NASA-ACEE/BOEING 737 GRAPHITE-EPOXY HORIZONTAL STABILIZER SERVICE

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INTRODUCTION

The 737 graphite-epoxy horizontal stabilizer was developed by Boeing as part of the NASA-ACEE (Aircraft Energy Efficiency) Advanced Composite Structures Program. NASA-ACEE programs challenged large-transport manufacturers to use graphite material in redesigning existing aircraft components. The goal of the program was to develop the necessary data and technology to achieve production commitments to advanced composites. Boeing designed, fabricated, and certified five shipsets of horizontal stabilizers for the 737-200 airframe. The program was initiated in July 1977 and certification was achieved in August 1982. Schedule highlights are shown in Figure 1. The work performed on this program is reported in NASA technical summaries and final reports, (ref. 1 thru 4).

Boeing introduced the stabilizer into commercial operation in 1984, and has maintained surveillance for seven years of in-service evaluation. Outstanding performance has been demonstrated with no service incidents attributed to the graphite-epoxy structure. Boeing will continue to monitor and support these aircraft, adding to the data base of commercial composite experience.

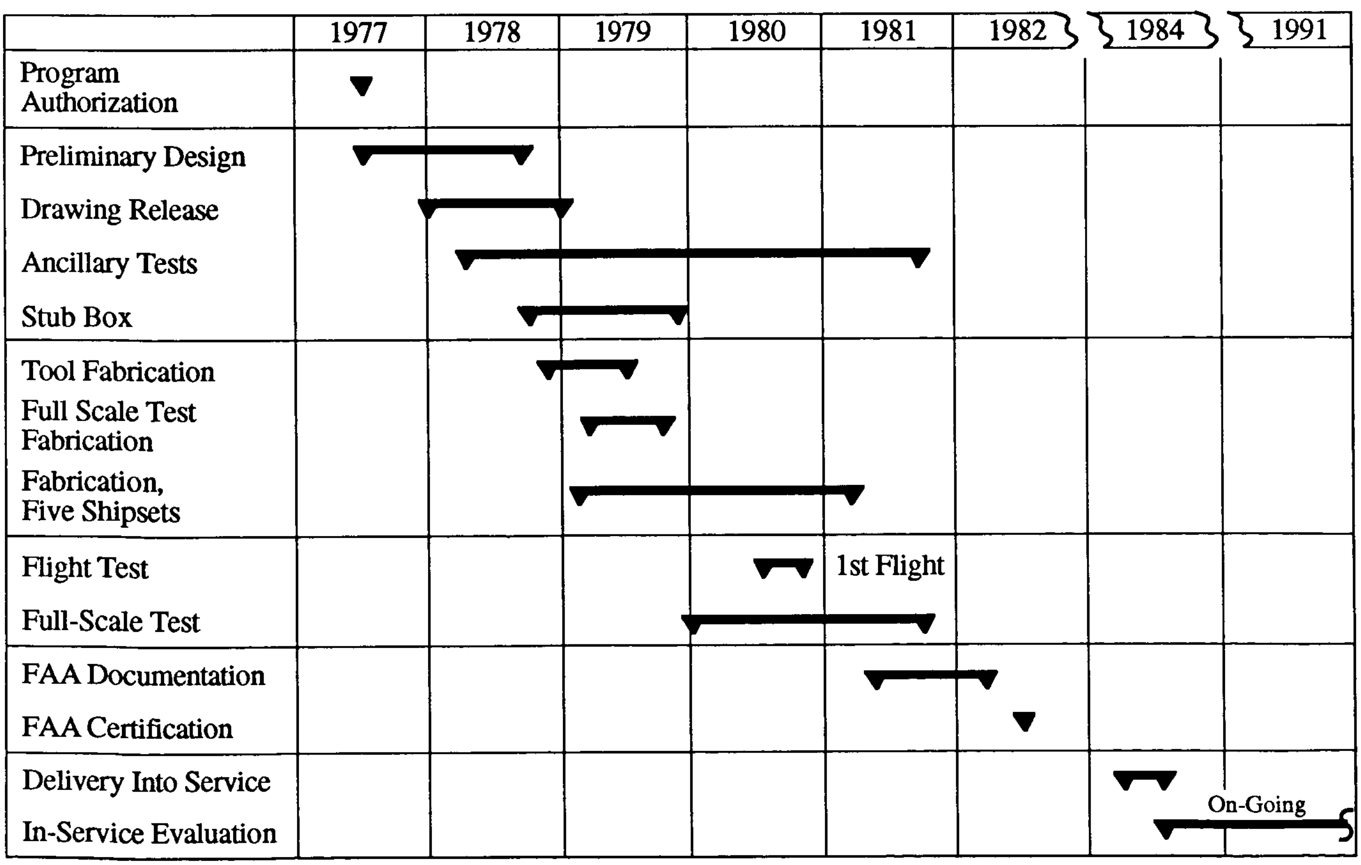


Figure 1. Program Schedule

STRUCTURAL ARRANGEMENT

Design and contract requirements specified that the graphite-epoxy structure would be interchangeable, both geometrically and functionally with the existing flying hardware. These criteria defined the structural interface, stiffness, aerodynamic shape, planform, and elevator interface. The general structural arrangement is shown in Figure 2. Trade-off considerations were given to element designs within the box. Details were selected that could be produced with the then current material systems and manufacturing technology while looking to future applications such as a wing design. The selected configuration, shown in Figure 3, was comprised of:

a) I-stiffened, co-cured laminate panels.
b) Shear-tied ribs using honeycomb webs and graphite-epoxy faces.
c) I-section solid laminate spars.

The material system selected was Narmco T300/5208. The predominant material form was fabric with selected use of tape. The structural details used hand-layup procedures throughout. Conventional fastening systems were used for assembly.

A requirement of the program was to use existing hardware to the greatest extent possible. Since the parts that were available for use were predominantly aluminum alloy, a protection system was developed to prevent corrosion. The protection system was designed to isolate graphite-epoxy surfaces from aluminum structure, minimizing the cathodic area (graphite) available for electro-chemical reaction. The system, shown in Figure 4, isolated the graphite-epoxy side of the interface with either co-cured fiberglass or primer and epoxy paint. The aluminum alloy was anodized or alodine treated, primed and enameled. Polysulfide sealant was applied to faying surfaces and fasteners at installation.

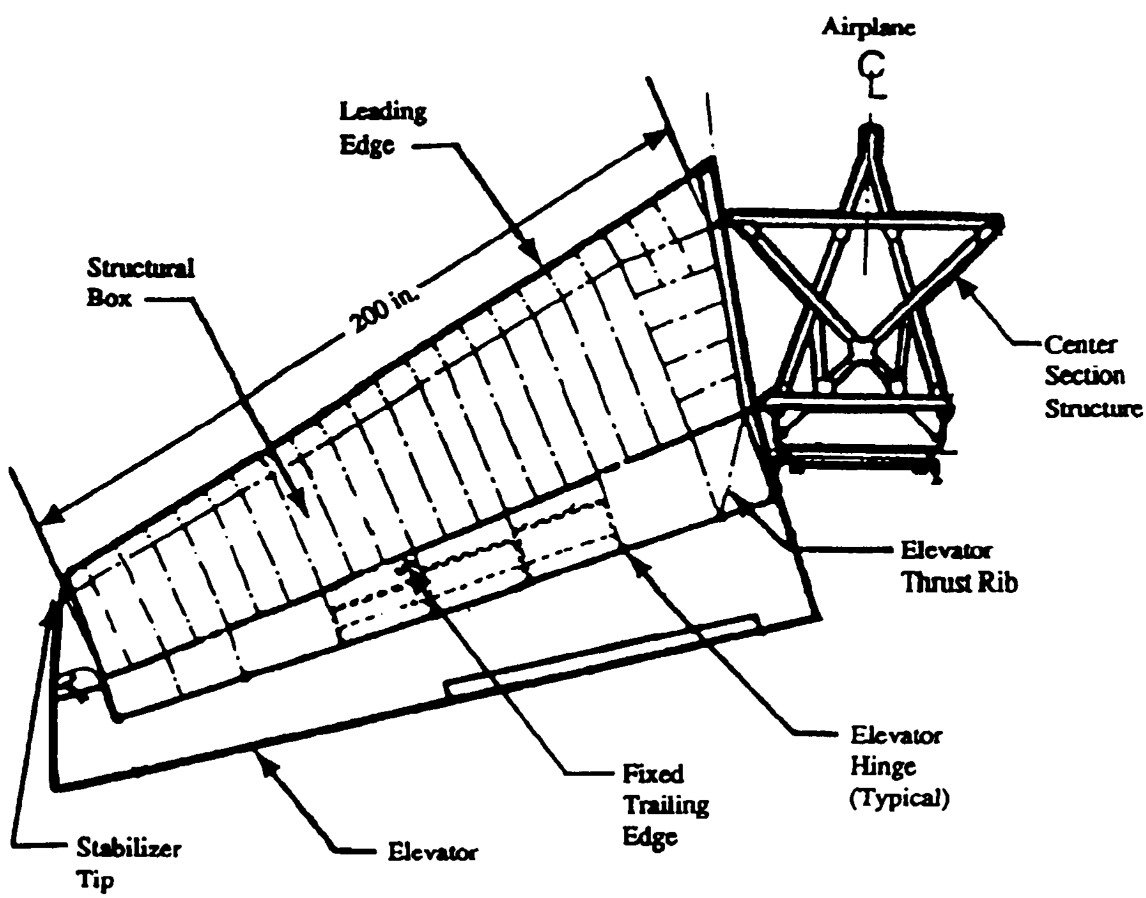


Figure 2. Horizontal Stabilizer - General Arrangement - Aluminum Alloy Baseline

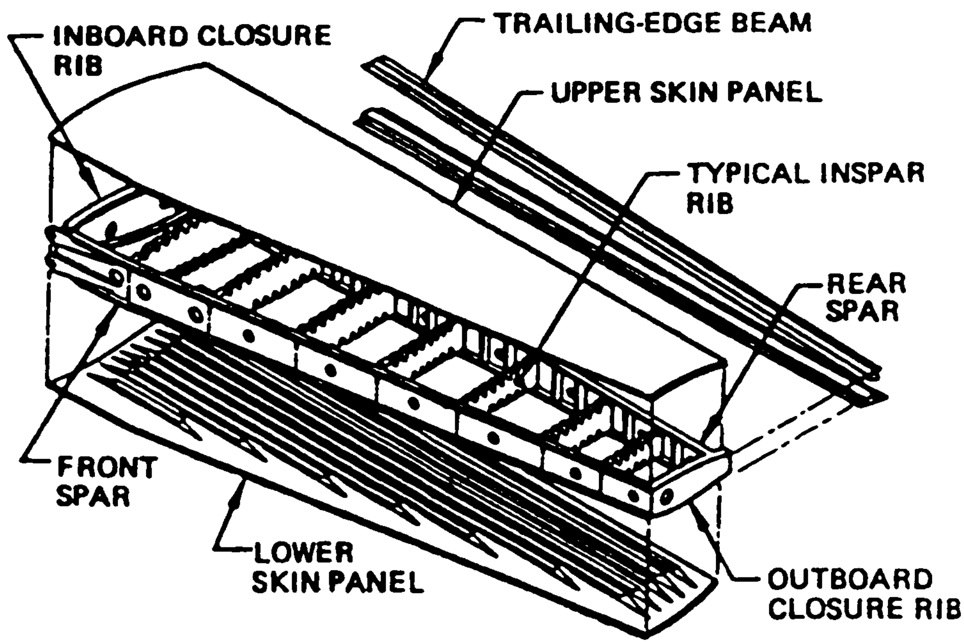


Figure 3. Advanced Composite Stabilizer Inspar Structural Arrangement

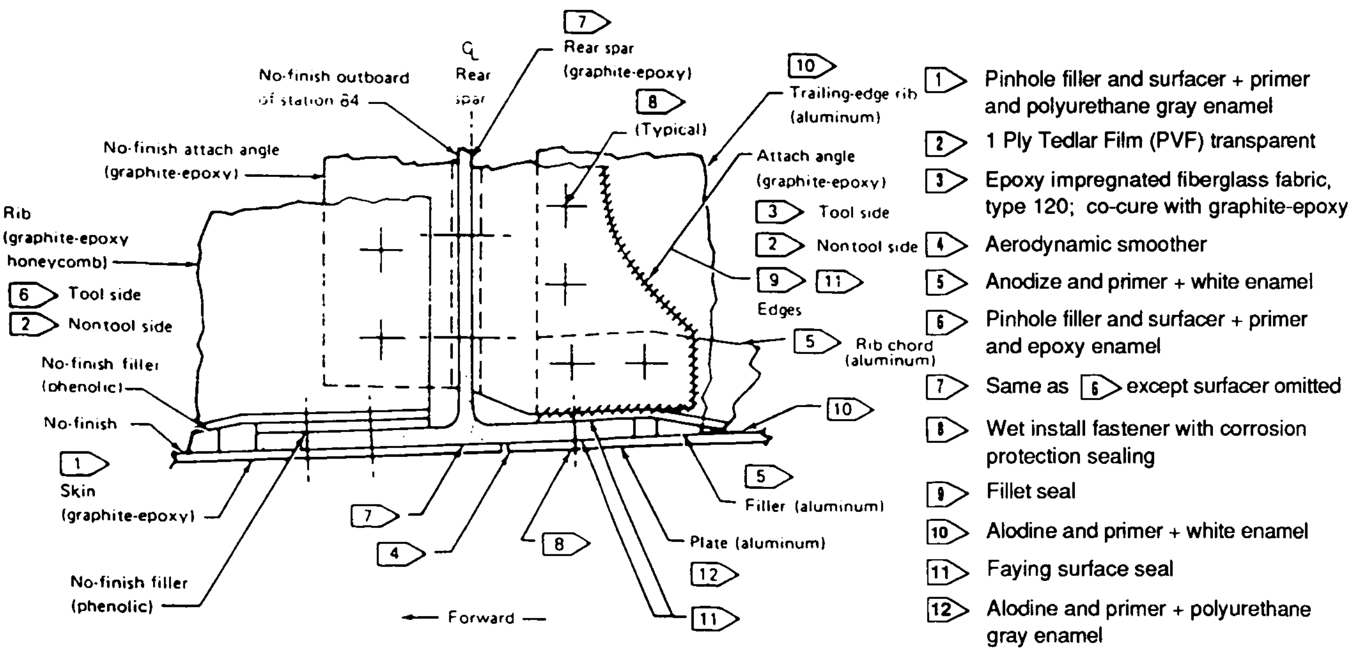


Figure 4. Corrosion Protection System

CERTIFICATION

Certification requirements for commercial transport aircraft are defined in Code of Federal Regulations, FAR Part 25, (ref. 5). An FAA advisory circular, AC 20-107, (ref. 6) set forth a recommended means of compliance with the regulations.

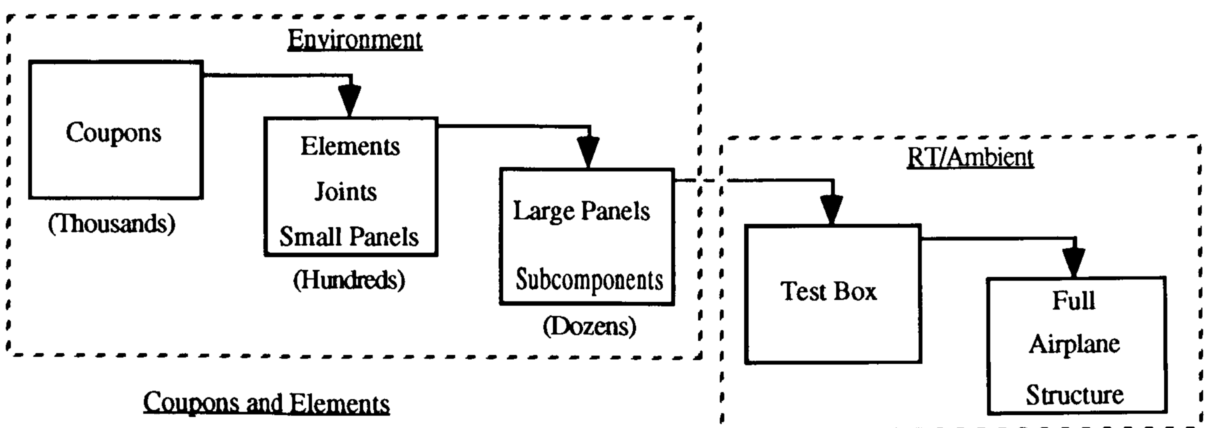
Boeing's certification approach, presented in detail in reference 7, was based on current and accepted practices and procedures. "Simply stated, the primary means of commercial aircraft certification is by the analytical process supported by appropriate test evidence" (ref. 7). Early coordination with the FAA established a detailed plan to certify the 737 hardware.

ANALYSIS - Analyses were performed during the program that encompassed external static and dynamic loads, sonic environment, electro-dynamic effects and environment. An extensive finite element model was developed to perform stress/strain analyses that addressed applied loads and environmental effects. Strains were calculated for static and residual strength including bird strike damage. Compliance with the requirements of the regulations was then demonstrated by comparing the maximum calculated strain to the allowable design value for a particular environmental condition.

TEST PROGRAM - A test program was implemented to provide the necessary supporting data for compliance with FAR Part 25. A "building block approach", (Figure 5) was developed that utilized:

a) Coupon, element, and panel tests that addressed material properties and point design characteristics and included the effects of environment.
b) An early stub box test that subjected critical structure to three-dimensional strain and validated design concepts.
c) A highly strained, bi-directionally loaded panel tested in various environments to demonstrate the validity of the analysis techniques used to calculate environmental strains.
d) A full scale ground test that verified calculated strain distributions, functional performance, durability, damage tolerance and ultimate load carrying capability.
e) A flight test that demonstrated equivalency to the aluminum stabilizer from a flutter and a stability and control standpoint.

References 7 and 8 discuss these elements in further detail.



Coupons and Elements

- Mechanical properties
- Interlaminar properties
- Stress concentrations
- Durability
- Bolted joints
- Impact damage characterization
- Environmental factors

Large Panels and Test Boxes

- Validate design concepts
- Verify analysis methods
- Provide substantiating data for material design values
- Demonstrate compliance with criteria
- Demonstrate ability of finite element models to predict strain values

Figure 5. The Building Block Approach

IN-SERVICE EXPERIENCE

MAINTENANCE PLANNING PROGRAM - A maintenance planning program was defined to assist the operator in establishing procedures that would insure continued safety and performance. The Boeing 737 had been in service for over ten years, therefore a primary groundrule for introducing a graphite-epoxy stabilizer was to provide the same level of safety while recognizing the unique characteristics of composite structure and creating a minimum impact on the operator.

A basic plan, (ref. 8) adjustable to the individual airline's existing procedure was established and FAA approval was received. Details of this plan were presented in references 2 and 9. The Maintenance Planning Schedule recommended by Boeing is shown on Table 1. As part of the certification proceedings Boeing agreed to support an additional (early) structural inspection that would be performed on the first two airplanes to reach 7000 hours of service. Non-destructive inspection techniques were developed that used equipment common to most operator maintenance depots. Repairs were designed and tested to demonstrate that the structure could be restored to a pre-damaged level of strength and durability in the event of in-service damage. A repair manual was prepared, and in combination with the maintenance plan and inspection techniques, provided the concluding data for certification.

Table 1. Maintenance Planning Schedule

Check	Inspection Interval (Flight Hr) [a]	Description
Preflight/transit	---	• Walk around
A	75	• Visual inspection of exterior surface, from ground level
B	300	• Visual inspection of external surfaces
C	1,200	• External visual inspection • Exposed rear spar area • Exposed hinge fittings and thermal linkage
	2,400	• Front and rear spar-to-center section attachment lugs • Inboard edge of rear spar web • Trailing-edge cavities
Structural	14,000 [b]	• External visual inspection • NDT inspection upper and lower skin from the rear spar forward to stringer 3 between the side-of-body and the rib at stabilizer station 111.1 • Front and rear spar attachment lugs, pins, bushing, and fittings • Internal trailing-edge structure • Internal structure, spars, stiffeners, closure ribs; access by removing gap covers, access hole covers, removeable leading edge, removeable lower trailing-edge panels and removeable tip

a) Boeing recommended for new operators b) Early inspection on the first two units to reach 7000 flight hours

SERVICE BEHAVIOR - The stabilizers were introduced into service in 1984 with Boeing committed to supporting the inspection and maintenance program. The current in-service status is shown on Table 2. Continued effort has been expended to ensure that the composite structure provides satisfactory service and meets design requirements. The objective of minimized corrosion and fatigue damage has been demonstrated. There have been no service reports of problems related to the composite material.

Table 2. In-Service Status May 31, 1991

Tail No.	Airline	Installation	Hours	Landings
N314DL	Delta	3-13-84	19622	19097
N307DL	Delta	3-16-84	19216	18690
[1> N670MA	Markair	5-11-84	17318	19308
N671MA	Markair	6-22-84	19175	19001
N672MA	Markair	8-18-84	19568	20966

[1> Status on 6-2-90

INSPECTION RESULTS - The early 7000 hour structural inspections of the composite stabilizers were performed on Delta Airlines aircraft N314DL and Markair aircraft N670MA as part of a regular "C" check per Table 1. Inspections were performed per the recommended plan (Table 1 and Figure 6). There were no structural problems or in service wear reported.The inspections required 24 and 17 hours down-time respectively, which is consistent with the inspection of metal structure. The Markair aircraft inspection showed no problems other than a debris strike on the lower surface. Damage was limited to the protective finish.

Both operators have continued to perform regularly scheduled "C" checks. No structural problems have been reported.

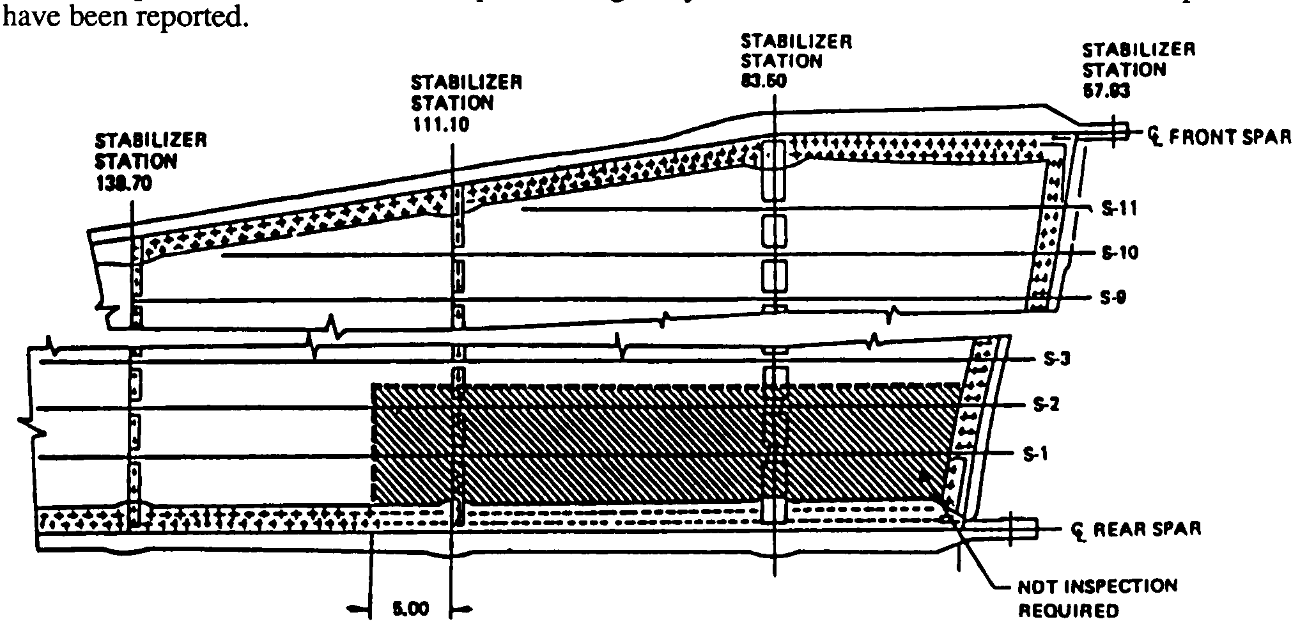


Figure 6. Upper and Lower Skin Panel NDT Inspection Requirements

IN-SERVICE DAMAGE

Markair has experienced two incidents that required repair. Damage to the skin panels occurred due to impact by a foreign object. Both damages were repaired using techniques developed during the test program. For example, the damage shown in Figure 7 was caused by debris resulting from an engine failure. Pulse-echo NDT inspection of the surrounding area determined that the damage was limited to the penetration through the skin and did not affect the stringers attached to the skin. The skin was scarfed and prepared for repair (Figure 8). The repair used a hot bond/vacuum bag procedure (Figure 9) that required tools readily available at maintenance depots. The completed patch (Figure 10) constituted terminating action and returned the structure to unrestricted flying status.

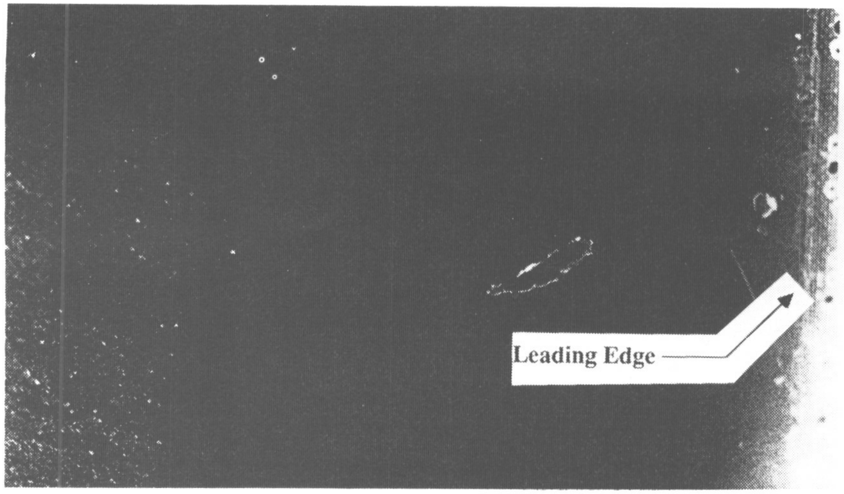


Figure 7. Damage from Runway Debris

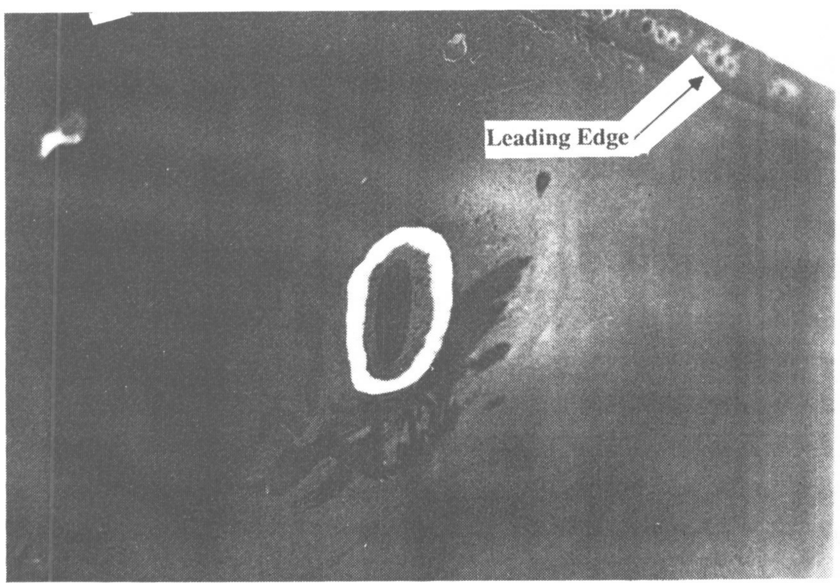


Figure 8. Damage Prepared for Repair

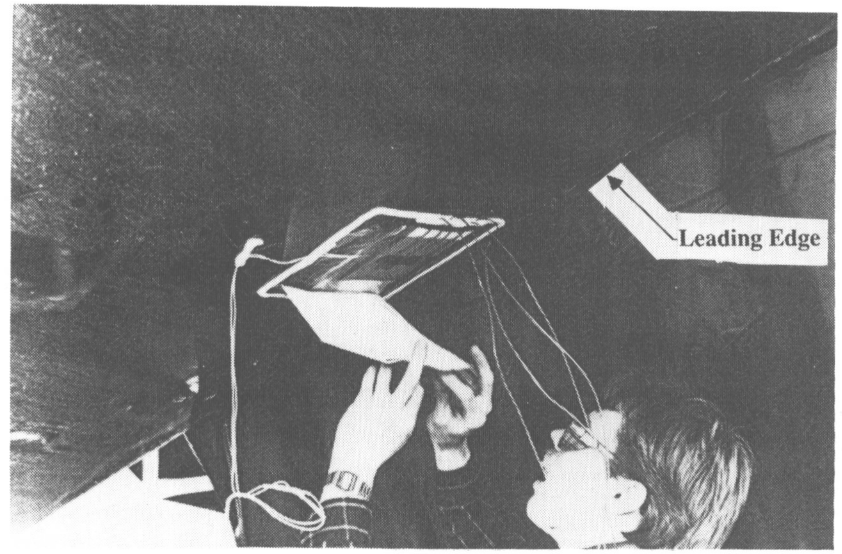


Figure 9. Installation of Heat Blanket

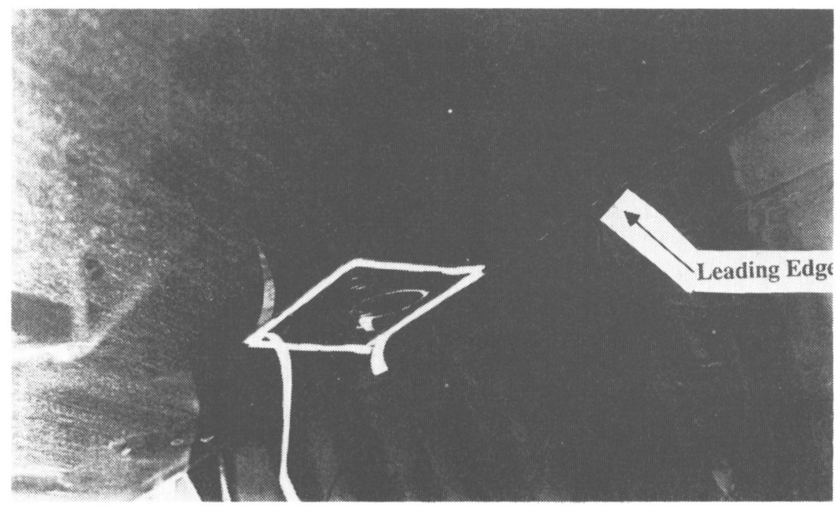


Figure 10. Finished Repair

TEARDOWN

In June 1990 a shipset of stabilizers became available for a teardown inspection. Markair, N670MA, crashed on landing approach to Unalakleet, Alaska. It was a non-revenue flight and there were no fatalities. The total time was 17318 hours and 19308 landings. The empennage portion of the airplane separated from the fuselage after impact, (Figure 11 and 12), with the left hand stabilizer receiving minimal damage.

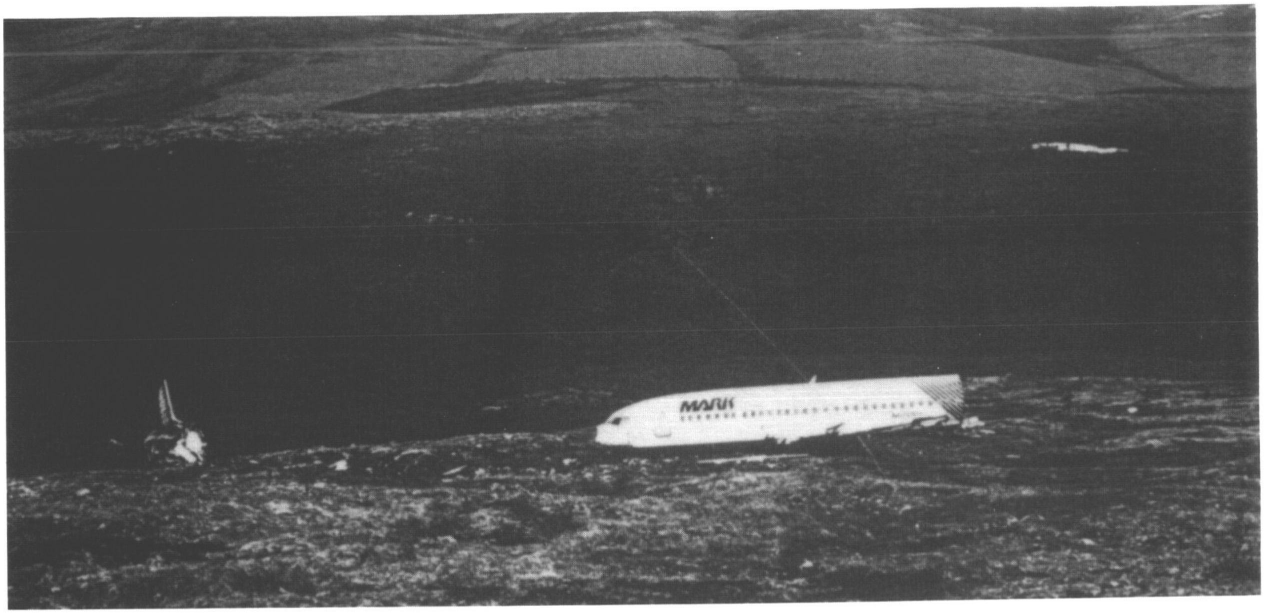


Figure 11. Markair N670MA

Figure 12. Markair N670MA Empennage

Boeing purchased the stabilizers and proceeded with a tear-down inspection. The left hand stabilizer was mounted in a fixture as shown in Figures 13-A and 13-B.

The initial inspection followed the Maintenance Planning Schedule, Table 1, for a structural check. Pulse-echo inspection of the critical areas of the upper and lower skin panels detected no damage (Figure 6). An extensive visual examination of the remainder of the structure revealed no evidence of service deterioration.

The inspection continued by systematically dismantling the box and inspecting each joint, the focus being directed to identify:

1. Any structural damage, delaminations, wear, fretting, etc., or
2. Any corrosion at the aluminum/graphite interfaces.

No structural damage or delaminations were found except for those resulting from the crash. The majority of the aluminum parts are located at the leading edge, trailing edge, and the inboard closure rib. The rib was removed (Figure 14). No corrosion was detected at any of the aluminum/graphite interfaces. The interior area of the box (Figure 15) was clean with no apparent moisture accumulation. All joints had the original protective system in place with no visual degradation or cracking. Fretting or wear was not apparent.

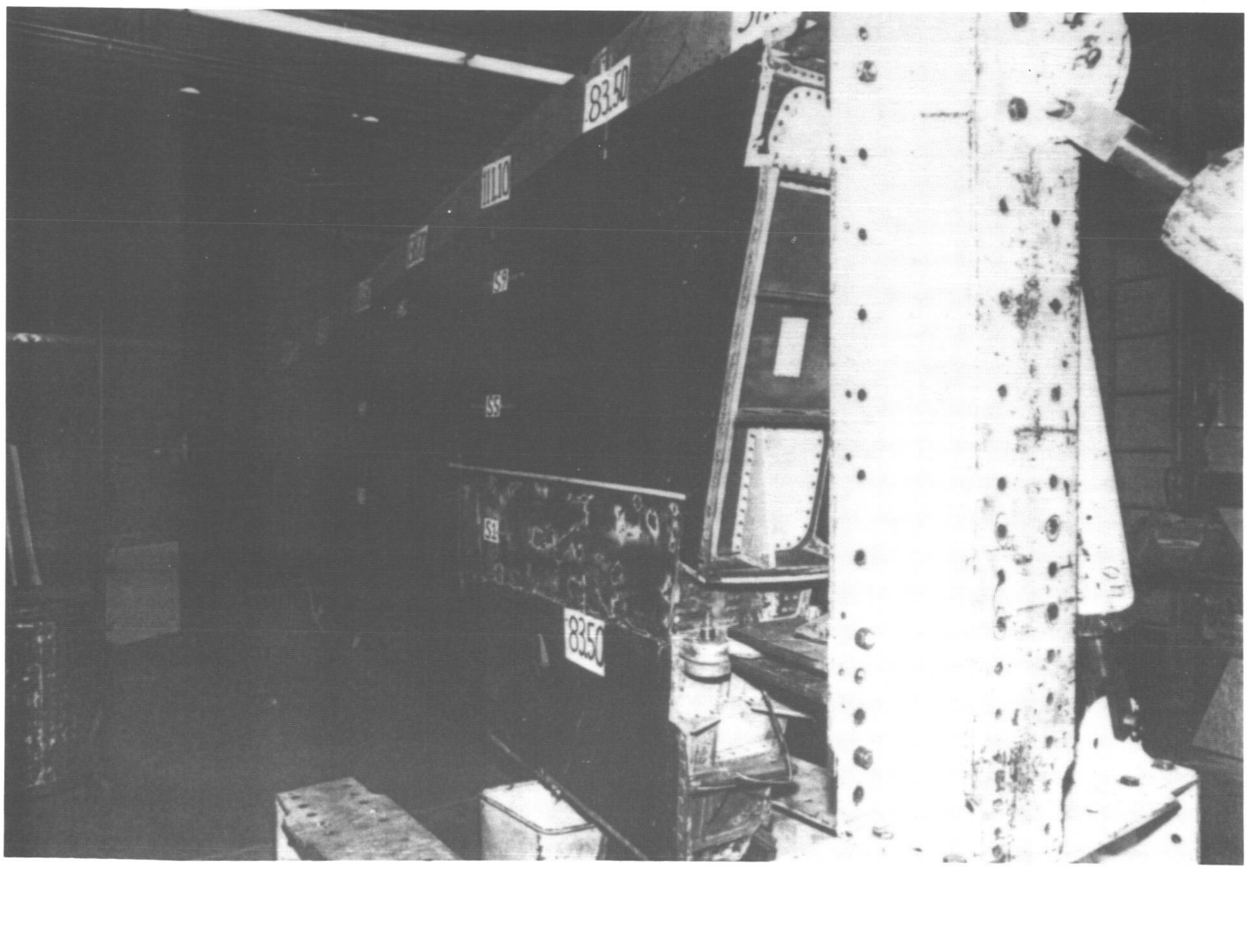


Figure 13-A. Stabilizer Mounted for Inspection, Upper Surface

The damage inflicted on the left hand stabilizer during the crash/skid was limited to abrasion of the tip structure and an impact on the lower surface. The results of lower surface impact are shown in Figure 13-B. Close visual examination of the structure verified that damage was limited to the immediate area adjacent to the impact. The skin panel laminate did not shatter or exhibit extensive delamination.

SUMMARY

The Boeing 737 graphite-epoxy horizontal stabilizer program has achieved its goals. Five shipsets were designed, fabricated, certified, and introduced into service.The graphite-epoxy structural box demonstrated a weight savings of 22% over the aluminum counterpart.

After six years of commercial airline service, the 737 graphite-epoxy horizontal stabilizers are demonstrating excellent performance. A thorough teardown inspection of one shipset of stabilizers found no signs of deterioration due to wear, fatigue or environmental factors. The corrosion protection system developed to protect mating aluminum surfaces performed as intended and no corrosion was detected. Composite repairs in the field were easily installed and inspections used equipment and techniques familiar to the operators. The 737 graphite-epoxy stabilizers continue to demonstrate the advantages of advanced composite materials in terms of outstanding performance at reduced weight.

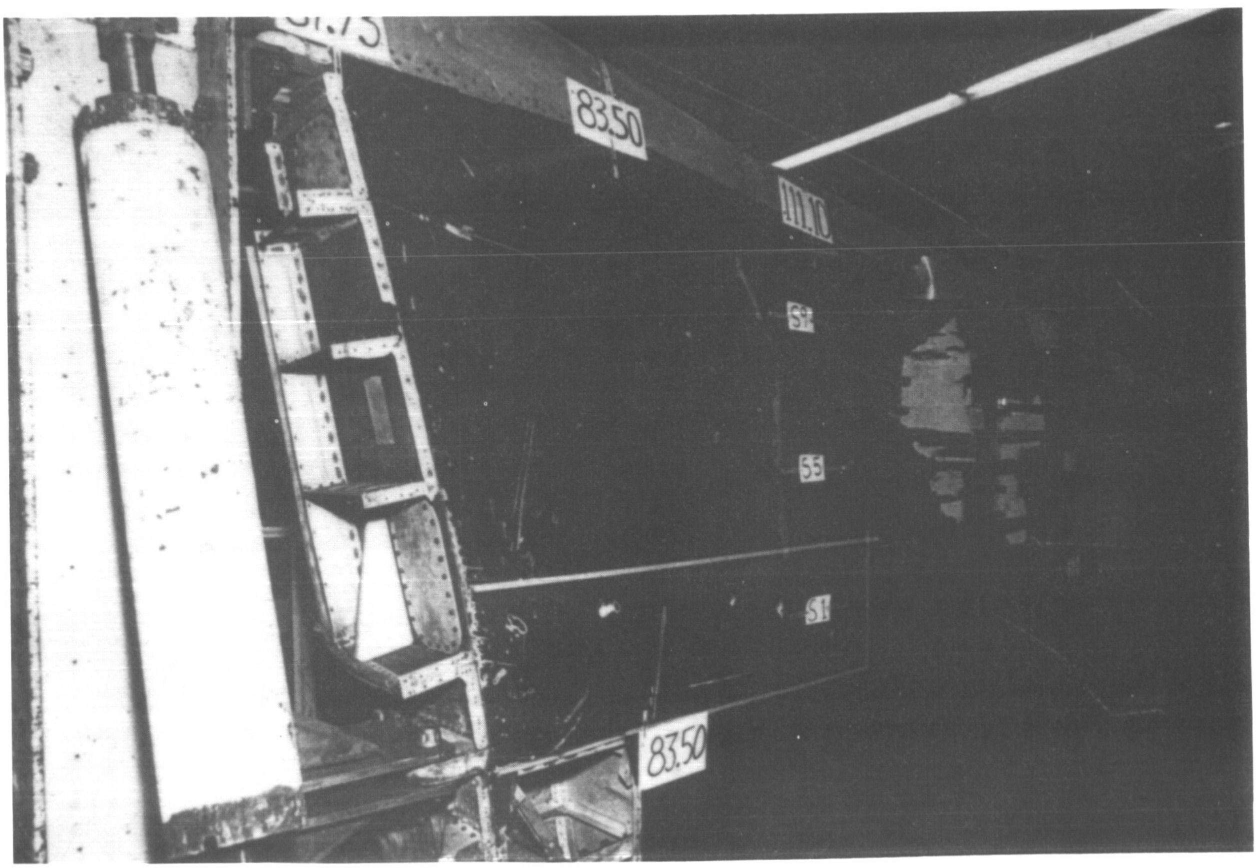


Figure 13-B. Stabilizer Mounted for Inspection, Lower Surface

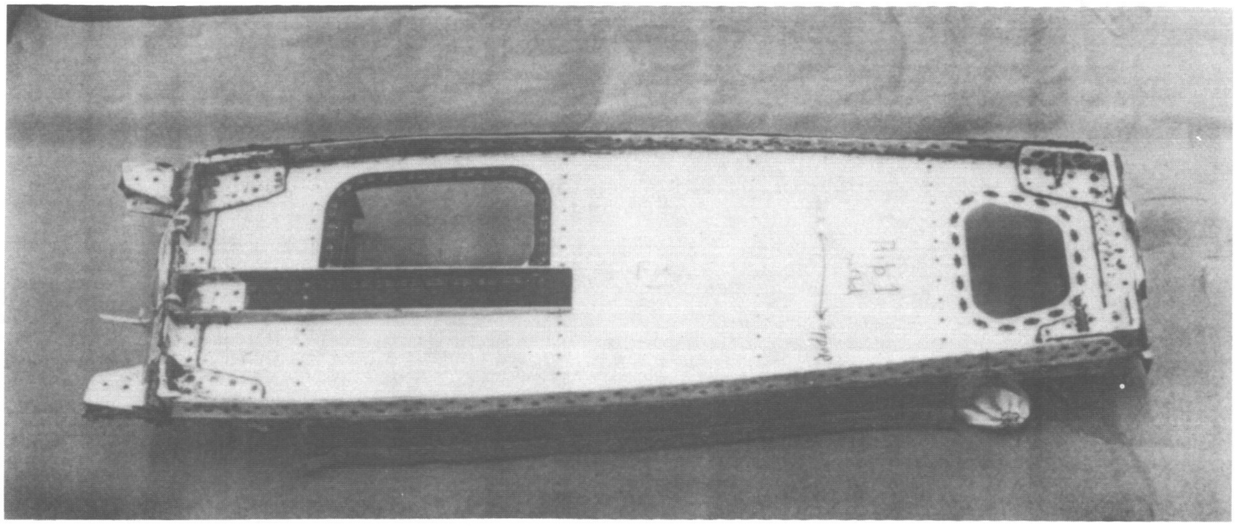


Figure 14. Inboard Closure Rib

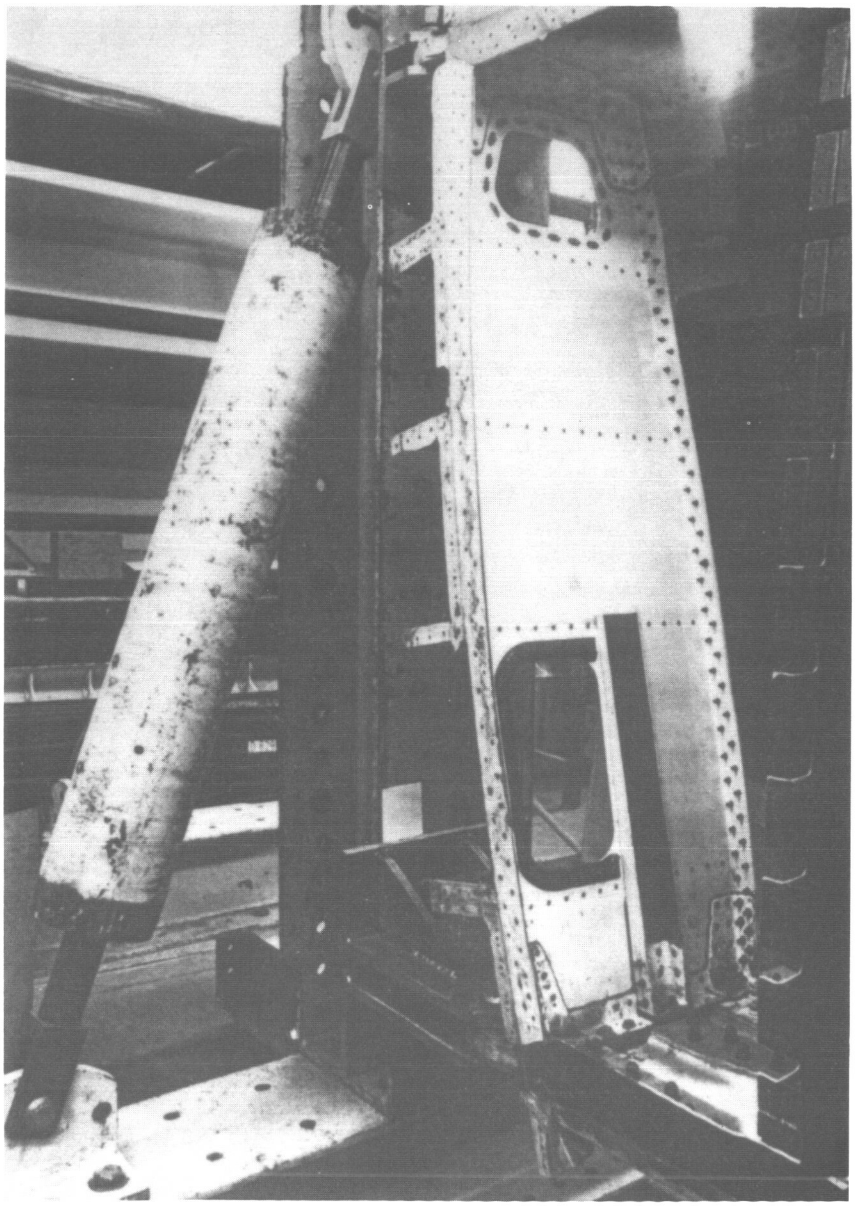


Figure 15. Interior of Box

REFERENCES

1. Aniversario, R.B. et al., "Design, Ancillary Testing, Analysis, and Fabrication Data for the Advanced Composite Stabilizer for Boeing 737 Aircraft", Volume I-Technical Summary, NASA CR-3648, December 1982.

2. Aniversario, R.B. et al., "Design, Ancillary Testing, Analysis, and Fabrication Data for the Advanced Composite Stabilizer for Boeing 737 Aircraft", Volume II-Final Report, NASA CR-166011, December 1982.

3. Aniversario, R.B. et al., "Full Scale Testing, Production, and Cost Analysis Data for the Advanced Composite Stabilizer for Boeing 737 Aircraft", Volume I-Technical Summary, NASA CR-3649, December 1982.

4. Aniversario, R.B. et al., "Full Scale Testing, Production, and Cost Analysis Data for the Advanced Composite Stabilizer for Boeing 737 Aircraft", Volume II-Final Report, NASA CR-166012, December 1982.

5. Federal Aviation Regulations, Part 25, Airworthiness Standards: Transport Category Airplanes, Department of Transportation, Federal Aviation Administration, December 1978.

6. Advisory Circular 20-107, Composite Aircraft Structure, Federal Aviation Administration, July 1978.

7. McCarty, J. E., Johnson, R.W., and Wilson, D. R., "737 Graphite-Epoxy Horizontal Stabilizer Certification, A Collection of Technical Papers," Part 1: Structures and Materials, AIAA No. 82-0745, AIAA/ASME/ASCE/ AHS 23rd Structures, Structural Dynamics and Materials Conference, New Orleans,May 1982.

8. D6-46036, Maintenance Planning Data, 737 Aircraft Structural Inspection, Composite Horizontal Stabilizer, The Boeing Company, December 11, 1981.

9. McCarty, J. E., Wilson, D. R., Advanced Composite Stabilizer for Boeing 737 Aircraft, Proceedings of the Sixth DOD/NASA Conference on Fibrous Composite in Structural Design, New Orleans, LA., January 24-27, 1983.