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Int. J. Fatigue Vol. 20, No. 6, pp. 413–431, 1997
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Printed in Great Britain
0142–1123/98/$19.00+.00

PII: S0142-1123(97)00029-7

Fatigue issues in aircraft maintenance and repairs

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(Received 10 February 1997)

Many design considerations are involved in ensuring structural integrity of Boeing jet transports, which have common design features validated by extensive analyses, tests, and service performance. Designing for continued structural integrity in the presence of damage such as fatigue or corrosion is an evolutionary process. Performance demands, increasing structural complexity, and aging fleet reassessments have required development of standards suitable for application by large teams of engineers. This presentation is focused on such methods with special emphasis on practical fatigue reliability considerations. Durability evaluations are based on quantitative structural fatigue ratings which incorporate reliability considerations for test data reduction and fleet performance predictions. Fatigue damage detection assessments are based on detection reliability estimates coupled to damage growth and residual strength evaluations. Data are presented to airline operators on detection check forms which permit efficient maintenance planning to achieve required fatigue damage detection reliability levels. © 1998 The Boeing Company. Published by Elsevier Science Ltd.

(Keywords: fatigue and damage tolerance; damage detection reliability; airline maintenance planning)

OVERVIEW

Criteria and procedures used in commercial jet transport design and manufacture over the last four decades have resulted in fail-safe/damage-tolerant structures with a credible safety record, *Figure 1*. Advancements in the capability to characterize structural performance by analysis have spurred adaptation of traditional fatigue and fracture mechanics technologies with large test and service databases to achieve development of technology standards over the last two decades. Major Boeing efforts have been focused on capturing lessons learned for future continuous design improvements with standardized durability and damage tolerance checking procedures similar to traditional strength checking procedures. The challenge of successfully implementing technology standards hinges on a practical balance between simplicity and technical credibility aimed at providing structural engineers with useful and service/test validated analysis tools. This paper provides fundamental principles behind durability and damage tolerance technology standards, as well as examples of test and service validation.

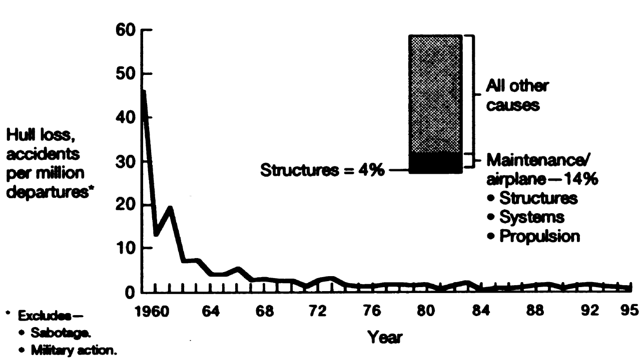

Figure 1 Safety record – worldwide commercial jet fleet

DESIGN CONSIDERATIONS

Structural integrity

Two basic structural integrity issues must be addressed. The first is to design and verify the ultimate strength of the undamaged structure for specified design maneuvers, gusts, flutter, ground loads, and pressurization. The second is to design the structure to sustain fail-safe loads with limited damage for a period of service prior to detection and repair. All Boeing jet transports are designed to this fail-safe principle, which requires fail-safe load capability at all times and restoration of the structure to ultimate load capability after damage detection. The fail-safe load factor is 2.5 g for maneuver design conditions, and an additional safety factor of 1.5 is applied to obtain the ultimate load requirement. The fail-safe (limit) load levels are selected to represent conditions that may occur once in a lifetime for a fleet of airplanes. Design gust levels are based on a similar remote probability of occurrence criterion. Static strength design criteria existing today,

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This paper was originally published in JIJF **19** Supp. 1, pp. 3–21.

including the factor of safety, have worked well, and concerns about static overload failures have essentially been eliminated in present-day commercial airplanes.

Several sources of damage must be evaluated to ensure structural safety during service. Both accidental damage and environmental deterioration are random events during the operational life of the airplane, and maintenance requirements must reflect inspectability for these types of damage. Fatigue damage is a cumulative process, and some cracking is expected in large fleets designed to reach an economic life goal with high reliability. Consequently, supplemental fatigue damage inspections may be required for older airplanes. The inspectability and accessibility characteristics of the structure must be such that general visual methods of damage detection can be confidently employed for most of the structure. Directed inspections involving sophisticated damage detection equipment may be acceptable in areas where inaccessibility dictates infrequent inspection.

Structural durability

Interaction between structural damage tolerance and durability characteristics must be recognized in the design, manufacturing, and operation of modern jet transports. Design evolution and maintenance requirements are motivated by both safety and economic concerns. Damage tolerance is primarily governed by certification requirements, while durability characteristics mainly influence the airplane cost of ownership and are dictated by the requirements of a competitive international market. There is no limit to the service life of damage-tolerant (fail-safe) airplane structures, provided the necessary inspections are carried out along with timely repairs and comprehensive corrosion prevention programs. Since operational efficiency is impacted by the cost and frequency of repair, durability may limit the productive life of the structure.

Fatigue tests of components or the entire airframe are extremely valuable in the early life of a given model, but proof of quality stems from the accumulated experience of maturing fleets, *Figure 2*. The Boeing Commercial Airplanes durability system was developed in the early 1970s to serve as a corporate memory of past design, *Figure 3*. Highlighted key parameters provide the means of timely extension and transfer of experience to new design and/or operating usage. The Boeing fleet is surveyed continuously and the information is summarized in terms of service-demonstrated fatigue lives of various components.

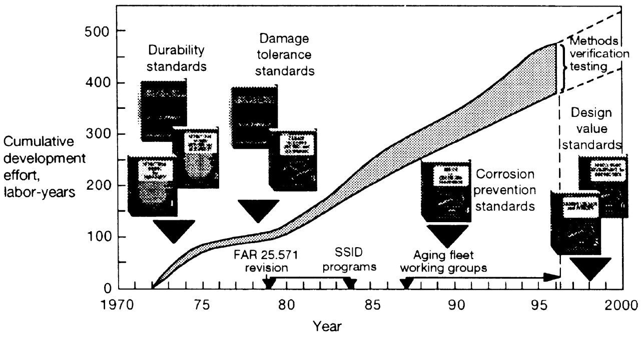


Figure 3 Boeing technology standards development

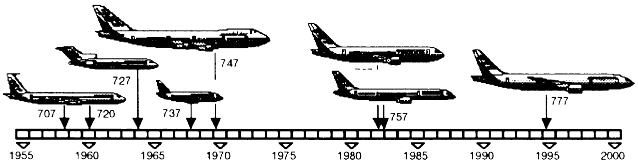
Damage tolerance

Certification of commercial jet transports requires damage-tolerant designs in all instances where they can be used without unreasonable penalty. The technical capability has now evolved to use damage growth to determine inspection requirements, which in the past were based on service experience. Appropriate multiple site damage must be considered in both new design and structural reassessments of older models.

Damage tolerance comprises three distinct elements of equal importance for achieving the desired level of safety:

- Damage limit – the maximum damage, including multiple secondary cracks, that the structure can sustain under limit load conditions;
- Damage growth – the interval of damage progression, from the detection threshold to damage limit; it varies with the magnitude of operating loads, sequence of loads, and environmental influences;
- Inspection program – a sequence of inspections of a fleet of airplanes with methods and intervals selected to achieve timely detection of damage.

These elements of damage tolerance are merged at Boeing Commercial Airplanes by a Damage Tolerance Rating (DTR) system to provide a quantitative measure of fatigue damage detection reliability, *Figure 4*.



Model	Total airplanes	Minimum service design objectives*		High-time airplanes**	
		Flights	Hours	Flights	Hours
707	728	20,000	60,000	40,700	89,600
720	153	30,000	60,000	45,000	69,300
727	1,819	60,000	50,000	72,900	78,400
737	2,706	75,000	51,000	90,100	81,100
747	1,051	20,000+	60,000	32,800	98,600
757	686	50,000+	50,000	23,100	45,000
767	582	50,000+	50,000	28,200	52,300

* At this point in the airplane lifetime, some initial fatigue might occur.
** Different airplanes are in high flights and high hours.
\+ Some derivatives have special design objectives.

Figure 2 Boeing commercial jet fleet summary

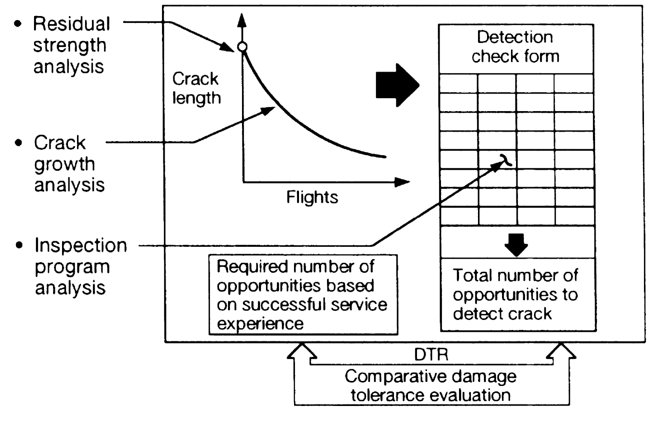


Figure 4 Damage detection evaluation

STRUCTURAL DURABILITY ASSESSMENTS

Fatigue ratings and allowables

Long-life structures are achieved by balancing detail design practices with the operating stress environment, *Figure 5*. Experience has shown that incompatibility between operating stresses and fatigue allowables causes 85% of the service problems. Standardizing the fatigue analysis process allows the service requirement analysis to be conducted independently of and prior to structural capability analysis. This design process provides the following benefits.

- Early attention directed toward fatigue prevention.
- Fatigue methods and allowables available to all structural engineers.
- Common quantifiable base for decision making.
- Emphasis on detail design to achieve minimum design service objectives.
- Trade studies leading to efficient weight/cost designs.

Structural configurations are selected to meet minimum design service objectives. This implies that some specific level of structural fatigue quality must be achieved, with the desired level of confidence and reliability, to provide competitive economic structures with very limited cracking during the anticipated service life. Service life calculations are based on fatigue damage models representing known test and service experience. The focal point in the damage model is defined by a Detail Fatigue Rating (DFR). A comprehensive inventory of service and test-proven design allowables is based on a family of damage curves for various mean and alternating stress combinations uniquely defined by given DFR values. Such DFRs permit quantitative compilation of the cumulative fatigue and design experience as shown in *Figure 6.*

Analytical fatigue allowables are also available to structural engineers to modify existing configurations proven by test and fleet experience, or to derive fatigue ratings for a completely new design. Base ratings are established for notches and mechanically fastened structures, and comprehensive libraries of modification factors accounting for different design parameters such as the type of detail, amount of load transfer, fastening system, surface finish, and material alloy type are provided.

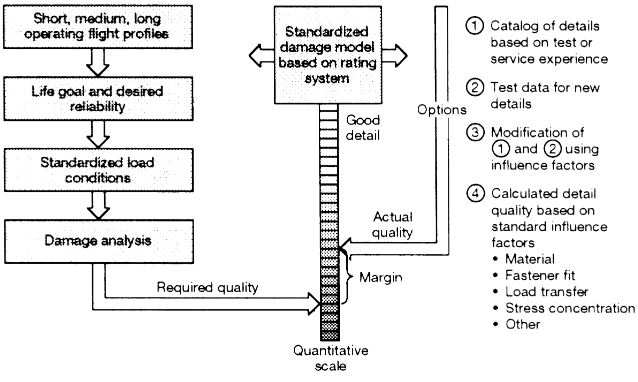


Figure 5 Durability design evaluation

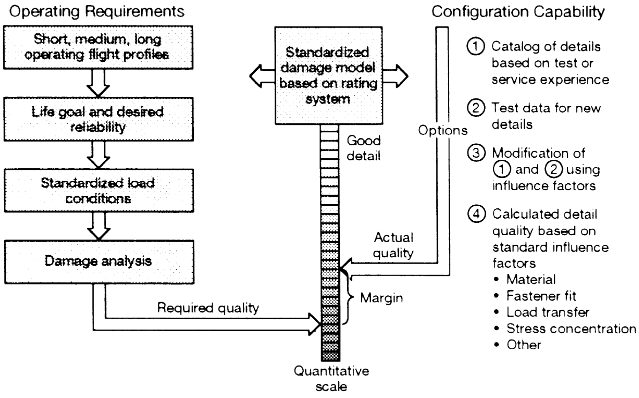


Figure 6 Normalized fatigue ratings

Fatigue reliability considerations

The structural design service objective is a minimum of 20 years of airline operation with only a small percentile of the population subject to repair because of the initiation of detectable fatigue cracks. This percentile varies from less than 5% for those structures that are easy to inspect and repair to extremely low percentiles for structures with difficult access. To obtain these levels of reliability, every structural engineer is required to design for fatigue prevention. This requirement has necessitated the use of straightforward procedures that are easily applied at the design stage.

The ‘scatter factor’ approach to structural fatigue reliability has been used in the airplane industry for decades, and scatter factors such as 2 and 4 are well established. Therefore, in deference to structural engineer familiarity, this approach of using statistically and physically meaningful scatter factors has been retained.

The two-parameter Weibull distribution is used for the structural life distribution mode. In this application structural life is defined as the operational life to initiation of a fatigue crack of detectable size. The Weibull distribution was selected after considerable USAF-sponsored research in the late 1960s and early 1970s. Furthermore, the two-parameter model was chosen to recognize the conservative possibility of a detectable fatigue crack being present at zero life.

Predefined shape parameters are used for the design process. These parameter values were established after reviewing literally thousands of fatigue test results and determining that the parameter was material dependent, and in the case of high strength steel was also stress concentration dependent. Design scatter factors are based on shape parameters that range from 2.2 for high strength steels to 4 for aluminum.

The scale parameter β defines the central tendency (characteristic) fatigue life of a structure and depends upon the quality of the structure and the stresses to which the structure is subjected during its operation. The characteristic fatigue life is either calculated by the designer or determined by testing. For design purposes, characteristic life is related to fatigue lives at higher levels of structural reliability via appropriate scatter factors.

The fatigue design procedure is divided into two major steps. The first step establishes a structure’s minimum design service objective in terms of operational flights with high structural reliability. The second step determines the structural fatigue quality required to attain this design objective. Scatter factors are used in both steps.

The first step uses a factor known as the Fatigue Reliability Factor (FRF). This factor has been normalized so that a value of unity translates to a minimum level of reliability of 95% over the structure's operational lifetime. FRF = 1 is limited to structures in which fatigue cracks are easily detected and repaired. Structural engineers are required to use FRFs that are increasingly greater than unity when establishing life goals for structures that are increasingly difficult to inspect and repair. This simple approach results in the more difficult structures being designed for longer lives. Therefore, at any time during an airplane's operational lifetime, a difficult-to-inspect/repair structural part would have less expectation of fatigue cracking, i.e. higher reliability, than an easy-to-inspect/repair part.

The second step of the fatigue design process requires fatigue allowables in order to determine the structural quality needed to achieve the economic design service objective. These allowables are usually referred to as *SN* curves, and they define the life of a structure at any given level of stress, *Figure 7*.

Fatigue design allowables (DFR curves) identify for any level of operational stress a minimum fatigue life that can be comfortably exceeded by all but the weakest extreme members of the structural population. These allowables are developed empirically from fatigue test results of structurally representative specimens subject to realistic operational loads. The fabrication and testing of specimens are carefully monitored and documented and the test results verified before acceptance as valid data. Four separate 'scatter factors' are used to reduce valid fatigue life data to reliable design allowables. As shown in *Figure 8*, these factors are as follows.

- Establish a lower bound interval estimate of central tendency fatigue life from the results of a limited number of test specimens. In keeping with long-established static strength allowables practice, the confidence bound is set at the 95% level.
- Account for the degree of simplification used in the fatigue test representation of the actual structural part and the real operational load conditions.
- Account for the influence of population size on fatigue life. This factor distinguishes between the fatigue performances of typically small test specimens, which contain few potential crack initiation locations, and large full-scale structures with their multitude of potential sizes for initiation of the earliest fatigue cracks.
- Establish the structure's design allowable fatigue life at the 95% reliability level; that is, the life at which 95% of the population of structures will be free of fatigue cracks of detectable size. The 95% reliability level was adopted for fatigue allowables as a simplification of the A and B basis static strength allowables, which have been set for decades at reliability levels of 99% and 90% respectively.

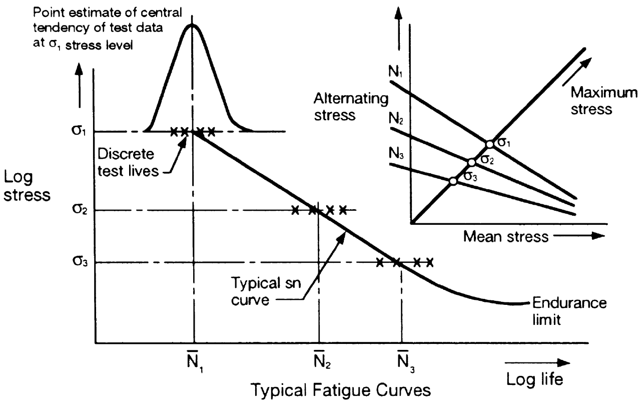


Figure 7 Fatigue damage model

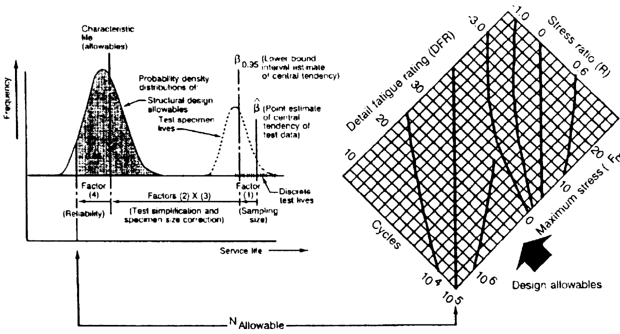


Figure 8 Fatigue design allowables considerations

The fatigue design procedure can be simply summarized as follows. The structural engineer first establishes a minimum design service objective for the structure per appropriate Design Requirements and Objectives document for each model. This design objective is then entered in an appropriate DFR curve and the design allowable stress determined. This stress is then compared to the actual stress that will be imposed on the structure during its operation, and a resultant fatigue margin is calculated by dividing the allowable stress by the operational stress. Clearly this margin must equal or exceed unity to attain the structure's reliability and life goal requirements.

Fatigue performance validation

Technology standards. Since the early 1970s, Boeing has devoted extensive efforts to developing methods and allowables that enhance analysis capability for new and aging airplane structures, see *Figure 3*. ('Allowables' are material properties and specific strength data used for design and analysis of airplane structures.)

Significant amounts of testing served as verification and validation of technology standards development. This testing included coupon, component, and full-scale fatigue testing and teardown inspections. ('Coupons' are small material test specimens used to determine allowables.)

Durability standards were developed first, followed by damage tolerance standards. These two standards were incorporated into the designs of the second generation of Boeing jet transports, the 757 and 767. The damage tolerance standards were utilized in the certification of the 757 and 767 as damage tolerant. This damage tolerance was certified per the US Federal Aviation Administration (FAA) Federal Airworthiness Regulation 25.571, Amendment 25-45. The Boeing damage tolerance standards were also utilized in the

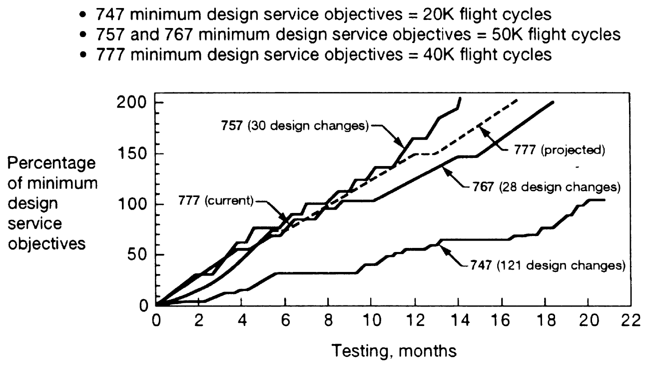


Figure 9 Major airframe fatigue tests

Supplemental Inspection Documents of aging airplane programs for the Boeing 707, 727, 737, and 747.

Since the early 1970s, corrosion has been recognized as one of the dominant factors in the inspection and maintenance activities of airline operations. Boeing has devoted extensive resources to the technology standards development in the areas of corrosion prevention and corrosion control. Expanded corrosion coverage, as a result of the corrosion standards development, has been incorporated into the production lines of all current production airplanes as well as the Aging Fleet Structures Working Groups. These groups include representatives from airframe manufacturers, airline operators, and regulatory agencies.

Figure 9 illustrates the significance of durability standards development to the structural improvement process. For example, the second generation 757 and 767 were tested to *twice* their respective Design Service Objectives (DSOs) in flight cycles; improved testing technology allowed this testing to be completed in less time than it took to test the first generation 747 to its *one* DSO in flight cycles. More significantly, the design changes identified in the 757 and the 767 fatigue testing in two DSO flight cycles are far fewer than the design changes identified for the 747 during fatigue testing for its one DSO in flight cycles. This improvement was possible because durability technology standards were incorporated into the original designs of both the 757 and 767.

Another measurement for the effectiveness of the design improvements is 'maintenance labor hours per airplane' compared for the initial 10 years of operation for each model, *Figures 10* and *11* show significant order of magnitude improvements between first and second generation wide and standard body airplanes.

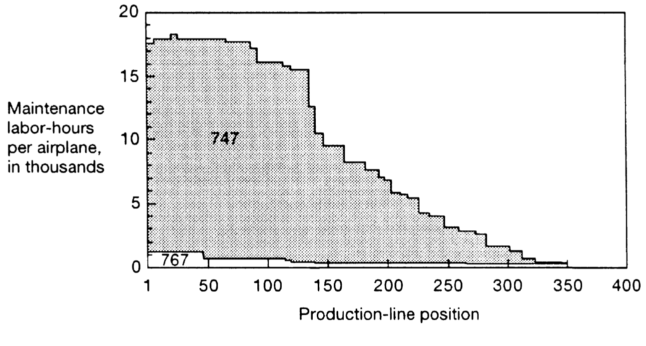


Figure 10 747/767 service bulletin: labor hours after 10 years of service to address corrosion and fatigue

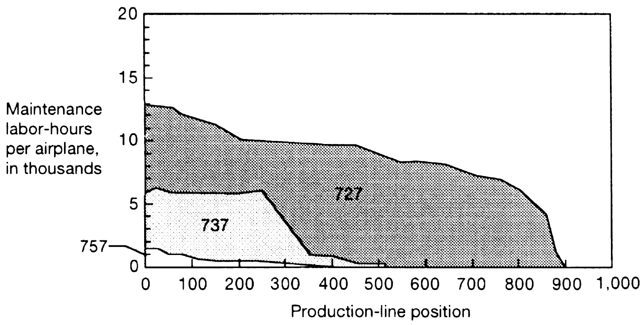


Figure 11 727/737/757 service bulletin: labor hours after 10 years of service to address corrosion and fatigue

These improvements are a result of implementation of lessons learned from past design practices for new airplanes.

Full-scale fatigue testing. Full-scale fatigue testing of airplanes is a major part of structural performance data development. In addition to providing the validation of aircraft design concepts, full-scale fatigue testing is often used to identify any preventative maintenance actions for the fleet, if the fatigue testing is done at the time of certification of a new model of jet transport (which is often the case at Boeing).

Figure 12 shows the minimum DSO in flight cycles and the full-scale fatigue testing in flight cycles. It may be seen from *Figure 12* that full-scale fatigue testing is generally accomplished to twice the minimum DSO, with two exceptions. The first exception is the model 727, which was originally fatigue tested to its DSO of 60,000 flight cycles. However, approximately two years ago, a 727 airplane with 47,000 accumulated flight cycles was acquired and the fuselage cyclic pressure tested to an additional 76,000 cycles. The second exception is the model 747, which was also originally fatigue tested to the DSO of 20,000 flight cycles. As in the case of the 727, a 747 airplane with 20,000 accumulated flight cycles was acquired and the fuselage cyclic pressure tested to an additional 20,000 cycles. In addition, the fuselage sections 41 and 42 of the derivative model 747-400 were cyclic pressure tested to 60,000 cycles, representing three DSOs.

Teardown inspections. Since the introduction of the 707, several teardown inspections and evaluations

Airplane	Minimum design service objective	Fatigue test cycles	Remarks
707	20,000	50,000	Fuselage Hydro-fatigue test
727	60,000	(a) 60,000	Complete airframe
		(b) 170,000	Complete fuselage 47,000 cycles in service, plus 123,000 pressure test cycles
737	75,000	(a) 150,000	Fuselage section/pressure and shear
		(b) 129,000	Complete aft fuselage 59,000 cycles in service, plus 70,000 pressure test cycles
747	20,000	(a) 20,000	Complete airframe
		(b) 40,000	Complete fuselage 20,000 cycles in service, plus 20,000 pressure test cycles
		(c) 60,000	747-400 sections 41 and 42 pressure test cycles
757	50,000	100,000	Complete airframe
767	50,000	100,000	Complete airframe
777	44,000	60,000 (ongoing)	Complete airframe (test in progress for early 1997 completion)

Figure 12 Full-scale fatigue test programs

of high-time airplanes have been conducted as part of a continuing assessment of airplane structure. These inspections permit a detailed examination of structural performance, and provide much useful information for forecasting future structural maintenance requirements. Sophisticated inspection techniques, capable of finding smaller cracks than typically found during routine airline inspections, are used on the disassembled structure. Teardowns also provide an excellent database for calibrating analysis tools, and developing structural modifications on future production airplanes, if required. Major teardown inspections supplementing normal fleet surveillance activities have been conducted on several models:

● 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	1988
● 747 wing and empennage	1989
● 747 fuselage	1991
● 727 wing and empennage	1994
● 727 fuselage	1995

Concerns related to an increased number of airplanes being used beyond their original design life objectives have spurred further activities to obtain airframes retired from service for teardown inspections. Boeing will continue to monitor the aging fleet to verify the effectiveness of preventative modifications incorporated as retrofit on older models and/or new model production improvements. Findings will be disseminated to operators by service bulletins as required and incorporated in maintenance recommendations.

Fleet surveys. The aging fleet surveys by engineering teams were initiated in 1986 to gain a better understanding of the condition of structures and systems and to observe the effectiveness of corrosion prevention features and other corrosion control actions taken by the operators, *Figure 13.* All manufacturers continually review reported service data and other first-hand information from customer airlines in order to promote safe and economic operation of the worldwide fleet. These surveys were primarily prompted by the projected upward trend in airplane age towards and beyond original design service objectives.

The initial fleet surveys showed that the majority of the airplanes were well maintained and in relatively good condition. However, there were a number of airplanes whose condition showed that finding corrosion discrepancies and repairing them was accepted practice and little or no attempt was made to apply any preventative measures. From the surveys and some similar incidents it became apparent that some airplanes were continually operating with significant structural corrosion and that this was on the increase as airplanes age. This in turn could significantly influence the fatigue cracking and damage tolerance capability of principal structural elements. Boeing formed a special Corrosion Task Force in 1988 and held meetings with airline maintenance executives as a result of these surveys.

Service-demonstrated fatigue lives. The commercial jet fleet is used as a large group of specimens loaded in real-life environments to demonstrate service-demonstrated fatigue life and to predict future fatigue performance. This fleet represents a database of over 8000 delivered airplanes, with a total fleet experience exceeding 150 million flight cycles, and daily utilization exceeding 23,000 flights, see *Figure 2.*

Where a statistically significant number of fatigue cracks have been reported in a fleet, maximum likelihood estimates of the Weibull shape and scale parameters are used to determine fleet-demonstrated DFR values. This provides a means of relating service experience for one model to other models with different utilization characteristics. Significant fleet findings, often augmented by extensive teardown inspections, are used to modify fatigue methods and allowables described previously. When no fatigue cracks have been observed, a simpler approach based on the design shape parameter is used to estimate service-demonstrated lives. Such information provides a fundamental check and balance for the fatigue analysis system, and new design and/or redesign evaluations can be related to accumulated fleet performance, *Figure 14.*

DAMAGE TOLERANCE ASSESSMENTS

Jet transports are designed to be damage tolerant, a concept that evolved from the fail-safe design principle introduced in the 1950s. The ability to a analyze damaged structure has improved steadily through more

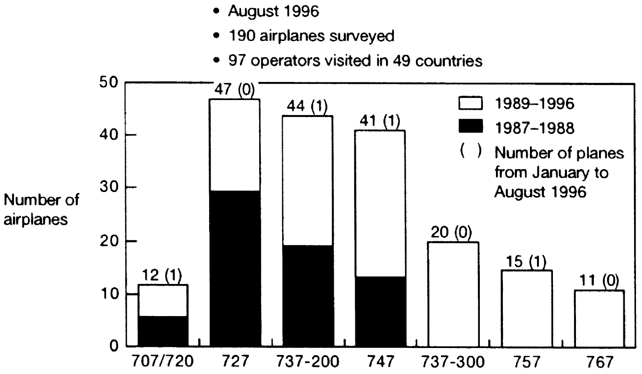
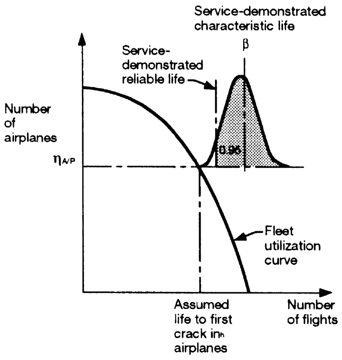


Figure 13 Boeing fleet surveys



1995 commercial fleet data			
Model	Number of airplanes in fleet	Highest flights in fleet, K	Demonstrated reliable (0.95) life, flights, K
707	728	41	40
720	153	45	36
727	1,819	73	101
737	2,706	90	104
747	1,051	33	31
757	686	23	21
767	582	28	24
777	13	1	4

Figure 14 Service-demonstrated fatigue lives

sophisticated application of fracture mechanics. Timely detection of damage is the ultimate control in ensuring structural safety. However, traditional damage growth and residual strength evaluations have failed to incorporate damage detection parameters that influence maintenance planning.

The effects of accidental, environmental, and fatigue damage must be assessed to achieve a balanced inspection program. Of these, fatigue damage, characterized by the initiation and subsequent growth of a crack, is the most amenable to rigorous analytical treatment. Major efforts during the last 15 years have focused on establishing quantitative damage detection rating systems that measure the efficiency of inspection programs. Extensive statistical evaluations of reported service data have resulted in estimates of damage detection reliability for different inspection methods.

Fatigue damage detection is normally considered in terms of a single event involving inspection for a given size of crack with a specified method. However, airline maintenance practices consist of multiple inspection levels, varying inspection intervals, and different methods of inspection. In addition, fatigue cracking is generally found on more than one airplane in the fleet within a relatively short period of time. This multiplicity of events significantly influences the timely detection of fatigue damage and needs to be reflected in damage detection assessments. It must be shown that there is a high probability of detecting fatigue damage in the fleet before such damage reduces airplane residual strength below specified levels. A DTR system suitable for ensuring timely detection of fatigue damage in the fleet was developed to accommodate these concepts, see *Figures 3* and *4*.

Elements of damage tolerance

The key objective for airplane structures designed to the damage tolerance concept has always been to carry regulatory fail-safe loads until detection and repair of any fatigue cracks, corrosion, or accidental damage occurring in service. The ability to analyze damaged structures has progressed significantly during the last 20 years through the evolution of fracture mechanics. Assessments now consider residual strength, damage growth, interactive multiple damage sites and quantitative structural maintenance evaluations. Structural maintenance is the cornerstone for ensuring continued airworthiness of damage-tolerant structures.

Residual strength. The maximum allowable damage that a structure can sustain at a critical fail-safe level is the key to the level of damage growth and inspection needed to ensure damage detection. Built-up airplane structures consist of multiple sheet, stiffener, and fastener elements. Interaction between these cracked and uncracked elements causes significant redistribution of stresses. Failures are often precipitated by local exhaustion of plastic strain capability of the most critical elements, and/or net section failures involving a mixture of fracture mechanics and transitional behavior in some elements, *Figure 15*.

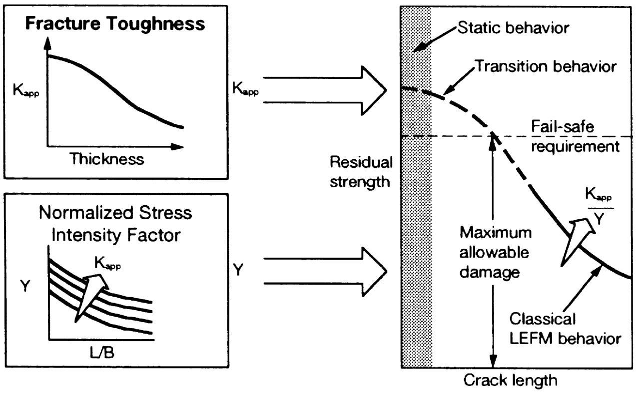


Figure 15 Residual strength evaluation

Crack growth. The rate of damage propagation is a function of material properties, structural configuration, environment, crack length of primary and secondary cracks, and operating stress exposure. Damage detection assessments require crack growth data from detection threshold lengths to the allowable damage determined by residual strength analyses. Use of normalized damage models for calculating relative growth per flight, including load sequence effects, permits separation of the material, geometry, and stress parameters, *Figure 16*.

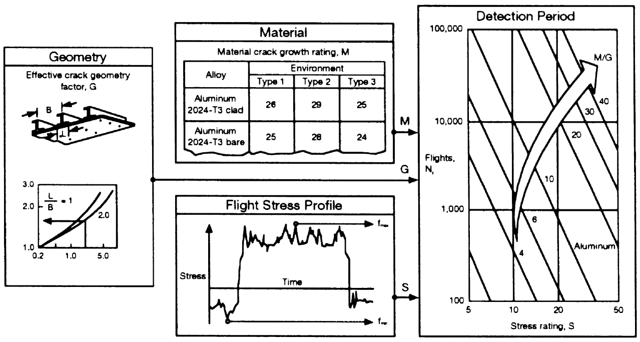


Figure 16 Crack growth evaluation

Damage detection. Both accidental damage and most forms of environmental damage can be considered as random events that can occur at any time during the operational life of an airplane. Fatigue damage is characterized by cumulative progression relating to airplane usage measured in flights. Detection ratings have been developed for accidental and environmental damage. A quantitative fatigue damage detection rating system is known as the DTR system. Damage detection is a function of fleet size, number of cracks, and number and type of inspections, *Figure 17*.

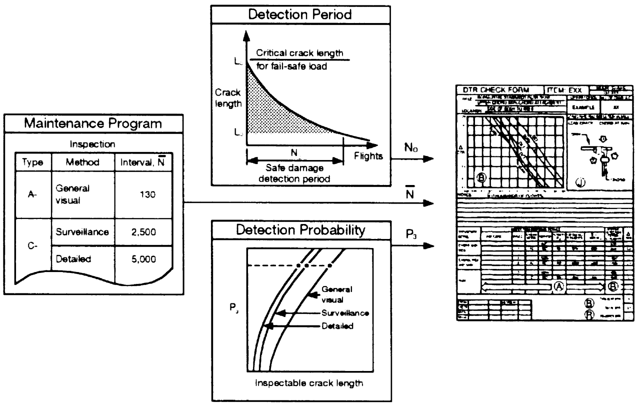


Figure 17 Damage detection

Structural maintenance considerations

Structural maintenance and inspections are the cornerstones of continuing airworthiness of jet transport structures. The advent of fracture mechanics technology has accelerated the knowledge for determination of crack growth rates and maximum allowable damage at limit load conditions. The research community has expanded the understanding and modeling of these structural characteristics. Although elastic–plastic analyses have their place, the added accuracy is often not consistent with the accuracy of other significant parameters governing residual strength. Significant understanding exists today to properly plan fatigue and crack growth tests in order to recognize sequence effects caused by spectrum loads. While analysis models can yield reasonable correlation with laboratory loading environments and simplified structural configurations, it is easy to have large uncertainties due to local load redistributions in cracked structures, flaw shapes, cracking patterns and a host of external and environmental characterization problems. While progress must be encouraged, it is truly necessary to pay attention to the overall sensitivity of stress histories and analysis assumptions in the final answer. In summary, prediction of fatigue crack growth for a host of complex structural details within a factor of 2 is not always as easy as advertised by complex models.

The practising structural maintenance engineer is charged with development of inspection programs from the time of airplane introduction into service. Three principal forms of structural damage must be evaluated to achieve a balanced structural inspection program for timely detection of environmental deterioration, accidental damage, and fatigue damage.

Environmental deterioration actually involves two forms of damage, corrosion and stress corrosion. Corrosion may or may not be time- and/or usage-dependent. For example, deterioration resulting from a breakdown in a surface protection system is more probable as calendar age increases; conversely, corrosion due to spillage or a leaking seal is treated as a random discrete event.

Accidental damage can also be considered in two categories. First, discrete source or large-scale damage, such as that caused by a large bird strike or uncontained engine disintegration, involves special regulations. Such damage detection is considered obvious, but it must be shown that a flight can be safely completed after it has occurred. Second, more general forms of accidental damage, such as dents and scratches, occurring during routine operation of the airplane must be considered in the inspection program.

Both accidental and most forms of environmental damage are random events that can occur at any time during the operation life of an airplane. However, experience has shown that some structural areas are more susceptible than others to these types of damage. This information is used to develop suitable inspection tasks.

Fatigue damage is characterized as the initiation of a crack, with subsequent propagation. This is a result of a continuous process whose effect is cumulative with respect to airplane usage (measured in flights or flight-hours). Comprehensive fatigue life, crack growth and residual strength evaluations are required. Using previous service experience to improve detail design results in a high level of structural durability. Large-scale panels and full-scale airplane fatigue tests are used to identify areas in which this durability is significantly lower than predicted. Changes to the production airplanes to rectify problems usually result. Most airplanes in the fleet are then expected to exceed the fatigue service objective without significant cracking. This does not preclude anticipated cracking before all airplanes reach the design life objective.

For safety critical structures, it must be demonstrated that there is a high probability of timely detection of any cracking throughout the operational life of the fleet, *Figure 18*. This means that the inspection program must be capable of timely detection of initial damage in the fleet. Subsequent action is necessary to detect or prevent any damage in the fleet.

The conflicts in structural maintenance planning often occur because of the focus on fracture mechanics-based damage tolerance evaluations. Inspection programs in place to provide timely detection of corrosive or accidental damage are often not addressed by the scientifically oriented structural engineer, who may be satisfied with inspection thresholds based on universally applied initial flaws and inspection intervals based on simple factoring of the damage detection period from an assumed detectable/inspectable damage size to the damage allowed at limit load conditions.

This section addresses some key issues related to inspection thresholds and intervals with emphasis on quantifying detection reliability aspects and sensitivity to key parameters and variables.

Structural characteristics

Airplane structures can be categorized for the purpose of determining safety analysis requirements, *Figure 19*. Any structural detail, element or assembly is classified as a Structurally Significant Item (SSI) if its failure reduces airplane residual strength below regulatory levels or results in an unacceptable loss of function. Most SSIs require damage tolerance evaluations comprising residual strength for Category 2 structures and all three elements of damage tolerance for Category 3 structures.

The structure of each airplane model undergoes a thorough examination to ascertain the functions of its components and, as necessary, to classify those components. For the new models, this evaluation is

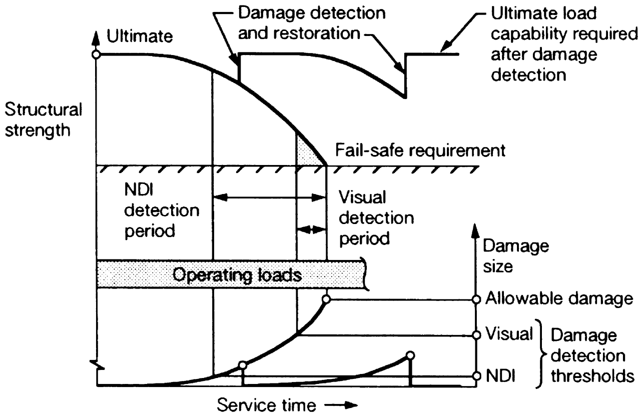


Figure 18 Strength requirements for damage-tolerant structure

Structural category			Technique of ensuring safety	Safety analysis requirements	Structural classification examples
Other structure	Damage tolerant design	① Secondary structure	Design for loss of component or safe separation	• Continued safe flight	Wing spoiler segment (safe separation or safe loss of function)
Structurally significant items or principal structural elements (primary structure)		② Damage obvious or malfunction evident	Adequate residual strength with extensive damage obvious during walkaround or indicated by malfunction	• Residual strength	Wing fuel leaks
		③ Damage detection by planned inspection	Inspection program matched to structural characteristics	• Residual strength • Crack growth • Inspection program	All primary structure not included in categories ② or ④
	Safe-life design	④ Safe life	Conservative fatigue life	• Fatigue	Landing gear structure (conservative fatigue life)

Figure 19 Structural classification examples

performed using the FAA approved guidelines of MSG3. These evaluations are conducted, in support of a Structures Working Group established jointly by Boeing and its operators, to develop the structural maintenance program. As a consequence of examinations, some 80 to 100 SSIs can typically be identified on each airplane model. As an example, 33 SSIs for a typical outer wingbox are shown in *Figure 20.* Each SSI may cover a broad expanse of structure. For example, the entire wing rear spar lower chord and skin may represent a single SSI. In consequence, the SSI may be divided into a number of details based on access, inspectability, stress level, material, and detail design differences. This example in *Figure 20* shows three details in a single rib bay. Detail A shows a typical rear spar structure; detail B shows the rear spar at a rib where internal inspection is restricted; detail C shows the rear spar at a rib where a main landing gear trunnion support fitting additionally restricts external inspection. Within each detail, the inspectable initial damage is assumed to occur in the most difficult location from the viewpoint of inspectability, regardless of the relative fatigue life of the component. In the selected lower chord example, crack growth calculations are performed for cracks in the chord itself, in the skin, and as appropriate in the web. These cracks grow interactively, with each influencing to some degree the behavior of the others. Separate analyses may occasionally be required to accommodate crack growth data necessary to evaluate the effectiveness of selected nondestructive testing techniques. Thus, in summary, a formal damage tolerance evaluation of an airplane structure may involve crack growth and probability of detection determination at several hundred details with two to three times as many crack growth curves to represent adjacent structural elements. Some 150 to 250 of these, representing the most critical, are published in formal certification documentation. Each crack growth analysis must take into account the unique aspects of load spectrum, stress level, material, geometry and interaction between adjacent structural elements.

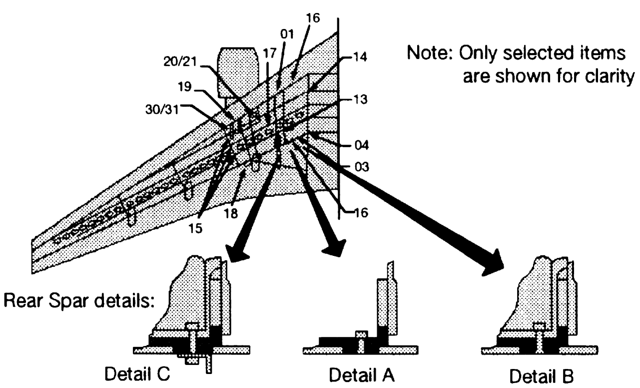


Figure 20 Structurally significant item examples for wingbox

Fatigue inspection threshold

The design service objectives are established for high utilization operators in terms of flight cycles for short, medium and long flights. Design service objectives are established with a minimum of 95% reliability. For typical aluminum alloys this implies a characteristic life of at least twice the design service objective excluding additional factors applied to achieve 99% reliability for most principal structural elements. Supplemental structural fatigue inspections based on fatigue principles are often initiated when the fleet leaders reach 75% of the design service objective. At this time the fleet exceeding 50% of the design objectives is included in a so-called candidate fleet. These principles were initially developed more than 10 years ago for the first generation of supplemental inspection programs. The rate of findings of previously unknown cracking does not support an often-advocated abandoning of this approach in favor of initial flaw growth periods critically factored by 2. While some provisions exist to adjust the initial flaw for inherent manufacturing quality and life enhancements, the end product of such assessments offers little advantage over service/test-demonstrated fatigue initiation data.

Increasing concerns for widespread fatigue damage have promulgated more pressure to establish thresholds for such structural damage which can significantly reduce the residual strength and accelerate damage progression link-up of adjacent cracks.

Widespread fatigue damage in a structure is characterized by the presence of multiple structural details with cracks that are of sufficient size and diversity whereby the structure will no longer meet its damage tolerance requirement (e.g. maintaining the required residual strength after partial failure), *Figure 21.* There are two distinct types of WFD:

- Multiple Site Damage (MSD) – simultaneous pres-

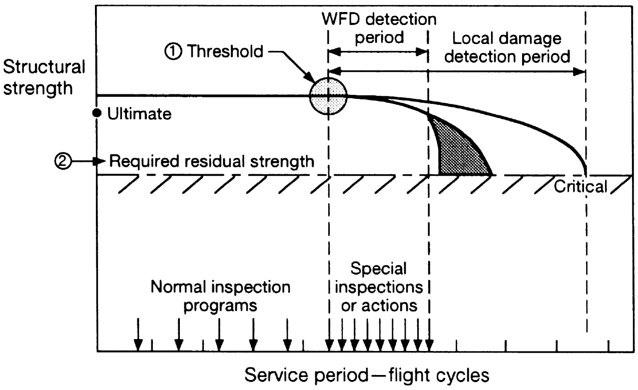


Figure 21 Damage detection comparisons for local and widespread fatigue damage

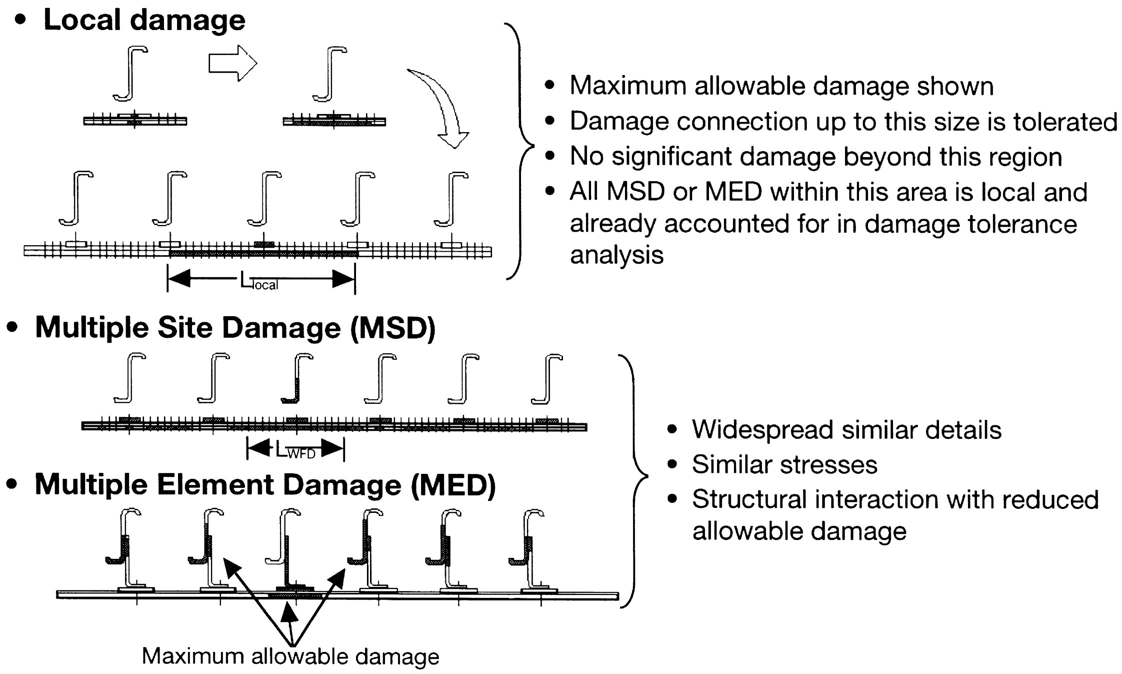


Figure 22 Example of local versus widespread MSD or MED

ence of fatigue cracks in the same structural elements;

- Multiple Element Damage (MED) – simultaneous presence of fatigue cracks in adjacent structural elements.

Dependent types of MSD and MED that are within the extent of existing damage tolerance regulation compliance assumptions are labeled 'local'. Such dependent damage is characterized by retention of residual strength capability after link-up of adjacent finite cracks. Independent types of WFD may reduce the residual strength and corresponding critical crack length substantially, *Figure 22.*

The concern for WFD thus exists when regions with similar structural details have the same high stress levels. Coalescence of multiple damage origins may potentially be catastrophic, and there is a lack of confidence in damage detection before such unsafe conditions may develop. *Figure 23* shows a typical trend for allowable local versus widespread damage which is discussed in more detail later.

Structural design philosophy is focused on the early, i.e. extreme, event, and consequently fatigue design criteria are in place which reflect this philosophy. For example, the statistical model used is Weibull, one of the family of extreme value distributions, instead of the log-normal distribution which is in more common use in the aviation industry. It should be noted that fleet data are monitored for lessons learned, to analyze early fatigue incidents when necessary, and develop and document the demonstrated fatigue ratings of the structures. This activity has been ongoing for very many years, resulting in design standards reflecting lessons learned from a large maintained database, and high confidence in the correlation between fatigue analysis prediction and service demonstrated performance.

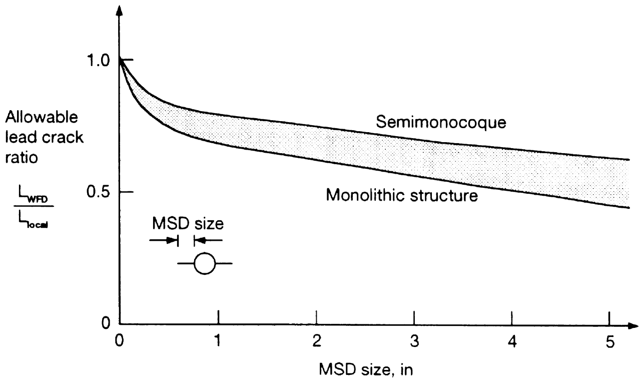


Figure 23 MSD influence on allowable lead crack size

Given this background, it is believed that a similar designer/analyst-oriented procedure could be used for predicting thresholds for WFD. Structural design criteria specify that any structural component must equal or exceed a specific level of reliability for the duration defined by the minimum DSO. These levels of reliability range from high to very high depending upon the criticality of the component. The concept of widespread fatigue damage may add another dimension, namely a consideration of order statistics. When designing for reliability today designers/analysts must select from a menu of fatigue reliability factors that are appropriate for their structural applications. These factors are Weibull based in order to provide sufficiently high levels of reliability in the fleet without the need to address fleet size, i.e. reliability in terms of percentage, e.g. 99%. However, in the case of WFD consideration may have to be given to the first, second, or *i*th event in a fleet of *n* structures. This would force unfamiliar scenarios on designers/analysts, such as the number of fatigue events within any single component, or within *n* components per airplane, or *m* airplanes in the fleet.

The Weibull parameters characterizing structural fatigue have already been known, verified and used

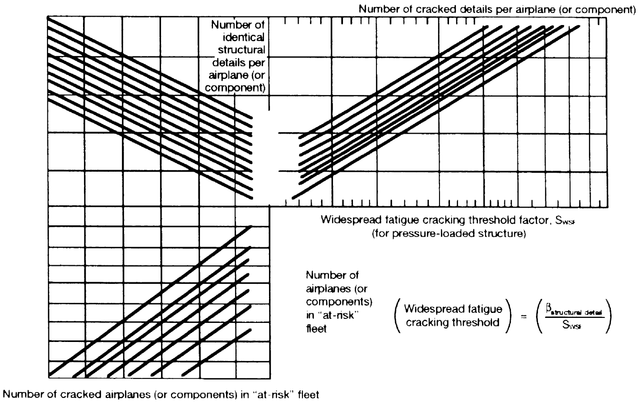


Figure 24 Nomograph for estimating WFD threshold factor for pressurized structures

over the past 30 years. It was therefore logical to expand on existing fatigue reliability factor design procedures to include a WFD threshold factor which considers i events in samples of size n. A nomograph was selected as the medium to present the WFD threshold factor. This was done to provide the designer/analyst with a visual aid (*Figure 24*) to the interactive relationships between i fatigue events and n sample size, whether it be details per component, or components per airplane, or airplanes per fleet. The initial nomograph was developed for application to fuselage structures, i.e. predominantly pressure-loaded structural details such as fuselage lap joints, circumferential splices, and frames (*Figure 25*). The underlying assumption for the nomograph is based on the observation that airplane-to-airplane variation in fatigue is greater than component-to-component variation within the same airplane. Therefore, the graph was developed using the inverse Weibull function and a series of Weibull shaped parameters:

$$\text{Reduction factor: } \left(\frac{\beta_{\text{pop}}}{\beta_i}\right)_{\text{STR}}$$

$$= [\ln(1 - F_{\text{STR}}(x_i))]^{-1/\alpha_{STR}}$$

in which the subscript STR represents structural detail, structural component, or airplane. For each structural category, β_{pop} = population characteristic life to specified damage for STR, β_i = characteristic life to ith occurrence of damaged STR in a sample of n STRs, x_i = expected life to ith occurrence of damaged STR in a sample of n STRs, $F_{\text{STR}}(x_i)$ = probability of damage for an STR at x_i flights = $i/(n + 0.5)$, α_{STR} = shape parameter for STR = 8.0 for rivet holes in a lap joint, 6.0 for lap joints in an airplane, 5.0 for airplanes in a fleet.

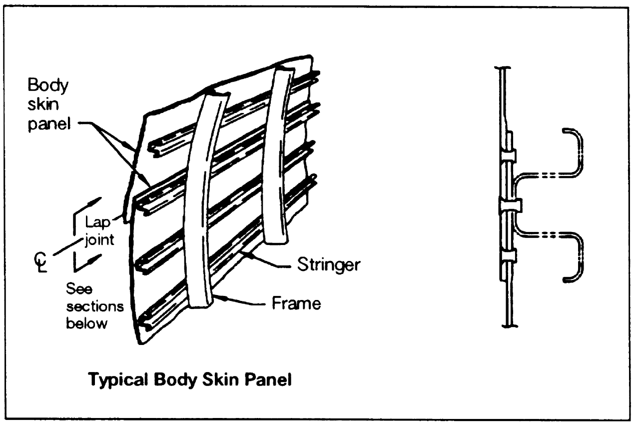


Figure 25 Typical body–skin lap joint – longitudinal

Analysts supporting the standard body and wide body airplane programs have been evaluating this procedure to ascertain the level of correlation between predictions based on the nomograph and observed fleet history. Some difficulties were encountered due to a lack of consensus on what damage extent constituted WFD. As is seen from *Figure 24*, the analyst must make certain decisions regarding sample size at risk of fatigue cracking and the WFD limit in terms of number of cracks. Nevertheless, predictions were found to be encouraging although somewhat more conservative than intended.

The example is based on a fleet of 323 airplanes with six identical lap joints per airplane and 380 equally critical rivet connections per lap joint. It was assumed that the WFD threshold was consistent with small cracks initiated at 10%, i.e. 38, of the rivet holes in a lap. *Figure 26* is a plot comparing the cracking history predicted via the factors from the nomograph against the service history as reported by the airplane operators. It is noted that the correlation at the first event is very close, but from there on the prediction becomes increasingly conservative.

Several other examples have been undertaken by program personnel and are at different stages of completion. To date all feedback indicates that the proposed S_{WSF} factor provides conservative estimates relative to service history; however, data are insufficient to proceed with refinement of the procedure. A nomograph for gust critical structures, e.g. wings, has also been developed and provided to airplane program personnel for evaluation, but there has been no feedback at this time.

Damage detection

Three principal sources of damage to airplane structures must be considered independently, *Figure 27.* Both accidental damage and most forms of environmental damage can be considered as random events that can occur at any time during the operational life of an airplane. Fatigue damage is characterized by a cumulative progression relating to airplane usage measure in flights. Detection ratings have been developed

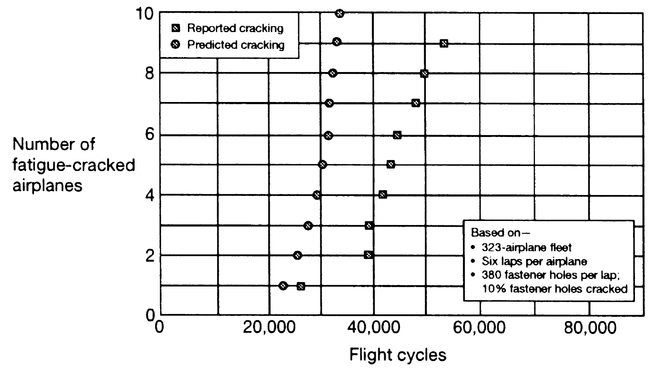


Figure 26 Comparison of predicted and actual cracking histories for example problem

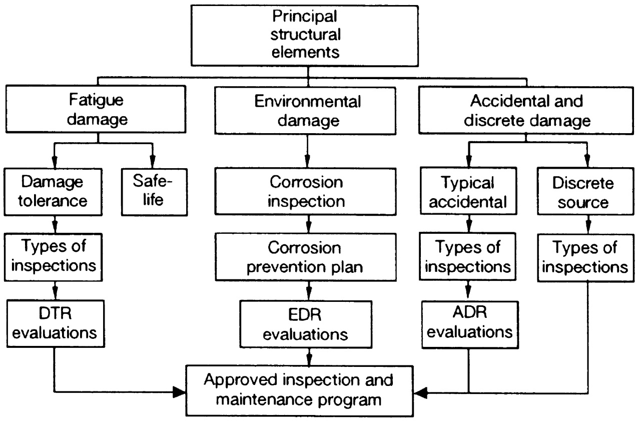


Figure 27 Principal damage sources for maintenance planning considerations

for accidental and environmental damage. A quantitative fatigue damage detection rating system is known as the DTR system. The concepts of this system have been described in earlier publications and this review focuses on application examples that demonstrate major features.

Damage detection is a function of fleet size, number of cracks, and number and type of inspections. Three independent probabilities determine the certainty of damage detection:

- P_1: probability of inspecting an airplane with damage;
- P_2: probability of inspecting a detail containing a crack;
- P_3: probability of detecting a crack in the detail.

For a single inspection of the detail considered on an airplane with damage, the probability of detection P_3 is a function of crack length, inspection check level, and detection method.

P_3 for visual inspections is based on an extensive review and analysis of fatigue cracks detected in service. Account has been taken of cracks remaining undetected during inspections prior to detection, including those assumed to have occurred but not yet detected, *Figure 28*. Detection thresholds and characteristic crack lengths are defined by a three-parameter Weibull distribution.

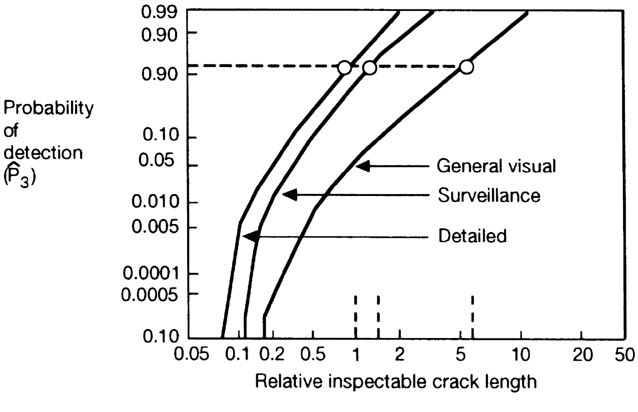


Figure 28 Relative probability of detection for visual inspection methods

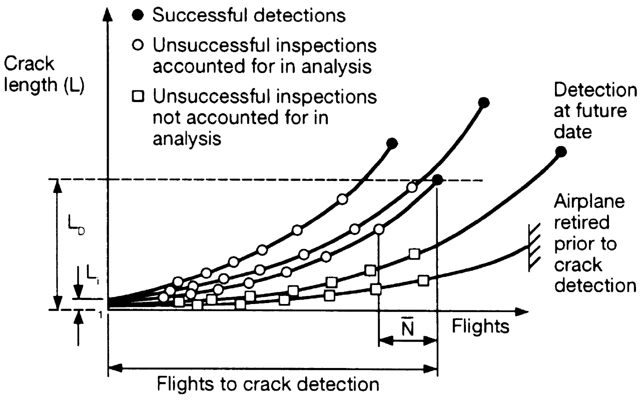


Figure 29 Detection and nondetection events

Detection standards used for fleet safety evaluations must recognize that many service inspections fail to detect damage beyond the detection threshold. A mean crack growth curve shape was used to describe the crack growth history prior to detection. Crack length, total flights at detection, and an assumed detection threshold after an appropriate period of service provided the necessary crack growth curve constants, *Figure 29*. Previous unsuccessful inspections correspond to nondetections that are usually 20 to 50 times more numerous than the detection events. Allowance was made for escalation in inspection intervals for the relevant period of collected service data and for cracks currently being missed that will be detected in the future. This latter point was demonstrated by successive elimination of detection events and analysis of the reduced sample. The total influence of the nondetection events is substantial, as illustrated in *Figure 30*.

Use of Nondestructive Inspection (NDI) procedures such as ultrasonic or low frequency eddy current may significantly increase the damage detection period, *Figure 31*. NDI procedures allow detection of smaller surface cracks than with visual inspection, and also allow subsurface crack detection. Therefore, an equal probability of detecting damage can be achieved with a reduced inspection frequency. Damage detection reliabilities have been established for different crack lengths in relation to the minimum detectable for typical inspection techniques and structural configurations, *Figure 32*. These P_3 curves are appropriately modified to account for visual detection of surface cracks and multiple probe applications at different locations along the same crack during the same inspection of subsurface cracks.

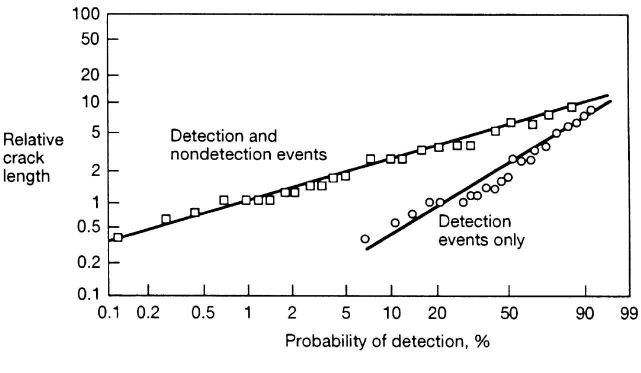


Figure 30 Effect of nondetection events on probability of detection

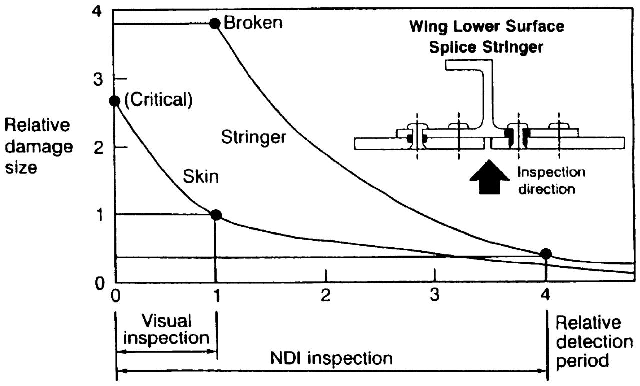


Figure 31 Visual versus NDI damage detection periods

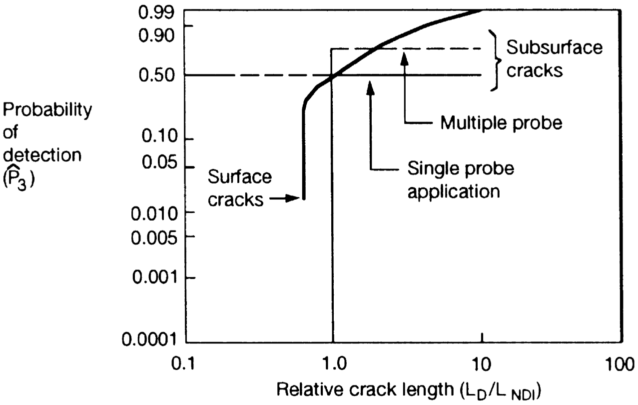


Figure 32 Probability of detection for NDI inspections

The crack length at the time of inspection is random. The last inspection occurs at some point during the final inspection interval, $\bar{N}$, *Figure 33*. Since P_3 varies significantly, the average value is determined by integrating individual P_3s over the interval. Previous inspection detection contributions can be approximated by the P_3 values for the midpoints of each inspection interval. The cumulative probability of crack detection in at least one of several inspections is $\hat{P}_3 = 1 - \Pi(1 - \hat{P}_{3i})$. In some cases the inspection interval $\bar{N}$ is greater than the damage detection period N_0, and the probability that the inspection will occur is accounted for by calculating the average $\hat{P}_3$ for the inspection interval assumed equal to N_0 and using $P_3 = \hat{P}_3 N_0/\bar{N}$ for damage detection assessments.

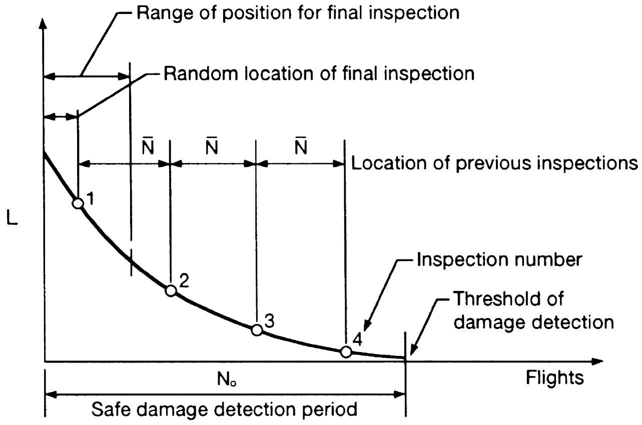


Figure 33 Multiple inspection detection consideration

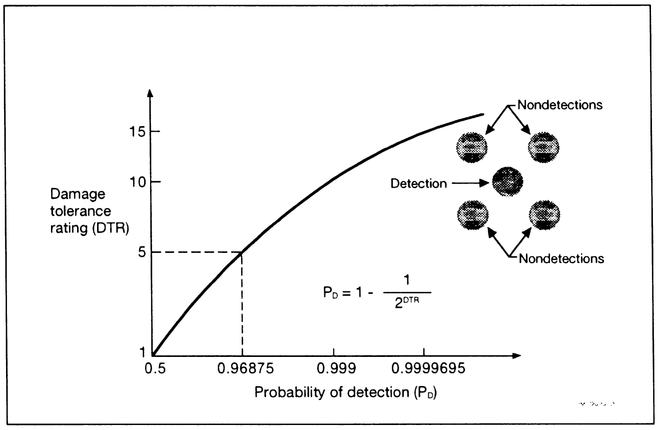


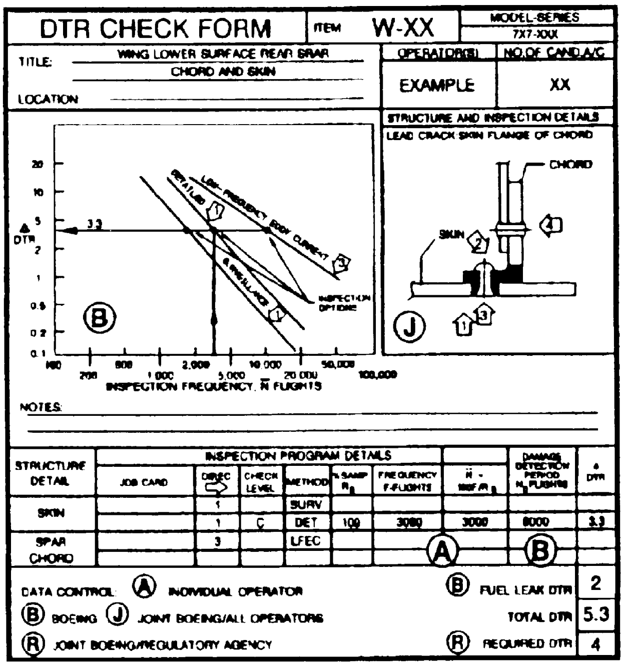
Figure 34 Probability of detection measurements

The calculated probability of detection does not provide a convenient measure of maintenance actions and requires products of nondetection probabilities to combine effects of types and/or levels of inspection. The DTR is a measure of detecting at least one fatigue crack. The measuring units are the equivalent number of opportunities for detection, each with an equal chance of detection or nondetection:

$$P_D = 1 - \frac{1}{2^{DTR}}$$

where $P_D = 1 - \Pi(1 - P_{di})$, $P_{di} = P_1 \cdot P_2 \cdot P_3$ for all applicable inspections.

The measurement of detectability by DTR values provides a better comparison between P_D levels on a suitable engineering scale, *Figure 34*. The detection evaluation can be performed for varying inspection intervals and methods which are summarized in a form suitable for individual operator use, *Figure 35*.


DTR CHECK FORM ITEM W-XX MODEL-SERIES 7X7-XXX

TITLE: WING LOWER SURFACE REAR SPAR CHORD AND SKIN

LOCATION

OPERATOR(S): EXAMPLE

NO.OF CAND.A/C: XX

STRUCTURE AND INSPECTION DETAILS

LEAD CRACK SKIN FLANGE OF CHORD

NOTES:

STRUCTURE DETAIL	INSPECTION PROGRAM DETAILS							DAMAGE DETECTION PERIOD N_s FLIGHTS	Δ DTR
	JOB CARD	DIREC ⇨	CHECK LEVEL	METHOD	% SAMP R_s	FREQUENCY F-FLIGHTS	$\ddot{N}$ - 100F/R_s		
SKIN		1		SURV					
		1	C	DET	100	3000	3000	8000	3.3
SPAR CHORD		3		LFEC					
							Ⓐ	Ⓑ	

DATA CONTROL: Ⓐ INDIVIDUAL OPERATOR

Ⓑ BOEING Ⓙ JOINT BOEING/ALL OPERATORS

Ⓡ JOINT BOEING/REGULATORY AGENCY

Ⓑ FUEL LEAK DTR 2

TOTAL DTR 5.3

Ⓡ REQUIRED DTR 4

Figure 35 Damage-tolerance rating check form for detection assessments

Inspection intervals

Structural inspection program planning involves fracture mechanics evaluations of crack growth and residual strength characteristics coupled to a damage detection assessment. Residual strength and fatigue crack growth evaluations are combined with service-based crack detection data to produce detection reliability representing multiple type and intervals of inspections in a fleet of airplanes subjected to exploratory inspections. Such data give operators freedom to adjust quantitatively their maintenance program in any manner that is desired as long as the required reliability of damage detection is preserved.

Traditional damage tolerance evaluations often concentrate predominantly on the fracture mechanics aspects and the inspection intervals are often simply chosen to reflect half of the damage growth period from detectable to critical damage sizes. Such evaluations often fail to reflect the combined benefits of visual inspections performed during normal maintenance programs focused primarily on corrosion and accidental damage sources. The value of cumulative contributions of multiple inspections in a fleet of airplanes must also be recognized by accounting for such additional detection opportunities before the most critical change in one airplane reaches limit load damage containment capability. Several of these damage detection considerations are discussed in the following sections.

Damage detection considerations

The inspectable crack length at the time of inspection may be significantly different from the total crack length obtained by fracture mechanics calculations, depending on several factors such as location of the cracks and direction and method of inspection. For example, consider the inspectable crack length for the detail shown in *Figure 36*. If inspected visually, the crack would be detectable past A or B, depending on the side of the detail inspected. The crack must grow far enough that the tip is beyond any obstruction, in this case the sheet and sealant on the top and the sealant over the fastener on the bottom. The inspectable crack length is zero when the tip clears the obstruction edge (locations A and B), even though the actual length is significantly greater. For inspections from the bottom of the detail after the crack tip reaches C, the inspectable length will not increase, because the crack past that point will not be visible.

Design objectives for damage tolerant structures include emphasis on accessibility and inspectability. The operator desires flexible maintenance programs which allow inspection intervals for fatigue damage inspections which are compatible with typical intervals used for corrosion and accidental damage inspections.

Changes in stress levels of about 15% can easily change the damage detection period by a factor of 2. Improved material properties can also influence the damage detection period by similar factors. Lack of accessibility for visual inspection can be alleviated by deploying nondestructive inspection techniques. Multiple site damage scenarios often lead to rapid linking of cracks in combination with reduced residual strength capability, i.e. smaller critical crack lengths.

The commonly used practice of setting inspection intervals to half the damage detection period fails to provide a quantitative damage detection reliability. Required detection probabilities result in quite different inspection intervals compared with simple factoring of the detection period by 2.

Damage detection requirements can often be met by a combination of visual and nondestructive inspections. See *Figure 31* for a simple example of visual external inspections and/or external NDI inspections. *Figure 37* shows the cumulative probabilities of detection for different combinations of inspections. It should again be noted that simple factoring of the visual or NDI detection periods by 2 gives quite different detection reliabilities.

Visual inspections can often be performed from different directions and the cumulative detection reliability must be derived accordingly. *Figure 38* shows a wing center section rear spar example for different cracking patterns (lead crack assumptions). Actual and inspectable crack growth curves for directions 1, 2 and 3 are shown in *Figure 39* for these three cracking patterns. Corresponding cumulative detection probabilities for different inspection options are shown in *Figure 40.* An example maintenance program providing sufficient detection probabilities is shown in *Figure 41.*

Fleet cracking detection contributions

Experience has shown that when damage is detected in the fleet, further inspections generally reveal additional damage in the same detail on other airplanes and/or in similar detail at another location. Additional

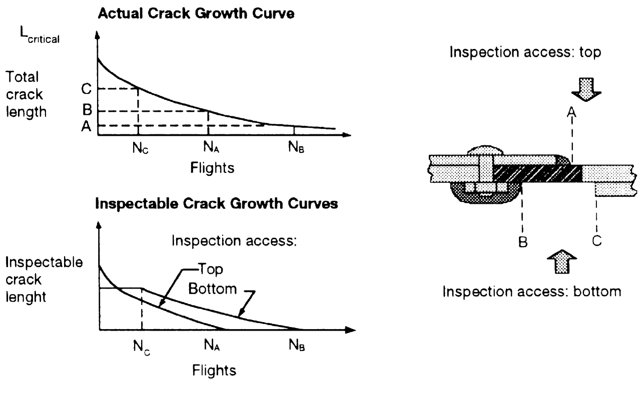


Figure 36 Inspectable crack length considerations

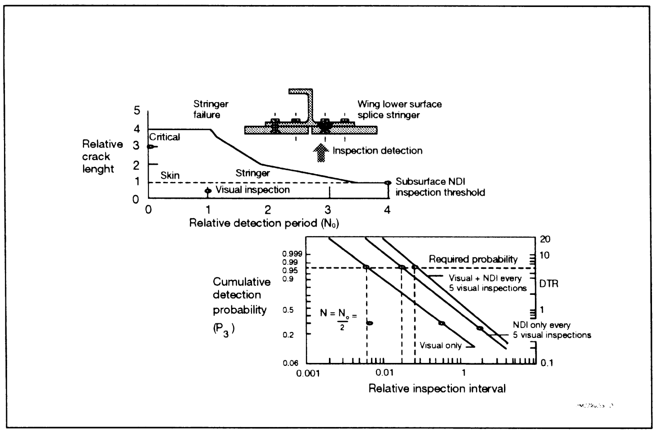


Figure 37 Cumulative detection probability – inspection method variation

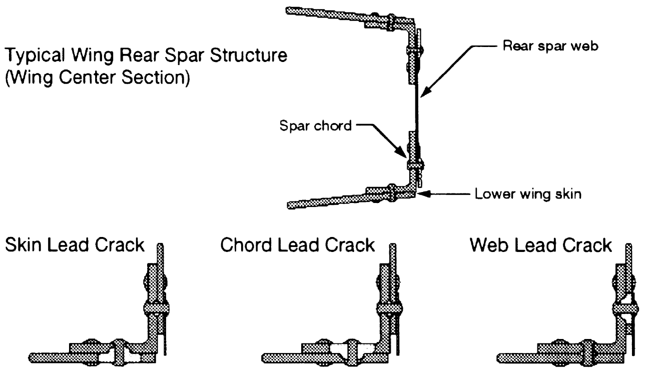


Figure 38 Wing spar chord cracking pattern examples

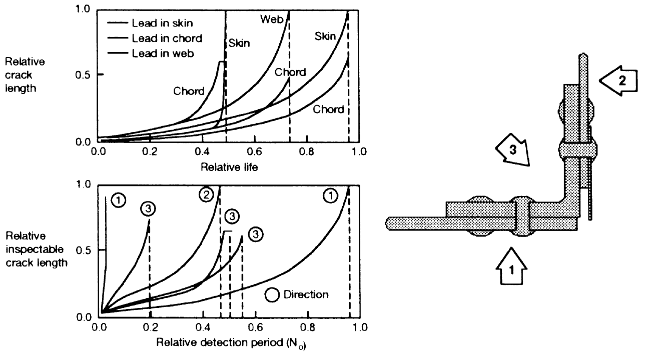


Figure 39 Spar chord crack growth curve examples – wing center section

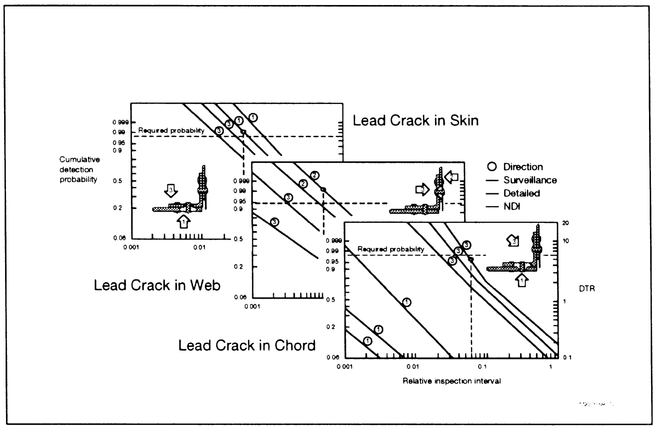


Figure 40 Cumulative detection probability – cracking pattern

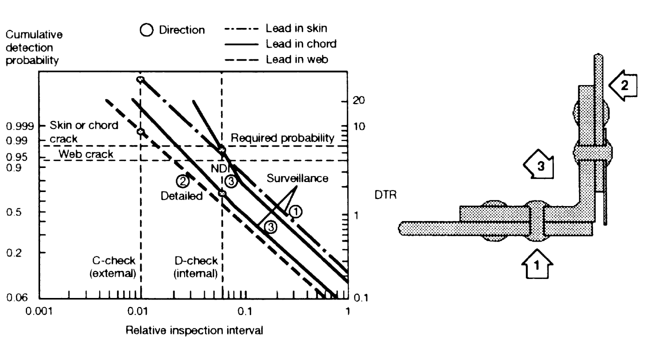


Figure 41 Cumulative detection probability – cracking pattern/variation inspection direction combinations

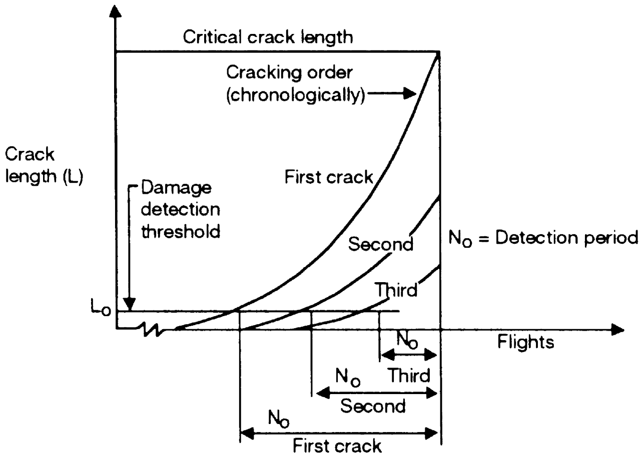


Figure 42 Multiple cracking in the fleet

damage in the fleet increases the probability of detecting at least one crack. The number of flights between occurrences in the fleet of fatigue damage to the same detail, ΔN, can be derived from actual fleet cracking statistics or from fleet usage and fatigue–life distribution. If the first damage is detectable at N_1 flights, the second damage will reach the same level of detectability at $N_1 + \Delta N$, and the third at $N_1 + 2\Delta N$, *Figure 42.*

Each successive crack occurring during the damage detection period, N_0 for the first crack, has a reduced interval for detection and a shorter crack length, *Figure 43*. Taking this into consideration, the cumulative probability of detection can be determined for each crack using the same procedure. From this the probability of crack detection in the fleet is calculated, using a given inspection method and frequency, as shown below:

$$P_3 = 1 - \prod_{i=1}^{m} \prod_{i=1}^{n} (1-\hat{P}_{3ij})$$

where $\hat{P}_{3ij}$ is the probability of detection during the ith inspection of the jth cracked airplane during the damage detection period N_0; m is the number of cracked airplanes; and n is the number of inspections performed on the jth cracked airplane.

For convenience an equivalent constant probability of detection for each inspection can be defined by

$$\bar{P}_3 = 1-(1-\hat{P}_3)\bar{N}/N_0$$

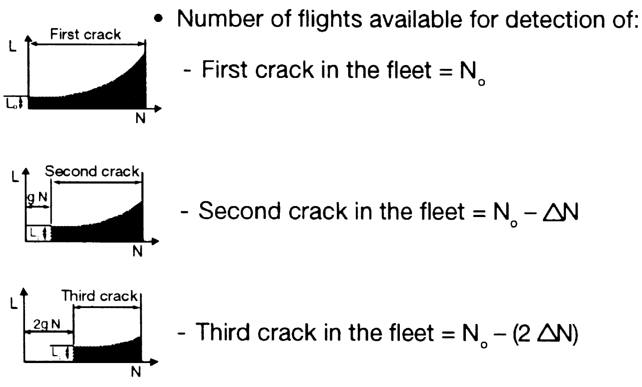


Figure 43 Multiple fleet cracking contributions to damage detection

Considering all levels of inspection in the fleet (A, B, C and D), the cumulative probability of damage detection is given by

$$P_D = 1 - \Pi(1 - P_{di})$$

where $P_D = P_1 \cdot P_2 \cdot P_3$, i = applicable inspections.

CONTINUING AIRWORTHINESS INITIATIVES

Continuing airworthiness concerns for aging jet transports has received attention over the last 15 years. Supplemental structural inspection programs were developed in the late 1970s to address fatigue cracking detection in airplanes designed to the fail-safe principles. These evaluations were performed in accordance with updated damage tolerance regulations to reflect the state-of-the-art in residual strength and crack growth analyses based on fracture mechanics principles. Damage at multiple sites was also addressed in terms of dependent damage size distributions in relation to assumed lead cracks in different structural members. Structural audits were performed in the mid 1980s to ascertain whether these supplemental inspection programs addressed independent multiple site damage in similar structural details subjected to similar stresses.

Boeing initiated aging fleet surveys by engineering teams in 1986 to gain a better understanding of the condition of structures and systems and to observe the effectiveness of corrosion prevention features and other corrosion control actions taken by the operators. Boeing, like other manufacturers, continually reviews reported service data and other first-hand information from customer airlines in order to promote safe and economic operation of the worldwide fleet. These surveys were primarily prompted by the projected upward trend in airplane age toward and beyond original design service objectives.

Extensive industry actions were initiated in 1988 to address aging fleet airworthiness concerns prompted by the explosive decompression of a 737 over Hawaii. Model-specific Structures Working Groups have demonstrated a cooperative determination over the last five year period to make the right things happen within and across models and throughout the industry. The achievements have been impressive in the accomplishing of results in five original tasks chartered by the Airworthiness Assurance Task Force, now known as the Airworthiness Assurance Working Group, *Figure 44*.

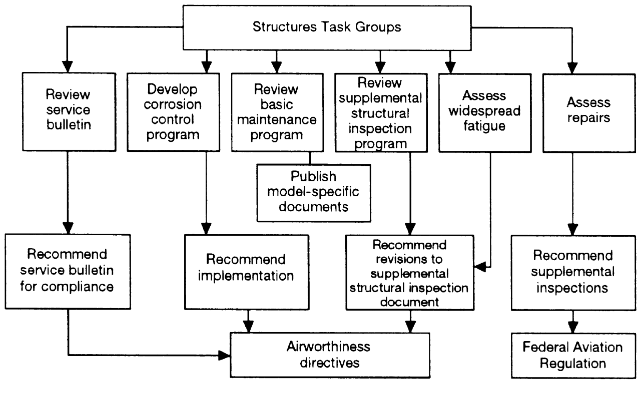


Figure 44 Continued airworthiness industry initiatives

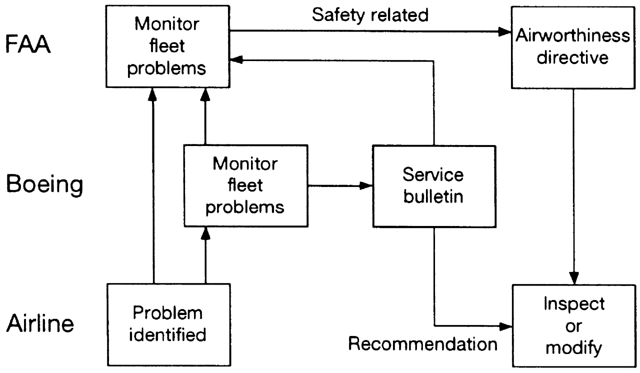


Figure 45 In-service problem actions

Service bulletin reviews and mandatory inspections

Continuing airworthiness of jet transport structures designed to the fail-safe principles has traditionally been ensured by inspection programs. In the event of known, specific fatigue cracking and/or corrosion problems, that if not detected and repaired had the potential to cause a significant degradation in airworthiness, the normal practice in the past was to introduce a service bulletin, *Figure 45*.

The net result of this process was to carry out inspections of all affected airplanes until damage was detected and then to perform the repair. Thus, continuing structural airworthiness was totally dependent on repetitive inspections. Aging airplane concerns prompted reassessment of the viability of indefinite repetitive inspections.

Aging fleet service bulletin summary documents were released in 1989 for each model formalizing Structures Working Group (SWG) recommendations for mandatory modifications or inspections, *Figure 46*.

It is important to note that cumulative service experience is incorporated in the design and reflected by less inspection/modification for later production units. In turn, these service experiences are incorporated in new models, often with orders of magnitude reduction in later modification efforts.

Corrosion prevention and control programs

While corrosion has always been recognized as a major factor in airplane maintenance, each airline has addressed it differently according to its operating environment and perceived needs. Manufacturers have published corrosion prevention manuals and guidelines

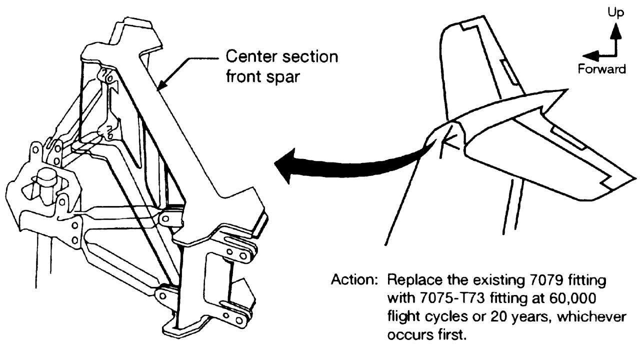


Figure 46 Mandatory service bulletin modification example for 727 horizontal stabilizer front spar center section with stress corrosion problems

to assist the operators, but until now there have never been mandatory corrosion control programs.

It became apparent that without effective corrosion control programs, the frequency and severity of corrosion were increasing with airplane age and, as such, corrosion was more likely to be associated with other forms of damage such as fatigue cracking. This, if allowed to continue, could lead to an unacceptable degradation of structural integrity, and in an extreme instance, the loss of an airplane.

The working groups have recognized the need for a universal baseline minimum corrosion control program for all airplanes to prevent corrosion from affecting airworthiness. Maximum commonality of approach within and between each manufacturer to ensure consistent and effective procedures throughout the world has been a key objective for the working groups. The program requirements apply to all airplanes that have reached or exceeded the specified implementation age threshold for each airplane area. The specific intervals and thresholds vary between models, but all programs follow the same basic philosophy.

> *The corrosion control and prevention program provides structural access and inspections of internal structure and structure hidden by fairings in a disciplined and consistent manner. While many operators may already have covered these areas in existing maintenance programs, the net effect has been an increased awareness for the value of Corrosion Prevention and Control Programs (CPCPs), Figure 47.*

There is general agreement in the airplane industry that corrosion prevention and control procedures are needed on all current in-production airplanes and for future generations of airplanes.

Supplemental fatigue inspection programs

Supplemental structural inspection documents were released between 1979 and 1983 for all aging Boeing jet transport models. Their purpose was to ensure continued operation of the aging fleet by timely detection of new fatigue damage locations. These documents have been updated on a regular basis to reflect service experience and operator inputs. In the light of current aging fleet concerns, these inspection programs were to ensure adequate protection of the aging fleet. The major focus of these reviews was:

- adequacy of the present fleet leader sampling;
- inclusion/deletion of principal structural elements.

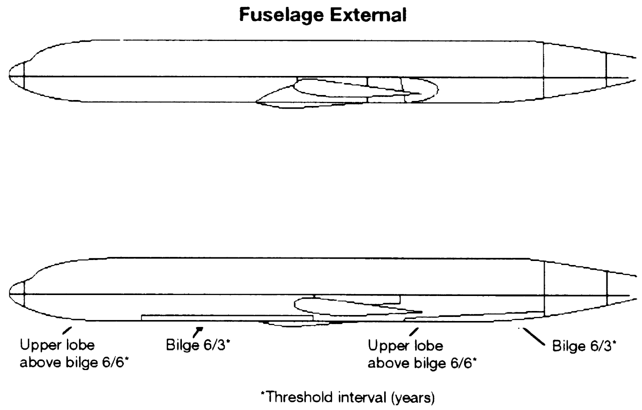


Figure 47 727 corrosion control program – example

Revisions to 707, 727, 737 and 747 SSIDs included changes to approximately 10 significant structural items for each model. Some PSEs were not included in the original SSID on the basis that damage would be obvious before safety was affected. A review of those items resulted in adding several items to the SSID, primarily some hidden wing structures previously deleted on the basis of fuel leaks to signify fatigue damage.

Thin gauge fuselage structure was not included in the initial SSIDs on the basis of test and service evidence that skin cracks would turn at frame locations and result in a safe decompression. Consideration of aging fleet damage in adjacent bays prompted coverage of thin gauge fuselage structure, 1.4 mm thick or less for models 727 and 737. The 747 fuselage skins were already included in the initial SSID because of thicker gauges.

Widespread fatigue damage

The present rules for airplane structural design have evolved from successful experience and lessons learned in service. As opposed to earlier commercial airplanes, the first generation of jet transports have not become technically obsolete before portions of the worldwide fleet have reached and exceeded original design service objectives. Dependent damage at multiple sites was recognized in revised damage tolerance regulations in the late 1970s. Independent damage in similar details subjected to similar stresses has long been recognized as a potential continuing airworthiness problem. Fuselage structure is typically more susceptible to WFD because of numerous similar details subjected to pressure cycle loads with moderate flight-by-flight variations.

An international task group was chartered in 1990 composed of manufacturers and operators to investigate and propose appropriate actions to address WFD concerns by timely discovery of any aging fleet problems. The Structural Audit and Evaluation Task Group (SAETG) performed an extensive data collection and analysis activity to determine candidate options that have applicability to the identified concerns. While all the adopted SAETG options are valid to some extent in predicting the onset and location of multiple site damage and multiple element damage, none of the options provides foolproof safeguards. Ultimately conscientious and reliable inspections of the airplane structure are the key to confidence in ensuring continuing airworthiness.

Structural repair assessments

Inevitably airplanes accumulate repairs. For each model, Structural Repair Manuals (SRMs) assist the operator in ensuring that typical repair action maintains the airframe structural integrity. Other larger repairs are handled by individually prepared and approved engineering drawings. Traditionally, these repairs have primarily focused on static strength and fail-safe aspects of the structure after repair, with commonsense attention to durability considerations. For several years, however, there has been an additional emphasis on the need for structures to be damage tolerant. Achieving damage tolerance demands knowledge of potentially critical structural elements, an understanding of damage growth and critical size, and an inspection program to ensure timely detection.

Repairs may affect damage tolerance in different ways. An external patch on the fuselage can hide the primary structure to an extent that supplemental inspections may be required, *Figure 48*. Other repairs may interfere with obvious means of detecting damage such as skin repairs on the lower wing with sealant that prevents fuel leakage. Repairs located in low stress areas with slow crack growth rate can have damage tolerance provided by existing maintenance. Several Structures Task Groups (STGs), manufacturer and AAWG subcommittee meetings were held during 1990 and 1991. Industry concern for the direction of these activities resulted in formation of the Repair Assessment Task Group (RATG). The thrust of these activities has been focused on updates of the SRMs and model-specific repair assessment documents approved by the FAA.

Model-specific SRMs are being updated by the manufacturers to reflect damage tolerance repair considerations. The goal is to complete these with initial emphasis on fuselage pressure boundary structures. Separate model-specific documents outside the SRMs have been prepared by Boeing for four aging airplane models. The uniformity/similarity of these repair assessment procedures are important to simplify operator workload. The manufacturers have spent considerable time over the last three years to achieve commonality of the repair assessment process.

Thresholds for assessments of existing repairs are based on fatigue damage considerations and specified for each model in flight cycles. While threshold recommendations vary between manufacturers, they are typically 75% of design service objectives and range from 15,000 to 60,000 flight cycles for long and short haul airplanes respectively. Guidance material documents for each model provide a list of structures for which repair assessments are required. *Figure 49* shows one example of model-specific Boeing repair assessment guidelines for inspection interval selections.

CONCLUSIONS

Timely damage detection is the key element in ensuring structural damage tolerance. Extensive testing, analysis and service records have been employed to provide new technology and procedures that meet damage tolerance regulations for new and aging jet transports. Damage detection assessments for environmental, accidental and fatigue damage sources should reflect a rational coupling between structural characteristics and maintenance program parameters.

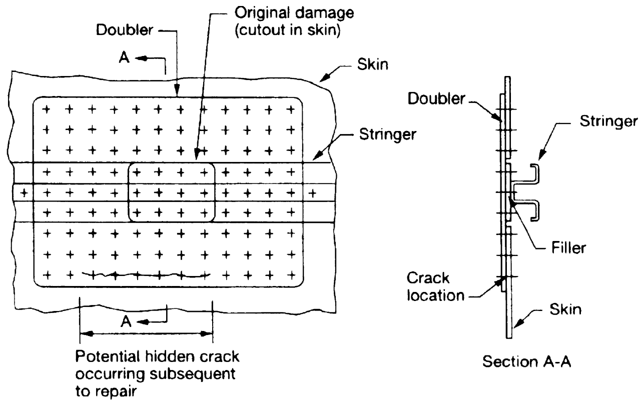
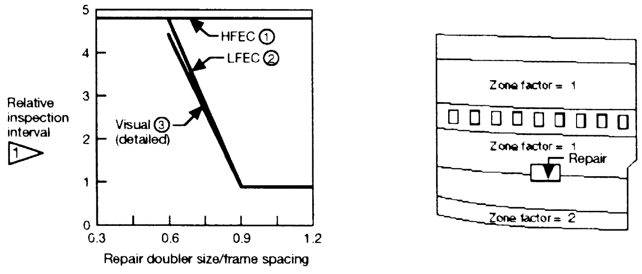


Figure 48 Typical fuselage external skin repair



1 Multiply intervals as required by the appropriate zone factor.

Figure 49 Inspection options for fuselage skin repairs requiring supplemental inspections

Damage tolerance verification includes assessments of allowable damage, damage detection periods for different cracking patterns, and inspection program efficiency. Traditional fracture mechanics research and applications tend to focus on structural characteristics, and the practising engineer is often encouraged to recommend inspections based on simple factoring of damage detection periods. This practice tends to result in variable and unknown fatigue damage detection reliability levels. This review has provided some examples of a more rational approach to development of flexible maintenance programs without compromising safety.

Continuing airworthiness challenges for aging airplanes have been addressed over the last 15 years. Aging fleet concerns have resulted in joint industry, operator and airworthiness authority actions. Mandatory modifications in lieu of continued inspections as well as mandated corrosion prevention programs are examples of prudent actions to permit continued safe operation of jet transports until their retirement from service for economic reasons. Structural repair assessment guidelines have also been established to ensure damage detection by supplemental inspections for some categories of repair.

Additional challenges of local damage tolerance capabilities have been addressed in recent years to establish positive initiatives to control widespread fatigue damage effects on continuing airworthiness.

The design, construction, operation and maintenance of airplanes take place in a changing and dynamic arena, with new technology needs and new players. The structural safety system may never be perfect, but it has produced an enviable record. Damage detection is a key element of damage tolerance assurance. Vigilance must be exercised to maintain focus on prudent inspections and preventative actions for environmental, accidental and fatigue damage.

ACKNOWLEDGEMENTS

The author would like to acknowledge the graphics and publications support from Mr W.J. Brewer from the Structures Engineering organization of Boeing Commercial Airplane Group, and Mr Floyd Stewart and staff from Boeing Information and Support Services, Graphic and Media Design Resources.

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