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Structural Integrity of Future Aging Airplanes

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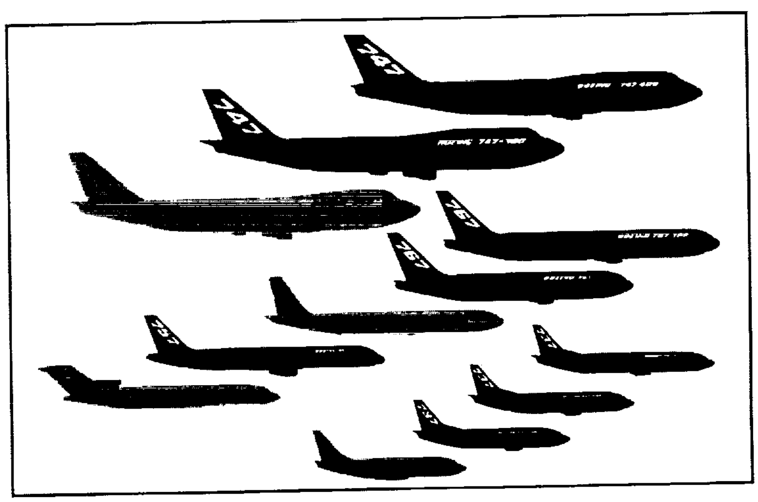
A multitude of design considerations is involved in ensuring the structural integrity of Boeing jet transports that have common design concepts validated by extensive analyses, tests, and three decades of service. As airplanes approach their design service objectives, the incidences of fatigue and corrosion may become widespread. Continuing airworthiness of the aging jet fleet requires diligent performance from the manufacturer, the airlines, and airworthiness authorities.

Aging fleet support includes timely development of supplemental structural inspection documents applicable to selected older airplanes, teardown inspections of high-time airframes retired from service, fatigue testing of older airframes, and structural surveys of more than 130 airplanes operated throughout the world. Lessons learned from these activities are incorporated in service bulletin recommendations, production line modifications, and design manual updates. This paper gives an overview of traditional Boeing fleet support activities and the anticipated benefits for future generations of commercial airplanes based on the continuous design improvement process.

BACKGROUND

This overview presentation is intended to focus more emphasis on the next generation of aging jet transports. These airplanes will benefit from lessons learned from current aging fleet programs both in terms of design improvements and maintenance-related issues.



Diligent attention to detail design, manufacturing, maintenance, and inspection procedures of the last three decades have produced long-life damage-tolerant structures with a credible safety record. The primary cause of hull loss accidents is attributed to human factors and weather with about 10% attributed directly to the airplane, systems, or propulsion components or how they were maintained. Approximately 3% of the hull loss accidents are caused by airplane structure failures.

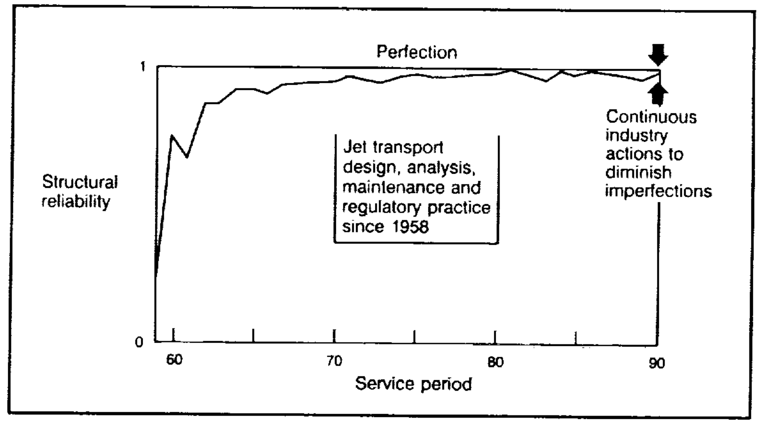
EXPERIENCE RETENTION

In 1971, The Boeing Company initiated the Structures Durability Program. The program was a major step in experience retention and the formulation of an engineering approach to fatigue detail design. A summary of discrete types of fatigue distress and structural areas prone to repetitive problems was generated.

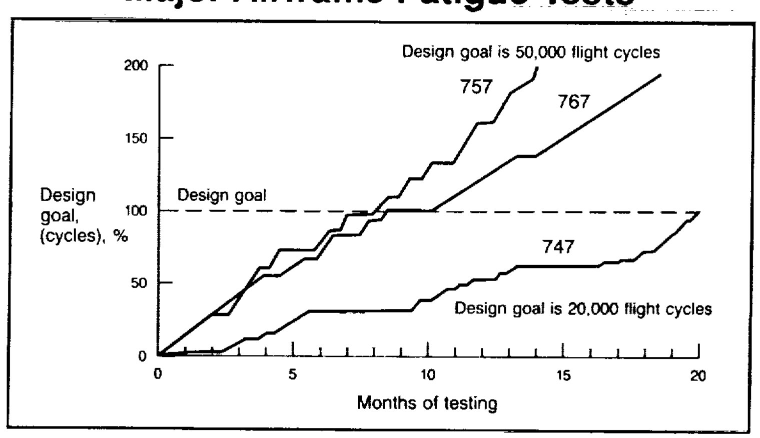
The knowledge gained provided a comprehensive understanding of detail design quality and became the foundation for building an improved fatigue design methodology. Fleet comparisons, additional testing and teardowns of high-time service airplanes added confidence in these new methods. Five years after the inception of this program, Boeing's Design for Durability manuals was made ready for application to new airplane design.

The durability methods used during development testing and interpretation of test data provided the confidence to proceed into the production design phases of the 757/767 airplanes at operating stress levels higher than those used on previous models. The effectiveness of the total design effort, however, was demonstrated by full-scale airframe fatigue tests. Both the 757 and the 767 airframe structures were subjected to comprehensive flight-by-flight fatigue tests. Major airframe inspections were conducted at intervals approximately equivalent to 10,000 flights. Visual inspections of the entire airframe, like those used by airlines, were performed. Inspection locations and procedures followed the maintenance planning data supplied for certification. After completion of 50,000 flights, a major inspection was conducted with loading fixtures and major reaction straps removed. After completion of 100,000 flights, a final teardown inspection was conducted. The fatigue test results of both the 757 and 767 major airplane tests were exceptional as proven by the rapid completion of 40 years (100,000 flights) of testing in record calendar

Structural Integrity Record



Major Airframe Fatigue Tests



time, without any down-time caused by structural fatigue cracking. The Structures Durability Program goal of reducing up to 85% of detail design problem areas was far exceeded.

RECENT TESTING

Test Verification

It is impractical to conduct verification testing for all critical loading conditions and portions of the airplane structure. Analysis methods and allowables verified by test are therefore used for airworthiness certification. Verification tests comprise small laboratory test specimens; large panels; major components representing wing, empennage, and fuselage structure; and full-scale airframes.

Full-scale static testing of new models is conducted to verify limit load carrying capability and satisfy certification requirements. In addition, full-scale fatigue tests are conducted to locate areas that may exhibit early fatigue problems. This allows necessary modifications of details that might exhibit early cracking and to demonstrate compliance with fatigue design objectives. Full-scale fatigue tests are also useful to develop and verify inspection and maintenance procedures. Fatigue tests are not intended to demonstrate "safe life" limits of structures certified as damage tolerant, nor are they an alternative to the inspections required for continued safe operation of aging airplanes.

Testing of new airplane structures does not incorporate corrosion and/or accidental damage that can accelerate fatigue cracking. Similar tests are conducted on older airframes to gain insight into the problems that might be experienced on high-time airplanes with repairs and service-caused defects.

747 Full-Scale Fuselage Testing

One of the Boeing initiatives to ensure continued safety and prudent maintenance of aging 747s was the testing of the fuselage of a retired 747-100 airplane that experienced 20,000 full pressure cycles. Extended cyclic pressure testing was conducted to evaluate the durability of the fuselage structure for operation beyond 20,000 full pressure cycles. A practical fuselage inspection

Full-Scale Fatigue Tests

Model	Fatigue test cycles	Remarks
707	50,000	Hydro-fatigue test
727	60,000	Full airframe
737	130,000	Aft fuselage
747	20,000	Full airframe
	40,000	**Fuselage**
	60,000	**Nose section**
757	100,000	Full airframe
767	100,000	Full airframe

747 Fuselage Fatigue Tests

Used airplane (747-100SR) fuselage:

- Line position 229 delivered to Japan Airlines 12-21-73
- 14 years of commercial operation (20,000 equivalent full-pressure cycles)

Production (747-400) fuselage:

- Line position 697
- Fuselage Sections 41 and 42 (redesigned Section 41)

program was developed based on the cyclic test results, extensive damage growth data, and the results of the detailed teardown inspections of the skin splices. The inspection program is for the 747-100, -200, and -300 models and is in addition to the other aging fleet actions defined by the joint Boeing, airline, and FAA working group. Appropriately modified programs apply to specific long- and short-range versions. A 747-400 forward fuselage was also cycled to verify the effectiveness of the continuous design improvements based on fleet experience. The 747-400s will require much less maintenance for fatigue than the earlier 747s for operation past 20,000 full pressure cycles.

The planning for this program was initiated in August 1986. The cyclic pressure testing and teardown inspections of both test articles were completed during April 1991. The 747-100 airplane was delivered to the customer in December 1973 and was in commercial operation for 14 years. The airplane was received back at Boeing in April 1988. The wings and empennage structure were removed from this airplane and extensively disassembled for detailed inspections. After removal of the interiors, systems, and electrical components, the fuselage was moved onto the test slab. During the cyclic test phase, 20,000 full pressure cycles were applied for a total of 40,000 full pressure cycles on this fuselage.

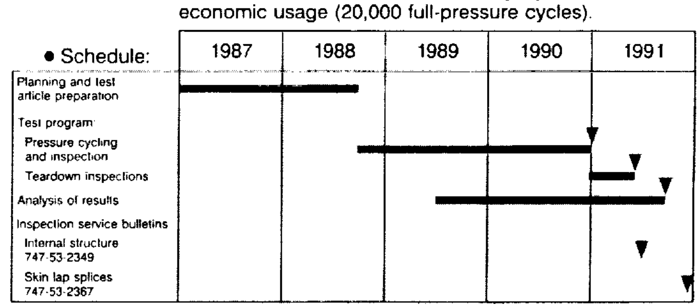
The 747-400 forward fuselage test article came off the production line in April 1988. The cycle testing of this article consisted of two phases. During the durability evaluation phase, this test article was cycled to 40,000 full pressure cycles. Following that, for the damage growth test phase the test article was cycled an additional 20,000 cycles for a total of 60,000 full pressure cycles. Both test articles were subjected to detailed teardown inspections at the conclusion of the cyclic testing.

The three major objectives of this test program were:

- To evaluate the durability of the fuselage structure of the 747-100, -200, and -300 models for operation past the economic design objective (20,000 full pressure cycles).

747 Fuselage Fatigue Tests
Test Program

- Objective: Evaluate durability of pressure critical fuselage structure for operation past the design goal for economic usage (20,000 full-pressure cycles).
- Schedule:



- To evaluate the durability of skin lap splices, obtain crack growth data for multiple site damage scenarios on skin lap splices, and obtain damage growth data for internal fuselage structural components.

- To evaluate the durability of design improvements incorporated over the years and the -400 model-unique structural configuration items.

All the above objectives were achieved from the data generated by the two test articles.

The 747-100 fuselage test article was subjected to a thorough inspection prior to test cycling. Detailed visual inspections were performed on both external skin and internal structural components. The upper row of fasteners on all skin lap splices was inspected using high-frequency eddy current. No fatigue cracks or corrosion was detected. The majority of the cracks on the internal structure of the other fuselage sections was detected after 32,000 full pressure cycles. Of these only 25% of the cracks were classified as significant. A number of frame cracks was monitored to obtain crack growth data. The cracks that were classified as not significant were those that did not noticeably grow from detection to 40,000 cycles.

The redesigned internal fuselage structure of the 747-400 nose section was practically crack-free up to 40,000 pressure cycles, verifying the durability of the redesigned structure. Very few cracks were detected in the rest of the fuselage structure. The two significant findings were cracks in the upper deck floor beams adjacent to the stretched upper deck stairwell cutout, and skin cracks in the electrical equipment cooling cutout unique to the -400 model. These cracks were detected past 33,500 test cycles. Production improvements have already been incorporated for these two items, and service bulletins have been issued to address the fleet.

Pressure Fixture Testing

The 707, designed in the 1950s, was the first commercial jet airliner to be developed at Boeing with a pressurized fuselage. Experience at that time taught the aircraft industry that the ability to tolerate a substantial amount

747 Fuselage Fatigue Tests
Test Results – Longitudinal Skin Lap Splices (Fay Sealed Configuration – C/L 201 and on)

- -100SR cycled to 40,000 full-pressure cycles; -400 (Sections 41 and 42) cycled to 60,000 full-pressure cycles
- Pressure cycling and teardown inspections have demonstrated that the basic lap splices exceed design goals (20,000 full-pressure cycles)
- Cracks detected in local areas only, beyond 30,000 pressure cycles
- Initial cracking occurs approximately at midbay, well away from frames
- Crack growth data from multiple-site damage scenarios indicates that from initial crack detection to linkup of cracks (crack length after linkup less than one frame bay) is between 10,000 and 15,000 cycles

Fuselage Damage Tolerance Tests

- Major airframe cyclic tests have been conducted to address damage tolerance

Model	Date	Remarks	Test type
707	1955	Quonset	Discrete source
727	1960	Fuselage pressure test	Fatigue Crack Growth (FCG)
737	1968	Quonset	Discrete source
	1987	Aft fuselage pressure test ▷	FCG
747	1968	Fuselage section	Discrete source, FCG
	1971	Full airframe	FCG
	1990	Fuselage pressure test ▷	FCG
	1990	-300/-400 forward fuselage	FCG
757	1983	Full airframe	FCG
767	1980	Fuselage section	FCG and residual strength
Generic		Fuselage panel in fixture	Starts mid-1990

▷ Retired service airplane

of damage was a requirement of modern airplanes. Therefore, the new pressurized fuselage had to be tested rigorously in order to prove airworthiness. The test structure employed for design development and verification was made of large pressurized panels configured in the shape of a Quonset hut. For the tests, various combinations of skin gages and types of tear straps and shear ties were subjected to saw cuts and punctures by guillotine blades.

To supplement airframe testing, two generic pressure test fixtures were fabricated in 1989. One fixture has a radius of curvature of 74 in (1.9m) to match narrow-body 727, 737, and 757 airplanes. The other has a radius of 127 in (3.2m) to match the widebody 747, 767, and 777 airplanes. Removable test sections are inserted in a cutout in these test fixtures and can be used for fatigue, fatigue crack growth, or residual strength tests. Tests are conducted under pressure loading only, using air as the pressurizing medium. Where appropriate, one crack will be inserted in the test article at a time, and repaired before conducting additional tests. Test sections are modeled using finite element techniques, and analysis results are compared with a comprehensive set of strain gage and crack opening displacement measurements. The structural modeling of crack behavior is refined, as necessary, to provide a validated tool for future airplane design.

Fuselage Pressure Test Fixtures

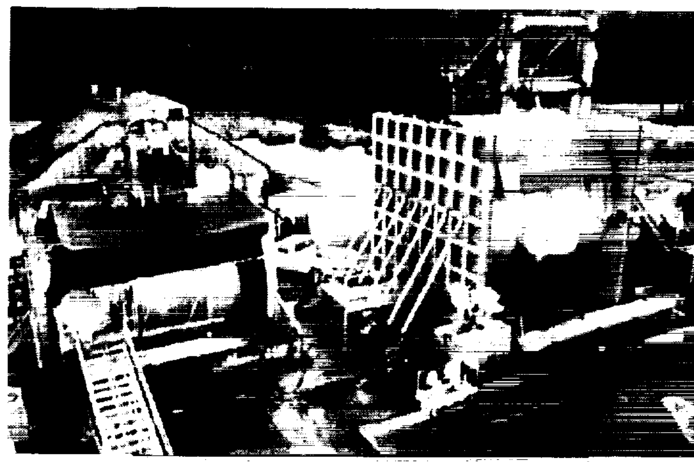
Objective:

- The test fixtures are used for crack growth and residual strength testing of a variety of fuselage structure configurations:
  - New designs
  - Fleet modifications
  - Repairs
  - Current design
  - Generic studies

Status:

- Narrow body tests
  - Total of 8 panels tested
- Wide-body tests
  - Total of 6 panels tested

Boeing Narrow- and Wide-Body Test Fixtures



Boeing Narrow-Body Fuselage Test Panel

Bonded Tear Straps

Safe Decompression at 30 in

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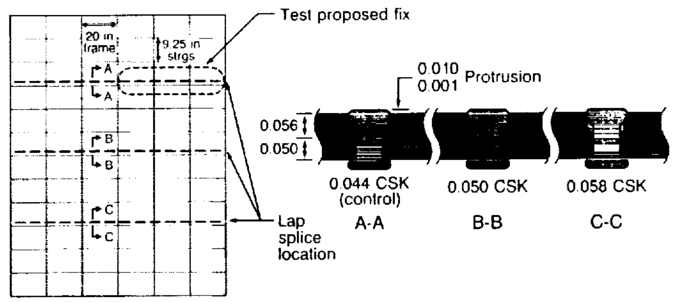
Although major efforts have been focused on the aging fleet, current production models receive substantial attention to ensure continued safe operation with a minimum maintenance burden. One example is the hand driven rivets installed on some 757 lap splices with excessive countersunk depth. Pressure fixture testing demonstrated that these lap joints have sufficient capability to reach lives beyond the SSID inspection thresholds of 37,500 flight cycles. These areas will receive directed inspections at that time to confirm validity of test results.

757 Skin Panel Fatigue Test

Purpose: To determine fatigue life of riveted joints not installed per specification.



757 Skin Panel Fatigue Test
Test Results (200,000 Cycles)

- The fatigue life of a knife edged countersink is greater than indicated by small scale coupon tests
- Crack growth rates have been slower than predicted analytically
- No cracks have been detected in lap splices with 0.050 in deep countersinks or standard countersinks

TEARDOWN INSPECTIONS

In addition to supporting the inservice fleet, Boeing has instituted a number of other efforts to gain more insight into the present and future behavior of aging structures. These efforts include extensive teardowns and inspection of models 707 and 727 retired from service to determine if any previously unknown or undetectable damage may be starting to develop. These programs started in 1965 and continued through the late 1970s. In some cases, teardown findings have led to design changes, service bulletins, and even airworthiness directives. In general the findings have confirmed previously known or anticipated behavior and have added confidence in both the structures and maintenance programs completed in 1991 as part of industrywide initiatives.

Boeing Teardown Inspections

- **Acquisition of suitable high-flight-cycle airframes**
- **Disassembly for detailed inspection**

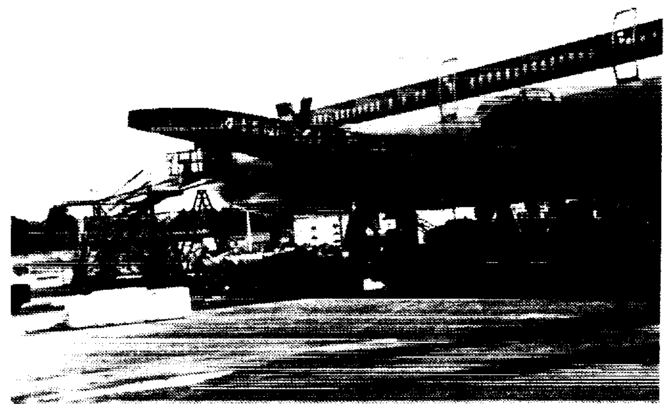
• 707 wing plus center section	1965
• 707 wing	1968
• 707 wing plus center section and fuselage	1973
• 707 empennage	1978
• 727 forward fuselage	1978
• 737 wing plus center section, forward fuselage, and empennage	1987
• 737 aft fuselage (after fatigue testing)	1988
• 747 wing plus center section and empennage	1988
• 747 fuselage (after fatigue testing)	1991

The wings and empennage structure of the retired 747-100 airplane were disassembled for detailed inspections. This airplane, which was retired from service in 1988, had the equivalent of approximately 15,000 long-range flights, which is 75% of the economic design objective. No significant findings requiring fleet actions resulted from the detailed inspections. The fuselage structure of the retired 747-100 airplane was also subjected to teardown inspections after completion of the cyclic pressure testing to 40,000 full pressure cycles. Some internal structure was disassembled and inspected, but the primary focus of the teardown inspections was the skin lap splices. A total of 14,600 upper row fasteners were removed from the lighter gage splices, and high-frequency eddy current inspections of the open holes were conducted. Only six cracks less than 0.05 inch long were confirmed from the teardown inspections. The cracks were in the forward fuselage generally adjacent to cracks detected during pressure cycling. No cracks were detected in the aft fuselage.

The 747-400 forward fuselage test article was also subjected to detailed teardown inspections after completion of the cyclic pressure testing to 60,000 cycles. A total of 8,000 upper row fasteners was removed from the skin lap splices, and high-frequency eddy current inspections of the open holes were conducted. Only 12 cracks less than 0.05 inch long were confirmed from the teardown inspections after 60,000 full pressure cycles. These cracks were also adjacent to cracks detected during pressure cycling. Some internal structure was disassembled and inspected on this test article also, with no significant findings.

One scenario of widespread fatigue damage in skin lap splices that has been put forth is the likelihood of cracks initiating at many fasteners and eventually linking up to form an extremely long crack across the skin panel. While cracks initiated at multiple fasteners on both test articles, evaluation of test results and teardown inspection data demonstrates that the occurrence of the above-stated scenario, due to fatigue, is highly unlikely during the period of cycles covered by the test.

Wing Removal of Retired 747 Airplane



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FLEET SUPPORT PROGRAMS

Boeing has in place a number of programs that help support the operation of commercial jet transports and promote a high level of airworthiness in the fleet. Reported service data and other firsthand information from customer airlines are continually reviewed to promote safe and economic operation of the worldwide fleet. Today there are more than 1,000 Boeing airplanes around the world that are over 20 years old, and this number will double by 1995. Approximately 150 Boeing airplanes had reached their design flight cycle goals in 1990, and this number will increase to about 500 by 1995 representing about 10% of the active Boeing fleet.

Inevitably, structural discrepancies are discovered during inspection and maintenance, and well-defined procedures exist to handle these problems wherever in the world they occur. In the United States, they are reported to the manufacturer and/or the FAA. The manufacturer in turn will inform all operators to determine if other operators have experienced similar problems. In many cases, the manufacturer will make a design change in production and/or issue a service bulletin that describes the problem and background and suggests means of corrective action for aircraft in service. For the majority of problems there is no safety issue and therefore no requirement for the operator to follow the service bulletin recommendations. However, for economic reasons, many operators will follow them, either by inspection and/or terminating modification action.

Structural maintenance is a cornerstone of continuing safety in commercial air transport. Aging fleet concerns have focused unprecedented attention on additional requirements, and the industry and airworthiness authorities are implementing additional maintenance actions to ensure continued safety. These are focused on mandatory modification rather than continued inspection, development of improved mandatory corrosion prevention and control programs, consolidation of basic maintenance programs, updates of supplemental structural inspection programs, and development of guidelines to determine the adequacy of structural repairs.

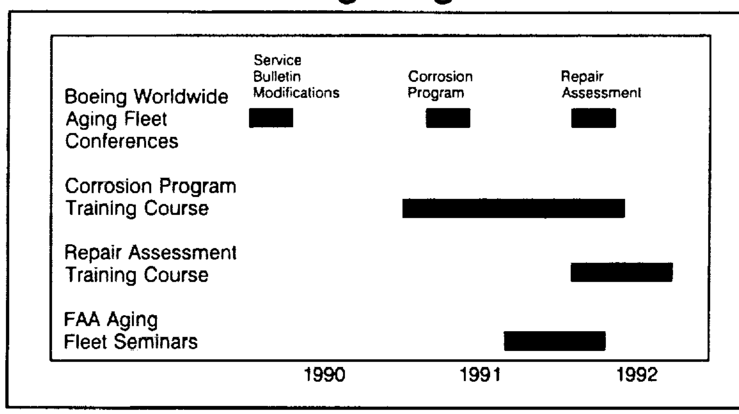
A major part of successful implementation of these programs is to provide adequate training of operator

Fleet Support Programs

Fleet Support Programs

1950s	1960s / 1970s	1986	1988	1989
Boeing Customer Support	SSID and other activities	Airplane Fleet Survey Program	Airworthiness Assurance Working Group*	Structures Operator Support Program
• Engineering • Maintenance engineering • Service engineering • Field service reps • Spares	Engineering and customer services	Engineering and customer services	FAA/ATA/AIA Congressional oversight * Industry program	Service engineering
• Service problems • Service bulletins • Maintenance programs • Repairs • Design changes • Operator conferences	• Supplemental structural inspection programs • Fatigue testing • Teardowns	• Survey individual airplanes • Aging and current fleet leaders • Structures and systems	• Aging airplanes • Structures oriented • All manufacturers	• Field service emphasis on structures • Region focal points • Channel to expedite customer needs

Aging Airplane Awareness and Training Programs



Corrosion Prevention and Control Program
Training

- Training program developed to achieve consistent implementation
- All groups involved with the program were invited -
  - Airline operators
  - Leasing companies
  - Repair stations
  - Regulatory agencies
  - Etc.
- The FAA also participated as instructors for the airworthiness directives section of the training program
- The course has been given 19 times in Seattle and 17 times in regional locations
- Over 1,300 people from nearly 300 groups have attended the training course

maintenance staffs. A number of courses addressing both general guidelines as well as specific corrosion prevention and control program details have been conducted worldwide by Boeing.

The lessons learned from the 707/727/737/747 corrosion prevention and control programs have also resulted in specific recommendations for update of the Maintenance Planning Documents (MPD) through the Maintenance Review Board (MRB) process. Similar activities are also progressing for models 757/767.

Recognizing this trend, Boeing implemented a new program to better understand the condition of older airplanes. The Aging Fleet Survey Program was developed during 1986 and implemented in 1987. The success of the program resulted in expansion to include new production airplane models such as the 737-300, 757, and 767, some of which have already seen 8 years of service. By reviewing the structural and systems performance of these airplanes during their early and maturing years, it is believed that Boeing and the operators can take the right actions to preclude the majority of aging fleet problems 10 years or so from now.

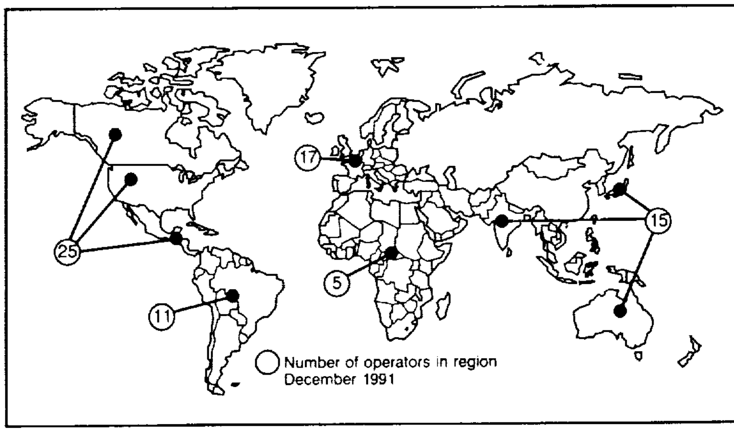
Airline acceptance of the program and cooperation with Boeing has been positive. Observing a significant number of airplanes in a variety of operating and climatic environments around the world provides a composite sample of each model and a better understanding of common and unique aspects within and between model fleets. As of December 1991, 138 airplanes owned by 73 operators have been visited in 40 countries around the world. Although the number of airplanes observed is a small percentage of the total fleet, it does represent about 15% of the high-time airplanes.

Considerable variation has been observed in both airplane condition and airline maintenance procedures, such as inspection intervals and corrosion prevention measures. The condition of the structure was generally good but considerably below expectation in a few cases. All significant findings pertaining to a specific visit are recorded and assigned to appropriate organizations for necessary fleet action. The collected data have been pooled for fleet evaluations to determine if there are trends requiring additional actions by Boeing and/or the

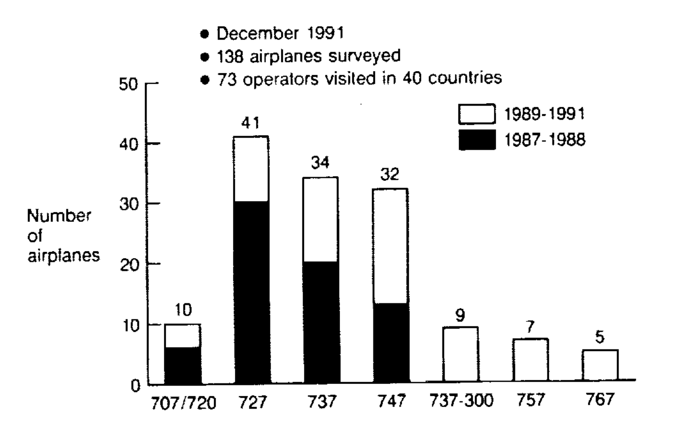
757/767 Corrosion Prevention and Control Program
Background

- A corrosion prevention and control program was proposed by Boeing for the 757/767 and endorsed by the AATF (AAWG)
- Structures working groups were formed and 757/767 corrosion programs were developed similar to the 727/737/747 programs
- 757/767 corrosion program was presented to and accepted by the industry steering committee on September 11, 1991
- Documentation and FAA control provided through MRB and MPD

Boeing Fleet Survey Participants



Airplanes Surveyed During Program



operators. A number of detailed action items have resulted from the surveys, and their applicability has been reviewed across all Boeing models. To ensure anonymity, all identifiable operator/airplane data are treated as confidential.

The fleet survey program is continuing with 26 airplanes observed in 1991. Recent findings indicate the condition of the airplanes generally is good and that they are receiving adequate and conscientious maintenance. Most discrepancies noted by the Boeing teams had already been recorded by the operator and corrective action was under way. Recent surveys have confirmed our belief that the aviation industry is more aware of the necessity of applying timely corrosion control and installing well-engineered repairs and, generally, has a more heightened awareness relative to sound maintenance practices.

DESIGN IMPROVEMENT PROCESS

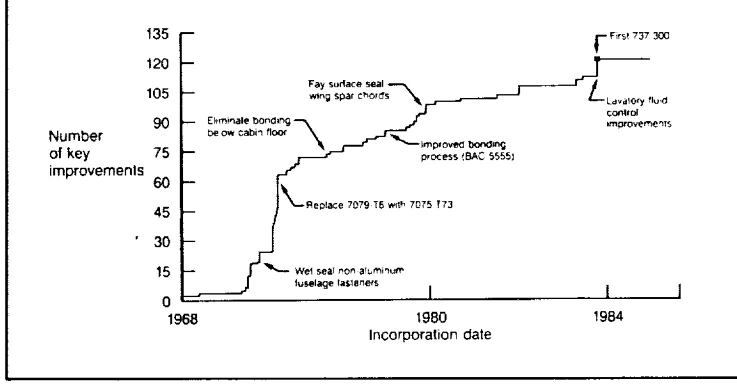
As airplanes mature, service experience provides a natural focus on design improvements, which are reflected in the relative modification costs for aging airplanes as they reach their design service objectives. A better understanding of how airplanes withstand the rigors of long-term use will help future generations of commercial airplanes to be safer and less maintenance-intensive with age. Just as today's airplanes have benefited from previous lessons learned, so must the knowledge and experience gained from today's efforts be used to improve the quality and performance of future airplanes. There will certainly be even more emphasis during design and construction on reducing the potential for corrosion. Specific design goals include improved corrosion-resistant alloys and finishes, improved sealing and drainage, and increased attention to accessibility and inspectability. These goals rank equally with strength, damage tolerance, durability, and cost/weight efficiency.

Boeing uses the experience of its 5000-airplane fleet to incorporate over 140 corrosion resistance improvements developed for new and derivative models. New aluminum material tempers are selected to provide high resistance to stress corrosion and galvanic corrosion. Graphite composites are isolated to inhibit galvanic

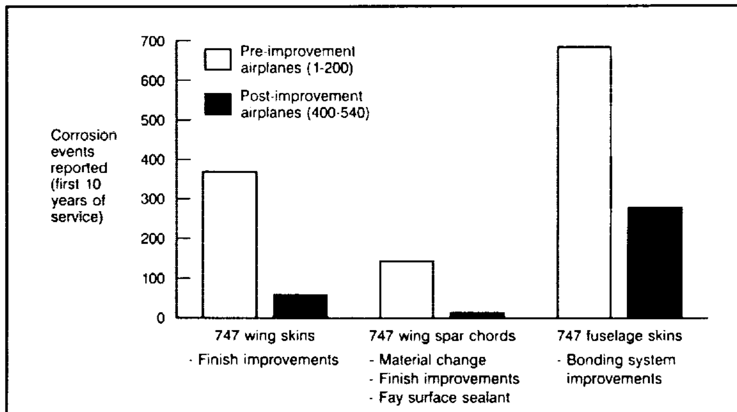
Airplane Fleet Survey Program Findings on 757/767

- A few, minor fatigue cracks only
- No stress corrosion cracking
- Some areas of corrosion
  - Generally, evidence shows corrosion improvements are effective
  - Areas under lavatories and galleys still pose problems
  - Drain paths not kept free of debris

Typical Corrosion Improvements Implemented on Boeing Airplanes



Effect of Corrosion Improvements on Model 747

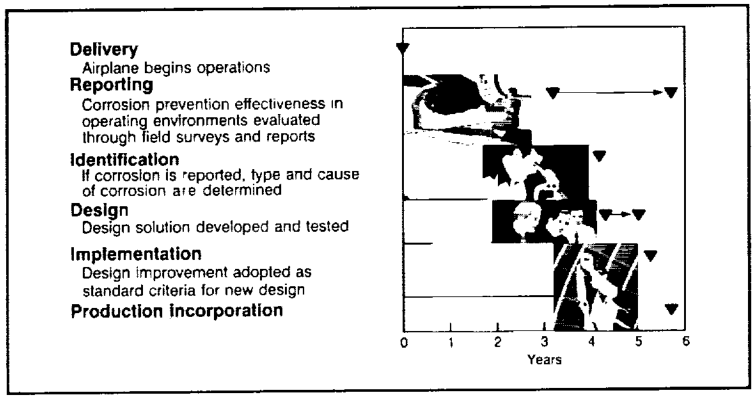


actions. No alloy steel fasteners are used in exterior skins. High-durability adhesive bonding with phosphoric-acid anodize surface preparation and corrosion-inhibiting adhesive primer are used to eliminate disbonding. This bonding durability has been proved by over 20 years of research and 14 years of in-service airline experience. Fuselage drainage has been improved by new, flexible leveling compound filler materials that eliminate wet pockets. Faying surface seal is used on wing details that attach to exterior surfaces of the skin. One-piece module construction with a watertight base is used to reduce corrosion in lavatories on newer models.

The development phasing of many of these corrosion protection improvements depends on timely inspection reporting to identify problems and to take necessary design improvement steps. The time typically required spans a 5- to 6-year cycle to achieve full implementation of corrosion prevention measures.

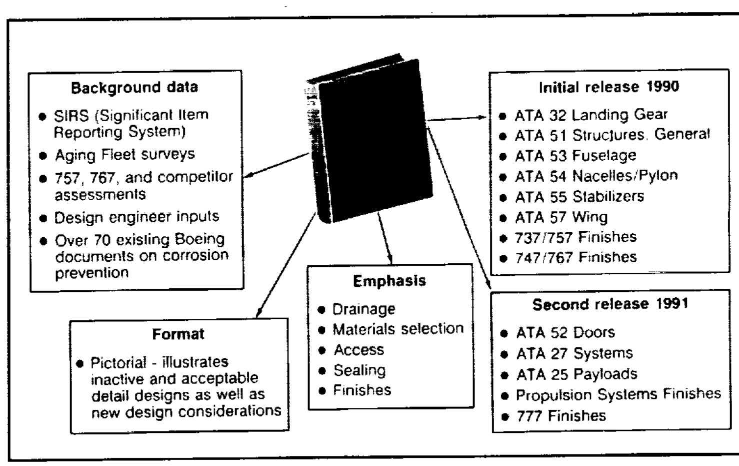
Boeing has recently developed a comprehensive Corrosion Design Handbook reflecting fleet experience to provide the structural engineer with the same corrosion prevention expertise that parallels methods used to develop producible, durable, and damage-tolerant structures. Similarly, improved structural arrangements and concepts will enhance the inherent robustness and forgiveness of the structure, facilitate simpler repairs when damage occurs, and facilitate accessibility and inspectability. The knowledge gained in the past 4 years will also enable better focus on the initial and continuing maintenance needs of new airplanes. In turn, this will allow the most effective and timely distribution of airline resources to maintain their airplanes indefinitely to achieve continued safe and economic operation.

Corrosion Prevention Improvements



Structural Damage Technology Handbooks

Design for Corrosion Prevention Handbook



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Knowledge from 30 years of producing and supporting jet airliners has been applied to the new wide body design. The fuselage shell, for example, employs new structural features to improve producibility, maintainability, and inspectability. Stiffeners with a hat cross section have been replaced by Zee stiffeners, which have fewer surfaces to attach or join. A circular cross section has simplified the frames, which can be roll-formed. Lessons from the older airplanes in service have also affected the design. The outer skin has been made thicker in proportion and drainage has been improved by eliminating discontinuities that are the result of bonded edges, tearstraps, and machined pockets.

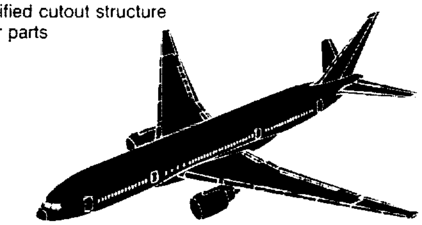
777 Fuselage Design
Body Monocoque

Improved producibility, maintainability, and inspectability

- Z versus hat stiffeners
- Simpler frames
- Simplified cutout structure
- Fewer parts

Incorporated "Aging Fleet" lessons learned

- Made outer skin more "robust"
- Improved drainage
- Controlled fluid flow



WIDESPREAD DAMAGE

Original fail-safe design criteria required limit-load strength for a fatigue failure or obvious partial failure of a single principal element. The capability to analyze damaged structure has improved in recent years through the application of advanced fracture mechanics. Federal regulations cited in FAR 25 were updated in 1978 to reflect such state-of-the-art developments to require consideration of damage growth at multiple sites in damage tolerance assessments. These new criteria also require attention to structural damage characteristics when developing an inspection program. This has accelerated development of better ways to ensure damage tolerance of new and aging jet transports by timely detection of unexpected fatigue, environmental deterioration, or accidental damage.

Damage Tolerance Regulations

Analysis	FAR 25.571 (pre-1978)	FAR 25.571 (post-1978)
Residual strength	• Single element or obvious partial failure	• Multiple active cracks
Crack growth	• No analysis required	• Extensive analysis required
Inspection program	• Based on service history • FAA air carrier approval	• Related to structural damage characteristics and past service history • Initial FAA engineering and air carrier approval

The general understanding of widespread structural damage (WSD) is often linked to the idea of an aircraft suffering damage over large regions of its structure. However, it is the synergistic effect of these damages which is identified as the principal concern. In this case, the approach for determination of the crack growth and the residual strength of isolated damages are no longer sufficient for determination of the inspection intervals. Therefore, the approach for maintaining damage tolerance of the structure needs to be reconsidered for both aging airplanes and for new design.

Those types of multiple site damage and multiple element damage whose extents are within the existing damage tolerance assumptions are termed as "local."

Widespread Fatigue Damage Definitions:

The presence of fatigue cracks at multiple sites of the airplane structure such that the interaction of these cracks degrades the damage tolerance capability of the structure more than any one crack acting independently.

There are two types of widespread fatigue damage:

- Multiple Site Damage (MSD)

Simultaneous development of fatigue cracks at multiple sites in the same structural element, such that fatigue cracks may coalesce to form one large crack.

> The initial multiple site damages could develop in one element from a number of initiation points, which are operating at similar stresses, are of similar design, and/or are in one cross section. These initial cracks are independent, and usually non-uniform, but could result in a significant increase in the crack propagation rate in the concerned element, compared to the propagation of any single crack, and may result in a reduction of the airframe damage tolerance capability.

- Multiple Element Damage (MED)

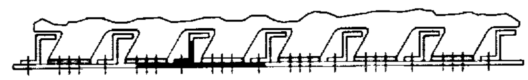
Simultaneous development of fatigue cracks in similar adjacent structural elements, leading to an interaction of these cracks.

> The initial fatigue cracks would typically develop simultaneously in similar adjacent elements of a multiple load path arrangement. These fatigue cracks are initially independent, and usually non-uniform, but may become dependent as they grow. This could result in a significant increase in the crack propagation rate in the concerned elements and/or a reduction of the residual strength capability.

Example – Local Versus Widespread MSD or MED

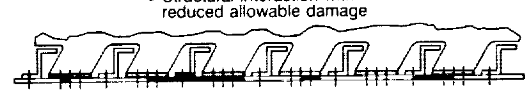
Example - Local MSD or MED

- Maximum allowable damage shown
- Damage connection up to this size is tolerated
- No significant damage beyond this region
- All MSD or MED within this area is local and already accounted for in damage tolerance analysis



Example - Widespread MSD or MED

- Widespread similar details
- Similar stresses
- Structural interaction with reduced allowable damage



Structures Potentially Susceptible to Widespread Fatigue Damage

Fuselage
- Longitudinal skin joints, frames, and tear straps
- Circumferential joints and stringers
- Frames
- Aft-pressure dome outer ring and dome-web splices
- Other pressure bulkheads attachment to skin and web attachment to stiffener
- Stringer-to-frame attachments
- Window surrounding structure
- Overwing fuselage attachments
- Latches and hinges of nonplug doors
- Skin at runout of large doubler

Wing and empennage
- Chordwise splices
- Rib-to-stiffener attachments
- Skins at sheer tie locations
- Stiffener modifications at tank-end ribs

SUMMARY

- Ongoing programs to support aging aircraft fleet
- Similar activities on current production models to prevent future aging fleet issues
- Lessons learned incorporated in new designs

Boeing is dedicated to design and manufacture of safe commercial jet transports. The successful accomplishment of this responsibility over the last three decades has contributed significantly to a position of industry leadership and reflects the top priority given to safety. The structural integrity assurance of commercial airplane structures is a serious and disciplined process. High standards must be maintained to ensure the safety of aging airplanes until economics dictate their retirement. Standard Boeing practices to ensure continuing structural integrity include providing structural maintenance programs, continuous communication through customer support services, and recommendations for maintenance actions through service letters, structural item interim advisories, and service bulletins. To help identify potential problems associated with the aging jet transport fleet, Boeing has implemented additional activities:

- Fatigue testing of older airframes to determine structural behavior in the presence of service-induced problems such a corrosion and repairs.
- Teardown of older airframes to help identify corrosion and other structural service defects.
- An engineering assessment of the condition of a representative sample of older Boeing airplanes to observe effectiveness of corrosion prevention features and acquire additional data that might improve maintenance recommendations to the operators.

The design, construction, operation, and maintenance of airplanes take place in a changing and dynamic arena, with new technology, new needs, and new players. The structural safety system may never be perfect but has produced an enviable record, and the aging fleet initiatives will measurably improve that record. If the lessons being learned today by the manufacturers, the operators, and the authorities are properly reflected in our next-generation airplanes, they should fly longer and more safely with progressive maintenance that ensures continued structural airworthiness until retirement from service for economic reasons.