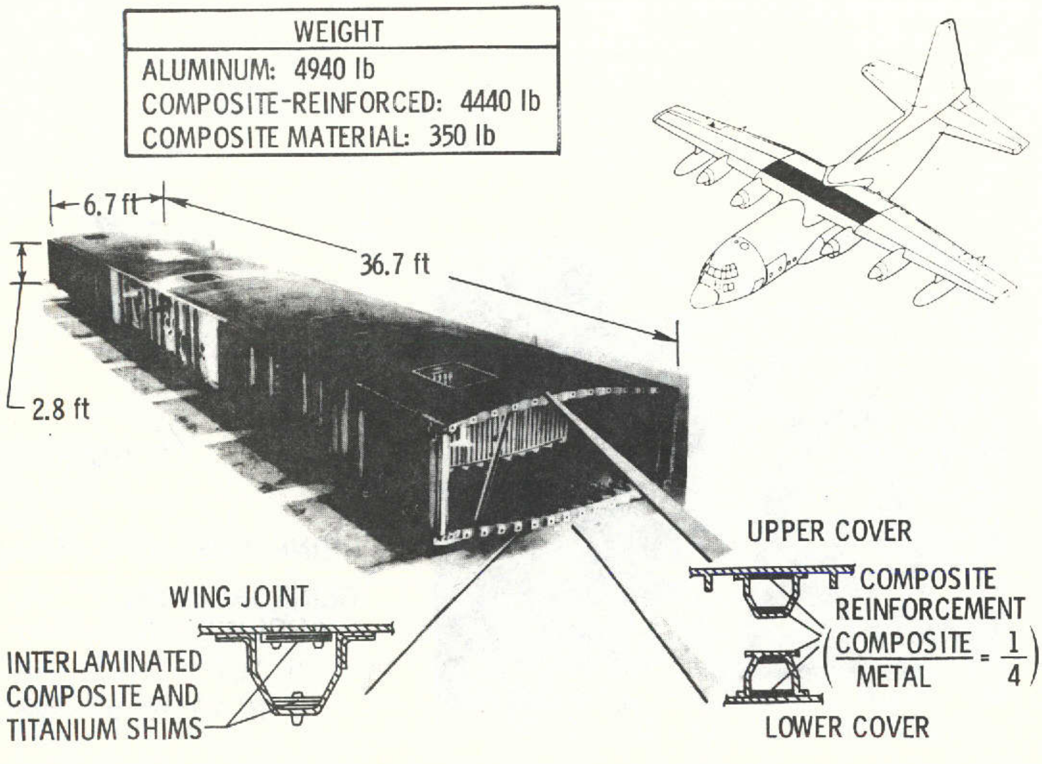


Figure 2. C-130 center wing box.

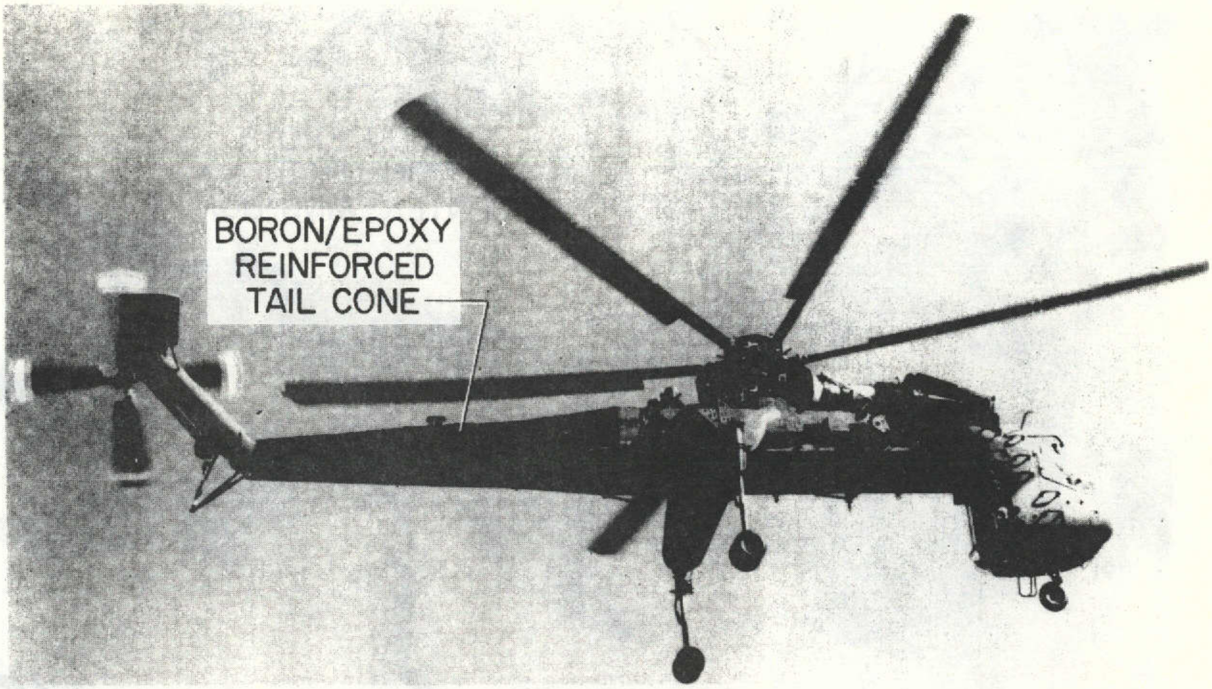


Figure 3. CH-54B helicopter.

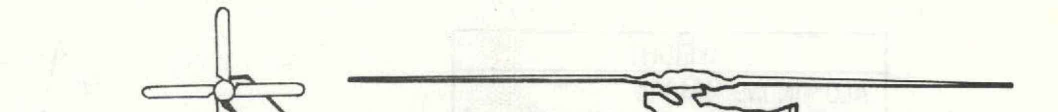


Figure 4. Composite reinforced tail cone for flight service on CH-54B helicopter.

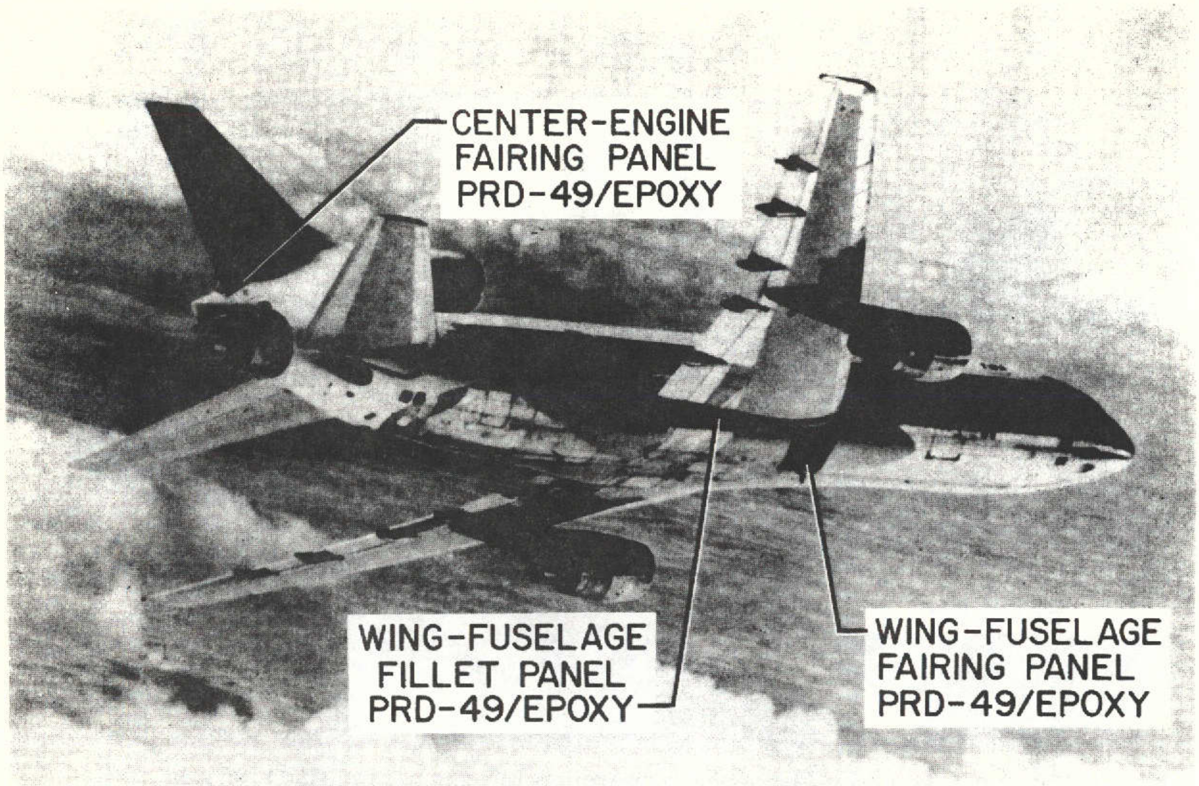
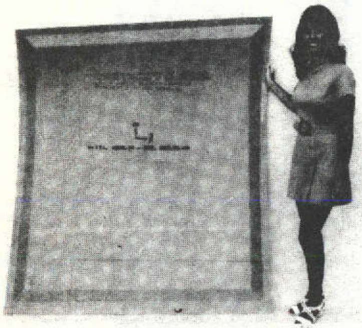
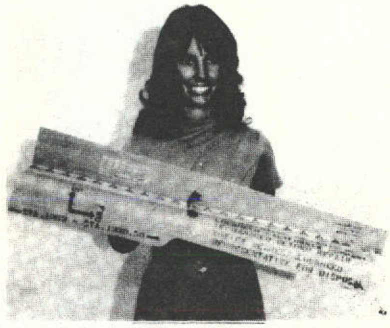


Figure 5. Composite panels for L-1011 transport.

CENTER ENGINE PANEL



WING TO BODY PANEL



WING TO BODY FILLET

Figure 6. PRD-49/epoxy fairing panels for L-1011 transport.

Figure 7. Composite spoilers for 737 commercial flight service.

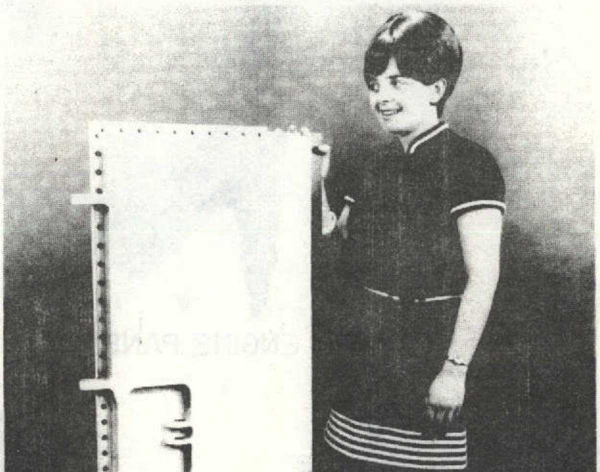


Figure 8. 737 spoiler.

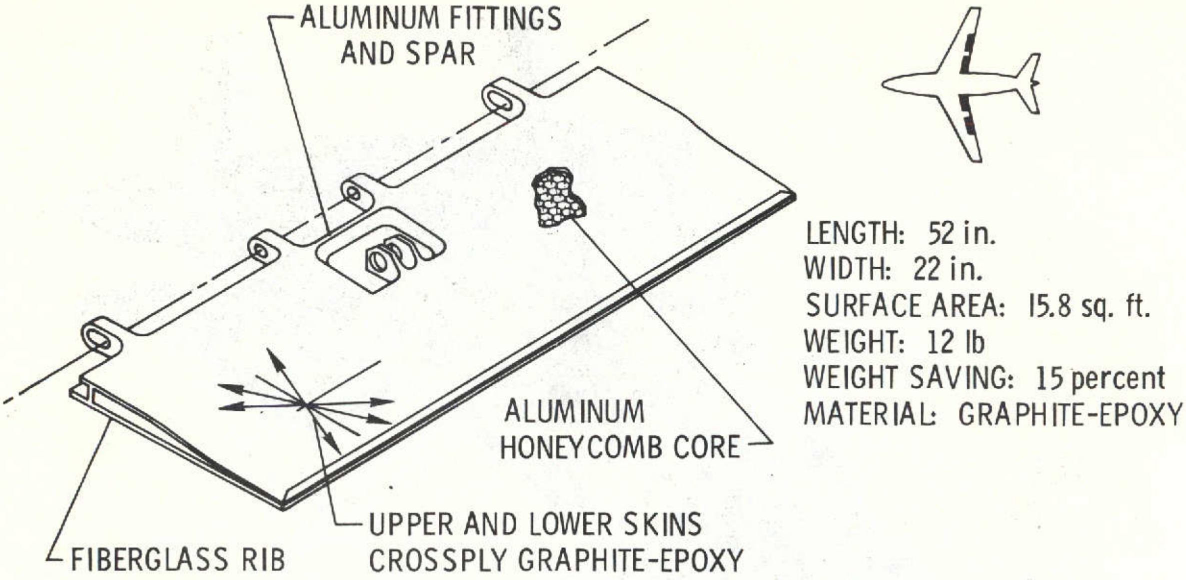


Figure 9. Detail of 737 composite spoiler.

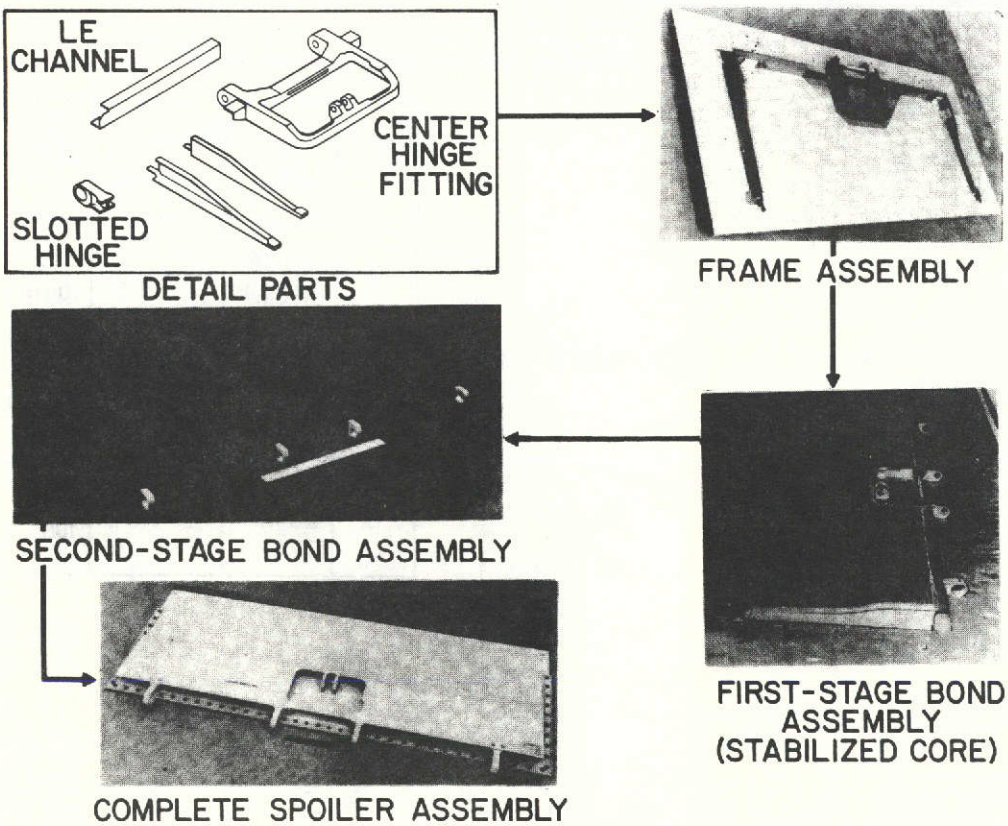


Figure 10. Construction of 737 composite spoiler.

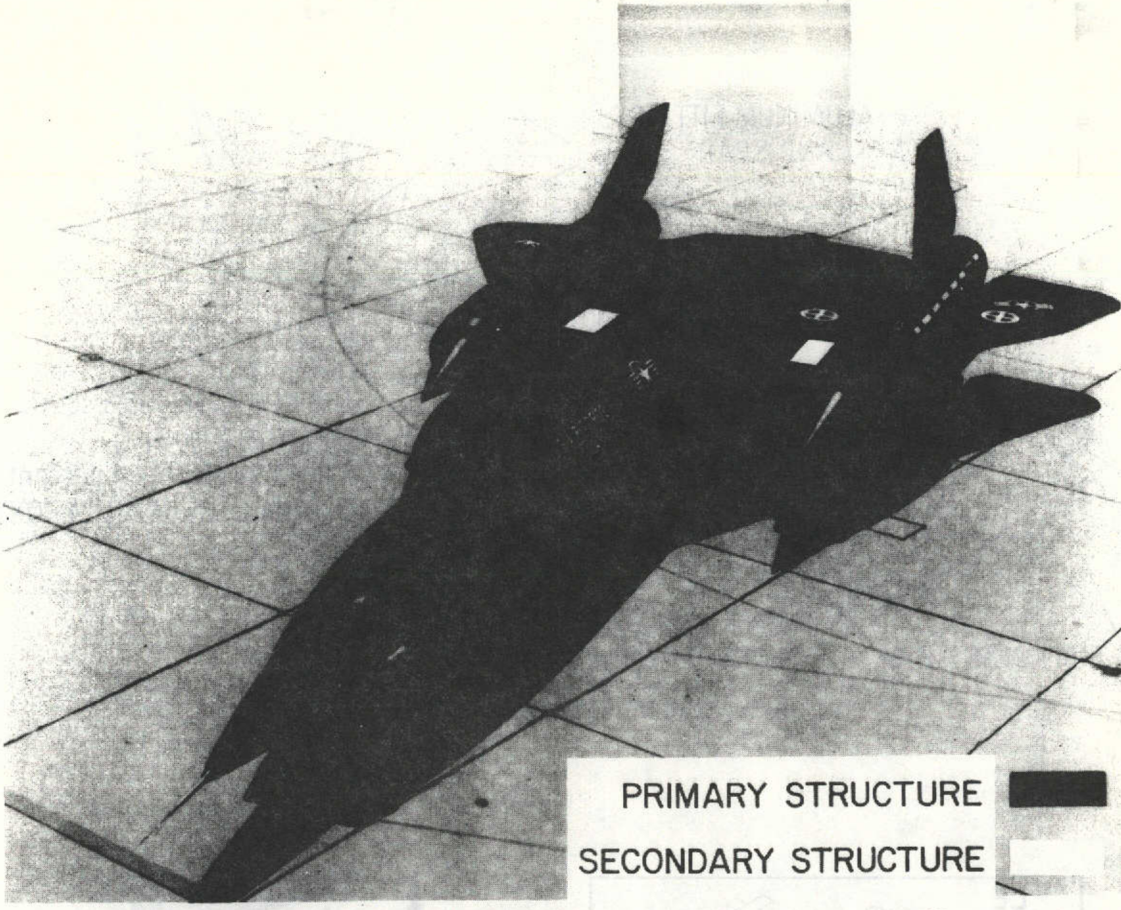
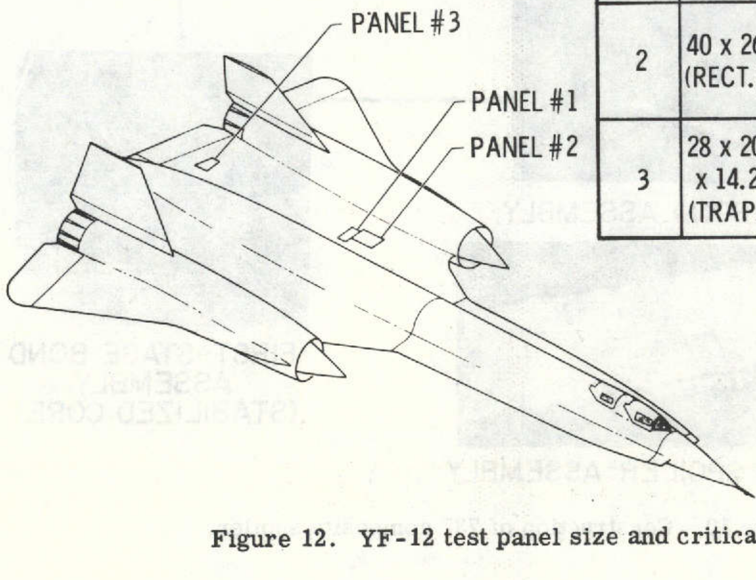


Figure 11. Structural panels for flight service on YF-12.



PANEL NO.	PANEL SIZE, in.	CRITICAL LOADING	DESIGN LOAD LEVEL	
			RT	$600^{\circ}F$
1	28 x 16 (RECT.)	SHEAR	3885 lb/in.	2425 lb/in.
2	40 x 26.4 (RECT.)	TRANS-VERSE PRESSURE	-6.7 psi	-4.6 psi
3	28 x 20.8 x 14.2 (TRAP.)	TENSION	8750 lb/in.	5450 lb/in.

Figure 12. YF-12 test panel size and critical loading.

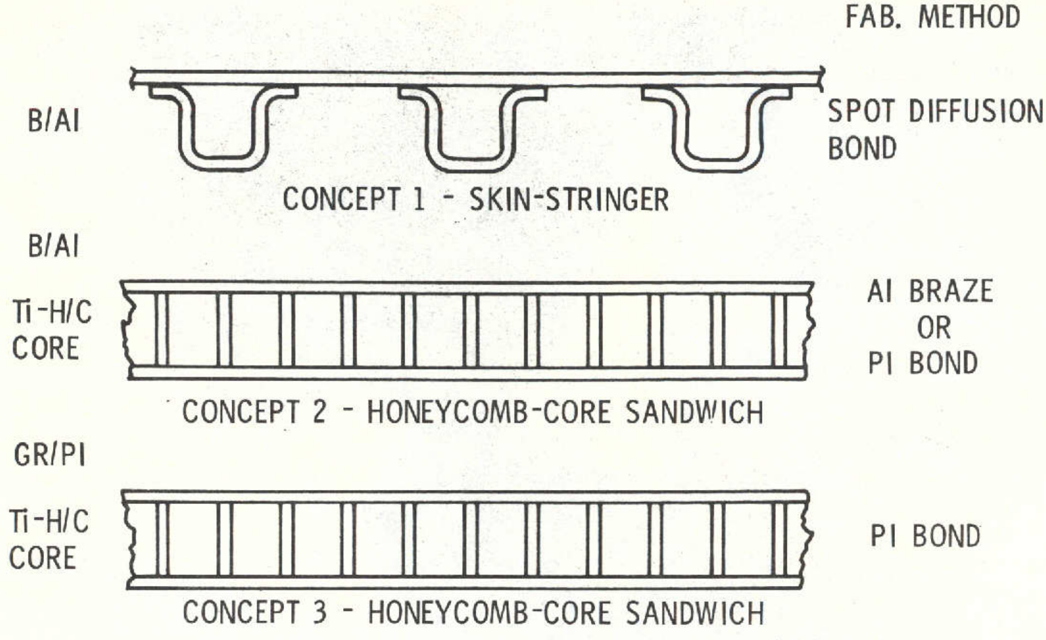


Figure 13. YF-12 structural panel program - composite panel concepts.

Figure 14. Composite upper aft rudder for DC-10 transport.

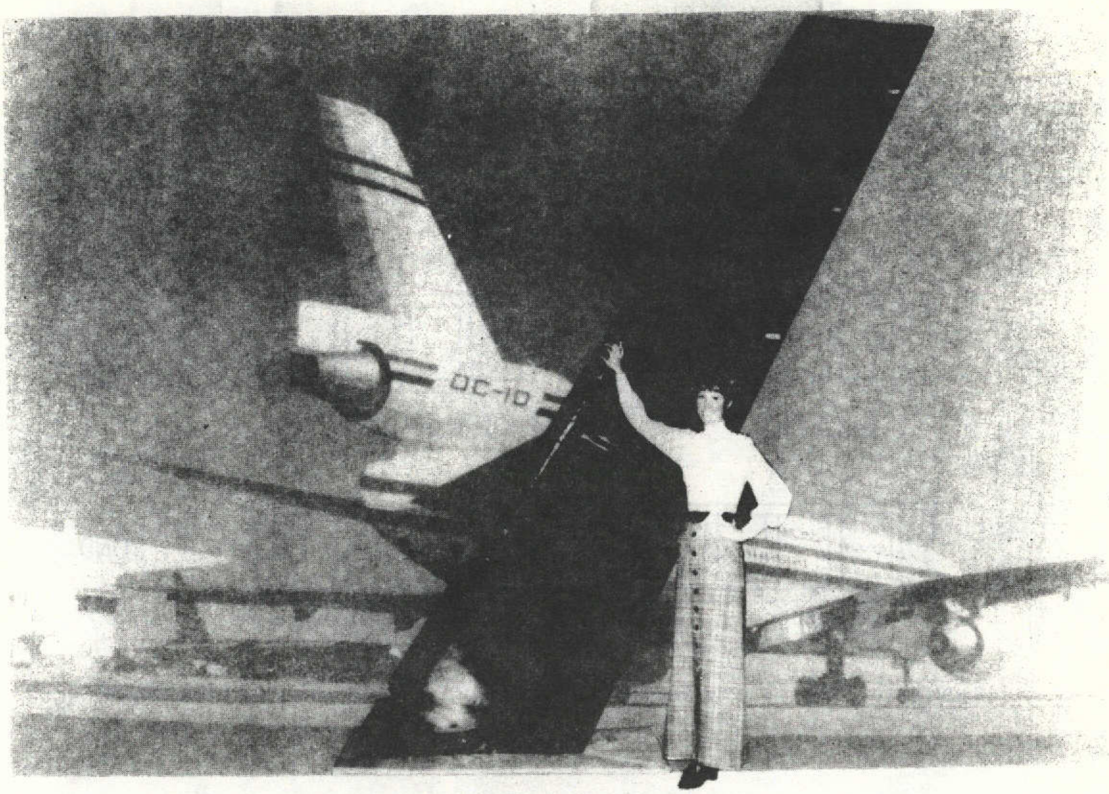


Figure 15. DC-10 upper aft rudder.

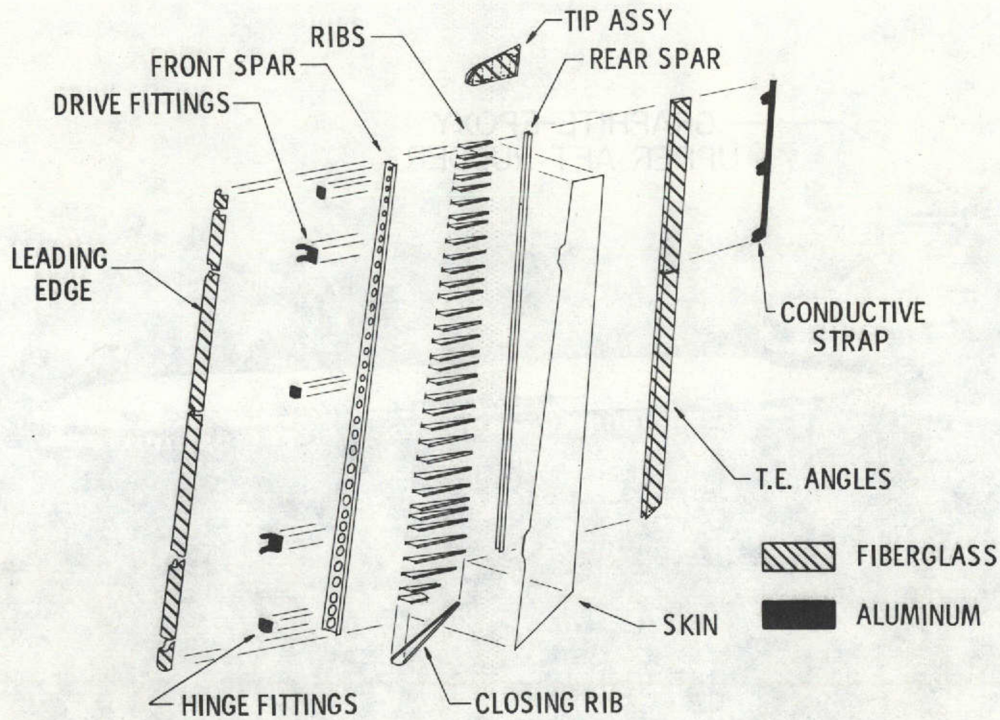


Figure 16. Composite upper aft rudder components.

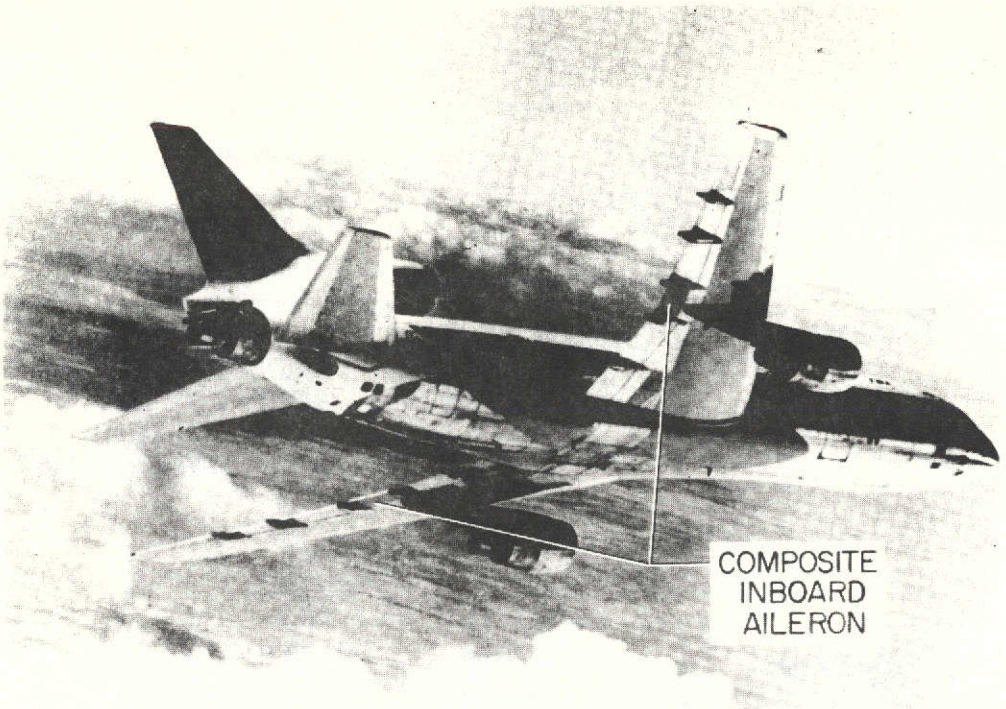


Figure 17. Composite aileron for L-1011 transport.

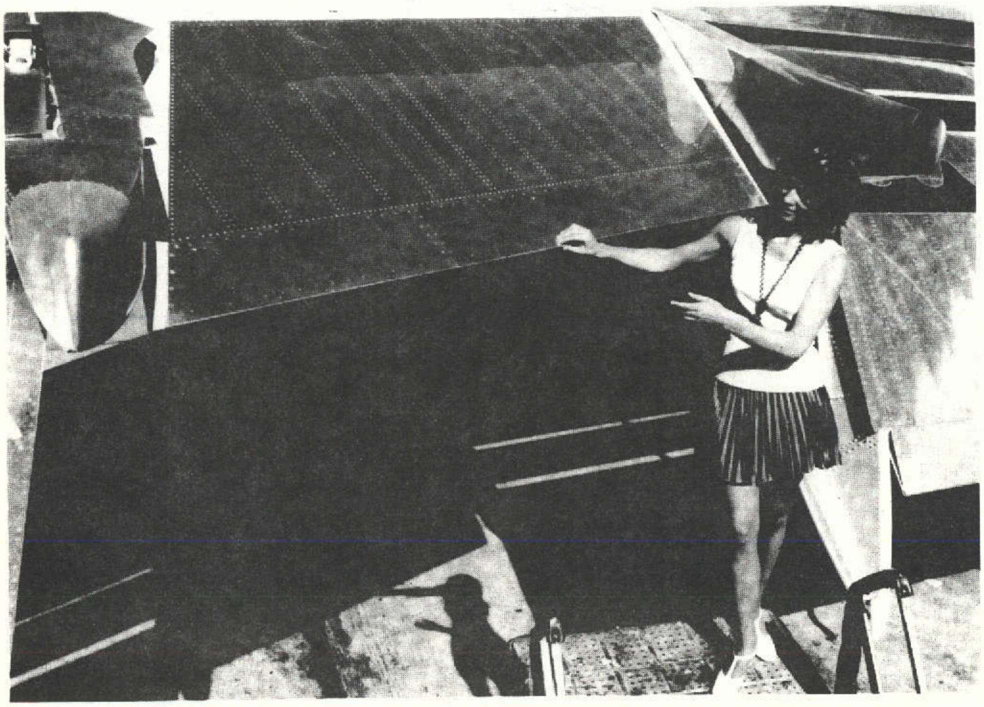


Figure 18. L-1011 inboard aileron.

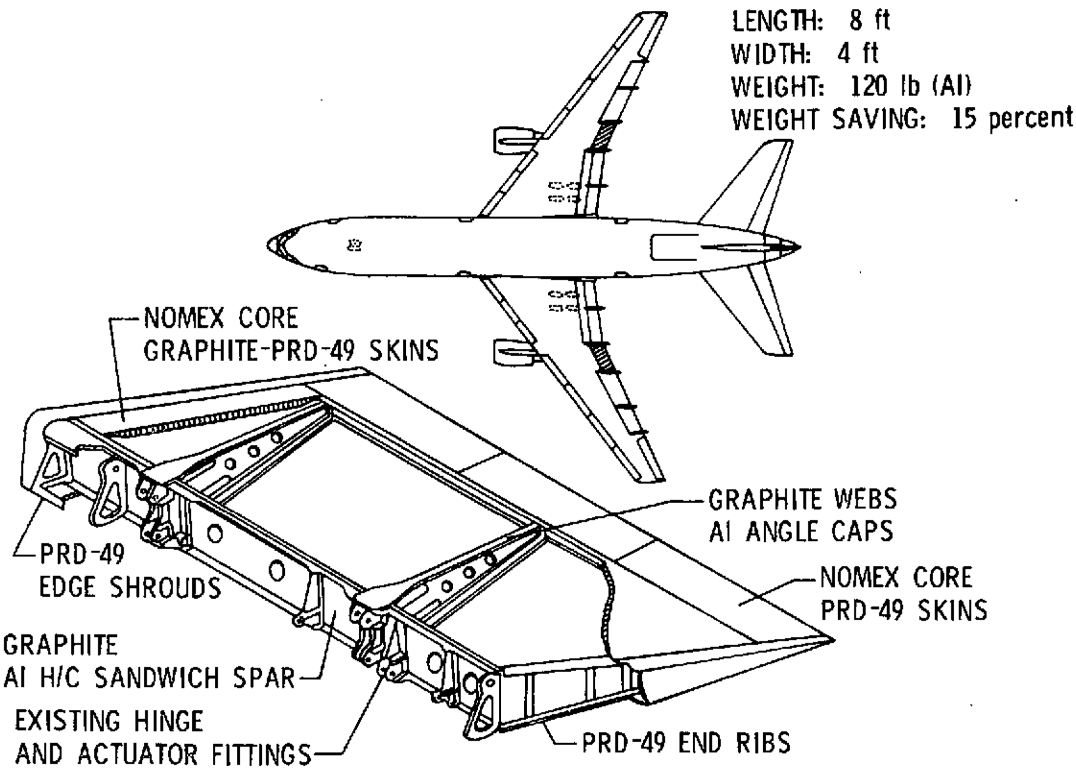


Figure 19. Composite concept for L-1011 aileron.