PRINCIPLES OF ACHIEVING DAMAGE TOLERANCE WITH FLEXIBLE MAINTENANCE PROGRAMS FOR NEW AND AGING AIRCRAFT

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Abstract

Boeing has developed new technology and procedures for determining flexible structural maintenance programs that meet damage tolerance regulations. Rating systems, based on past maintenance, are used to develop inspection programs to ensure timely detection of structural damage from environmental deterioration (EDR), accident (ADR), or fatigue (DTR).

The inspection program consists of two phases. Initially, the program is based on evaluations for detecting corrosion, stress corrosion, and accidental damage using the EDR and ADR systems. As the fleet matures, inspection tasks for detecting fatigue damage, based on the DTR evaluations, are incorporated into the program.

I. Introduction

Commercial jet transport structures have been designed and certified according to a fail-safe philosophy for over 20 years. Airframes thus have the ability to sustain maximum anticipated or fail-safe loads with significant structural damage; for example, wing structures were designed to carry the full design-limit load with a skin crack extending across two stringer bays. Experience has shown that this design philosophy has generally allowed sufficient opportunities for timely detection of structural damage. However, actual cracking patterns are frequently different, particularly when fatigue is the primary damage source. Structure adjacent to a primary fatigue crack will itself generally contain a number of secondary cracks. Such multiple-site damage can significantly reduce the residual strength and crack-arresting capability of the structure. This was recognized in the recent revision of the Federal regulations for damage tolerance (FAR 25.571), with which Boeing models 757 and 767 comply (fig. 1).

ANALYSIS	OLD FAR 25.571 (PRE-1978)	NEW 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

Figure 1. Damage Tolerance Regulation Comparison

The term "damage tolerance" has replaced "fail-safe" to reflect another major change in the regulations. In addition to a high residual strength, or fail-safe capability, there must be a high probability of detecting damage before strength is reduced below regulatory limits (fig. 2). Effectively, this means that the initial structural inspection program and procedures for changing the program have become part of the type certification of the airplane.

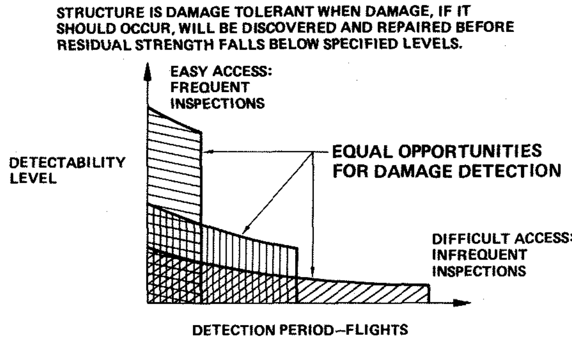


Figure 2. Opportunities for Damage Detection

Sources of Structural Damage

Three principal forms of structural damage must be evaluated to achieve a balanced structural inspection program (fig. 3): environmental deterioration (ED), accidental damage (AD), and fatigue damage (FD).

DAMAGE PHASE	PRINCIPAL PARAMETERS CONTROLLING GIVEN SOURCE OF DAMAGE AND DAMAGE PHASE		
	FATIGUE	ENVIRONMENTAL DETERIORATION	ACCIDENTAL
INITIATION	• QUALITY (DFR) • CYCLIC STRESS • OPERATING ENVIRONMENT • FLIGHT CYCLES/HOURS	• CORROSION –OPERATING ENVIRONMENT –PROTECTIVE SYSTEM • STRESS CORROSION –MATERIAL SENSITIVITY –LEVEL OF SUSTAINED TENSILE STRESS	• RANDOM DISCRETE EVENT FROM A CAUSE NOT NORMALLY ENCOUNTERED DURING FLEET OPERATIONS
GROWTH	• MATERIAL • GEOMETRY • CYCLIC STRESS • ENVIRONMENT • FLIGHT CYCLES/HOURS	• EXTENT OF CONDITIONS THAT CAUSED DAMAGE INITIATION • MAY RESULT IN SUBSEQUENT CRACK GROWTH IF NOT DETECTED AND REPAIRED	• MAY RESULT IN SUBSEQUENT CRACK GROWTH IF NOT DETECTED AND REPAIRED

Figure 3. Principal Damage Sources

Environmental Deterioration. 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. Accidental damage can also be considered in two categories. First, discrete-source or large-scale AD, such as that caused by a large bird strike or uncontained engine disintegration, involves special regulations. Such damage is considered obviously detectable, 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 AD and most forms of ED are random events that can occur at any time during the operational 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 as described in section II.

Fatigue Damage. Fatigue damage is characterized by the initiation of a crack, with subsequent propagation. It is a result of a continuous process whose effect is cumulative with respect to aircraft usage (measured in flights or flight-hours). Comprehensive fatigue-life, crack-growth and residual-strength evaluations are performed with standardized computer programs. 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-life objective without significant cracking. This does not preclude anticipated cracking before all aircraft reach the design-life objective. In a large fleet, some cracking may occur before the life goal is exceeded, even if structural fatigue life meets the economic 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 (fig. 4). 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.

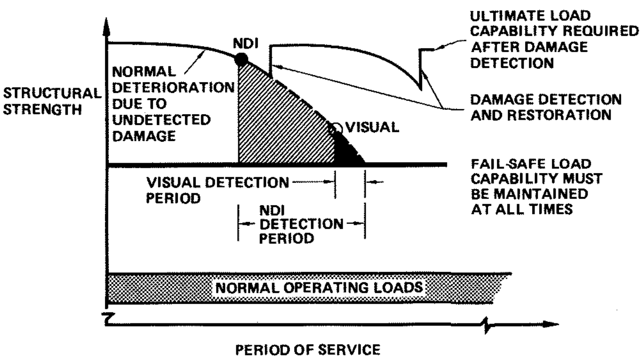


Figure 4. Strength Requirements for Damage-Tolerant Structure

Damage Thresholds

Environmental Deterioration and Accidental Damage. Environmental deterioration and accidental damage are random events that can occur at any time (fig. 5). Inspection requirements related to these damage sources apply to all aircraft in the fleet. The threshold for inspection is the first scheduled maintenance check interval corresponding to the repeat interval determined for the structure. For example, if the repeat inspection interval for a particular structural item is a C-check, the first inspection corresponds to the first C-check on each airplane.

Corrosion caused by breakdown of a protective surface in the presence of an adverse environment can vary significantly between operators. There can also be significant differences in corrosion initiation and rate of growth as a consequence of geographic location, type of cargo, and other factors. The most efficient way for each operator to determine its particular threshold is an age-exploration program. This generally involves inspecting selected structural details at a fixed repeat interval on a rotating portion of the fleet. Age-exploration allows an operator to gradually check difficult-to-access structure on all airplanes.

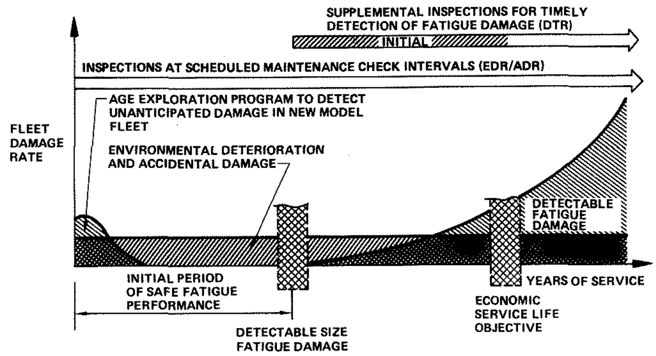


Figure 5. Damage and Inspection Program Phases in a Fleet of Aircraft

All operators are notified if any operator reports signs of structural distress. This generally results in full-fleet inspections and/or preventive repair or modification.

Fatigue Damage. Fatigue cracking can be anticipated in a large fleet of airplanes even when the structure meets the design objective. For example, consider a structure designed for 20 years of operation with 95% reliability. In a fleet of 500 airplanes, 475 can be expected to exceed 20 years and 200 exceed 40 years of service without cracking. Conversely, up to 25 airplanes may be cracked by the time the fleet has completed 20 years of service. More important, the first crack can occur as early as midway into the design life. Because cracking order is randomly distributed within the fleet, it is unlikely that the first airplane to reach midlife will be cracked. However, midlife appears to be a reasonable threshold for the most critical structure.

A variable threshold can be defined where routine inspections provide some opportunity for detecting FD. This will also make implementation of the supplemental inspections more manageable and avoid a sudden increase in maintenance tasks. Further details of this variable threshold are given in section II.

The rate of cracking of identical structural components in a fleet of aircraft is another parameter that can be predicted. This prediction, coupled with multiple inspections, significantly influences the probability of timely detection of fatigue damage, as described in section II.

Fatigue cracking that occurs earlier than anticipated is generally caused by an event or events not identified by the analysis or test. Examples are additional loads or higher loads than expected, locally higher stresses, or interaction of loads from various sources. In many cases, the unanticipated cracking is caused by a set of circumstances on only one or a few airplanes, such as a misdrilled hole. These types of cracking generally occur relatively early in the life of the airplane, and associated multiple-site cracking is unlikely, resulting in correspondingly higher residual strength and crack-stopping capability. This single-element cracking is similar to the cracking that may follow AD. Inspection requirements can therefore be the same as for AD.

Structural Categories

Airplane structure can be categorized to determine safety analysis requirements and corresponding maintenance considerations (fig. 6). The first breakdown is a determination of the item's function in relation to structural integrity. Any structural detail, element, or assembly judged significant because its failure reduces aircraft residual strength or results in loss of function is

Structural Category			Safety Analysis Requirements		Structural Maintenance Considerations		
			Technique of Assuring Safety	Technology Control Method	Primary Purpose	Requirements	Planning Basis
Other Structure	Damage-Tolerant Design	① Secondary Structure	Design for loss of component or safe separation	• Continued safe flight	Economics	Scheduled maintenance tasks for detection and repair or prevention of damage	Previous experience when similar to existing structure Manufacturer's recommendations when new material and/or concept
Structurally Significant Items		② Damage obvious or malfunction evident	Adequate residual strength with extensive damage—obvious during walkaround or indicated by malfunction	• Residual strength			
		③ Damage detection by planned inspection	Inspection program matched to structural characteristics	• Residual strength • Crack growth • Inspection program	Safety	Adequate inspections for timely detection and repair or prevention of damage	Manufacturer controlled rating systems • Accidental damage[a] • Environmental deterioration[a] • Fatigue damage[b]
	Safe-Life Design	④ Safe life	Conservative fatigue life	• Fatigue	Safety	Detection and repair or prevention of accidental damage and corrosion	Manufacturer controlled rating systems

[a]Applicable throughout operational life.
[b]Applicable after aircraft reaches threshold for detectable size fatigue damage.

Figure 6. Structural Analysis Requirements and Maintenance Considerations

classified as a structural significant item (SSI). Included in this classification is a structure whose failure could cause loss of a safety-critical system, excessive deformation, or flutter. Items not in this category are classed as secondary or other structure.

There are two design principles for obtaining structural operating safety. These are "damage tolerance" and "safe life." Damage tolerance relies on some means of detecting damage before airplane safety is jeopardized. This is the preferred design principle whenever practical. A safe-life principle is used where there is little or no chance of detecting damage before residual strength is reduced below acceptable limits. A conservative FD threshold is used to limit the service life. On modern commercial jet transports, this design concept is generally limited to high-strength steel landing-gear components for which the critical crack lengths are small.

For "other structure," safety is ensured by demonstrating that a flight can be completed safely after the component has separated from the aircraft. Structural maintenance is dictated by the economic consequences of major damage or loss of the component compared to those of an inspection program required to find damage early. This is the most desirable category for structural design, because failure to detect damage will not affect flight safety.

The second most desirable category is damage-tolerant design where damage is obvious or malfunction evident before reaching critical size. Examples of this are significant fuel tank leakage or controlled cabin depressurization. In this category, safety is ensured by providing adequate residual strength with extensive damage that is obvious during walk-around or functioning checks to personnel whose primary responsibility may not be structural inspection. Economics again dictates structural maintenance where it may be desirable to detect damage early.

Most airplane structure falls into a third category, in which structural integrity is maintained by timely damage detection in a planned inspection program. Inspection program requirements are matched to structural characteristics that include residual strength, crack growth rate, and damage detectability. Structural maintenance programs are dictated by safety requirements but can be upgraded for economic reasons. Regulations now require proof of adequate inspections for timely detection and repair of damage throughout the operational life of the airplane. To achieve this, rating systems are used to evaluate inspection requirements for the three principal forms of damage. The systems used by the The Boeing Company are outlined in section II. Two of these systems are also used in the fourth structural category, safe life. Again, safety is the primary maintenance consideration. Structural maintenance must be used to detect or prevent corrosion or AD, both of which may reduce fatigue life.

II. Structural Maintenance Program Development

The primary objective of a structural maintenance program is to maintain an acceptable level of structural airworthiness throughout the operational life of the airplane, in the most economical manner possible. In some cases the desire to limit structural damage to a reparable or economically acceptable level may dictate a program more stringent than required by safety. However, safety requirements must always be satisfied, but economic considerations are optional. Guidelines for achieving the primary objective are given in the Air Transport Association of America document, "Airline/Manufacturer Maintenance Program Planning Document, MSG-3".[1] This document, which was developed by committees representing both airlines and manufacturers, has been approved by the Federal Aviation Administration (FAA) as a means of complying with the revised damage-tolerance regulations of FAR 25.571. (MSG-3 was the basis for development of the structural maintenance programs for the 757 and 767.)

The MSG-3 logic depends on the use of rating systems for each of the three major forms of damage (fig. 7). Unlike MSG-1, used for the 747, and MSG-2, used for the DC-10 and L-1011, MSG-3 has no specific numerical rating system.[2][3] Responsibility for developing rating systems has been assigned to the individual maintenance program review teams. The rating schemes will be incorporated, as required, in appendixes to MSG-3, such as appendix II, "Structural Maintenance Planning for Boeing Commercial Jet Transports."

The principal considerations used in developing the three rating systems are --

a. Devise a structural inspection program that utilizes available maintenance resources most efficiently to ensure timely detection or prevention of damage caused by environmental deterioration, accident, or fatigue.
b. Combine damage-tolerance evaluations with service experience and engineering judgment.
c. Allow an individual operator the flexibility to change programs without complex procedures requiring specialized knowledge.
d. Maintain, as far as practical, existing procedures for approving changes to the maintenance program.
e. Reflect continuing service experience.

The rating systems for ED and AD apply to all aircraft in the fleet throughout their operational life. Actual service experience will dictate changes in the inspection programs for these types of damage. Conversely, the rating system for fatigue damage applies only to a maturing fleet--to aircraft exceeding the threshold of detectable damage. Fatigue damage chronologically is most likely to occur in airplanes with the most flight cycles. Therefore, a fleet-leader sampling program can be used when additional inspections are required to detect this type of damage.

Detection requirements for the three principal forms of damage must be evaluated before type certification of the aircraft. However, the initial inspection program is based primarily on detection requirements for ED and AD. Therefore, the structural maintenance program development has two distinct parts, the initial program and the mature airplane program.

Initial Program

Structural maintenance programs are developed by a top-down approach with a zonal basis (fig. 8). Each aircraft model is subdivided into major zones (300 empennage), submajor zones (330/340 horizontal stabilizer), and zones (334/344 front spar to rear spar) (fig. 9). Each zone can be subdivided into convenient locations (such as upper surface) for grouping SSI's, which can in turn be considered internally or externally.

A preliminary maintenance plan is developed for all SSI's or parts of SSI's in the location, based on the ED and AD requirements. Development of this preliminary plan requires both operator and manufacturer input in the decision process, as described under the ED and AD rating systems.

Other locations and other zones are similarly considered, resulting in a target scheduled maintenance plan for each submajor zone. The same procedure is used for other sub-major and major zones, resulting in an aircraft structural maintenance plan that must be approved by the FAA. All supporting data used in these evaluations must be documented for use during the maintenance review board (MRB) process and type certification of the aircraft.

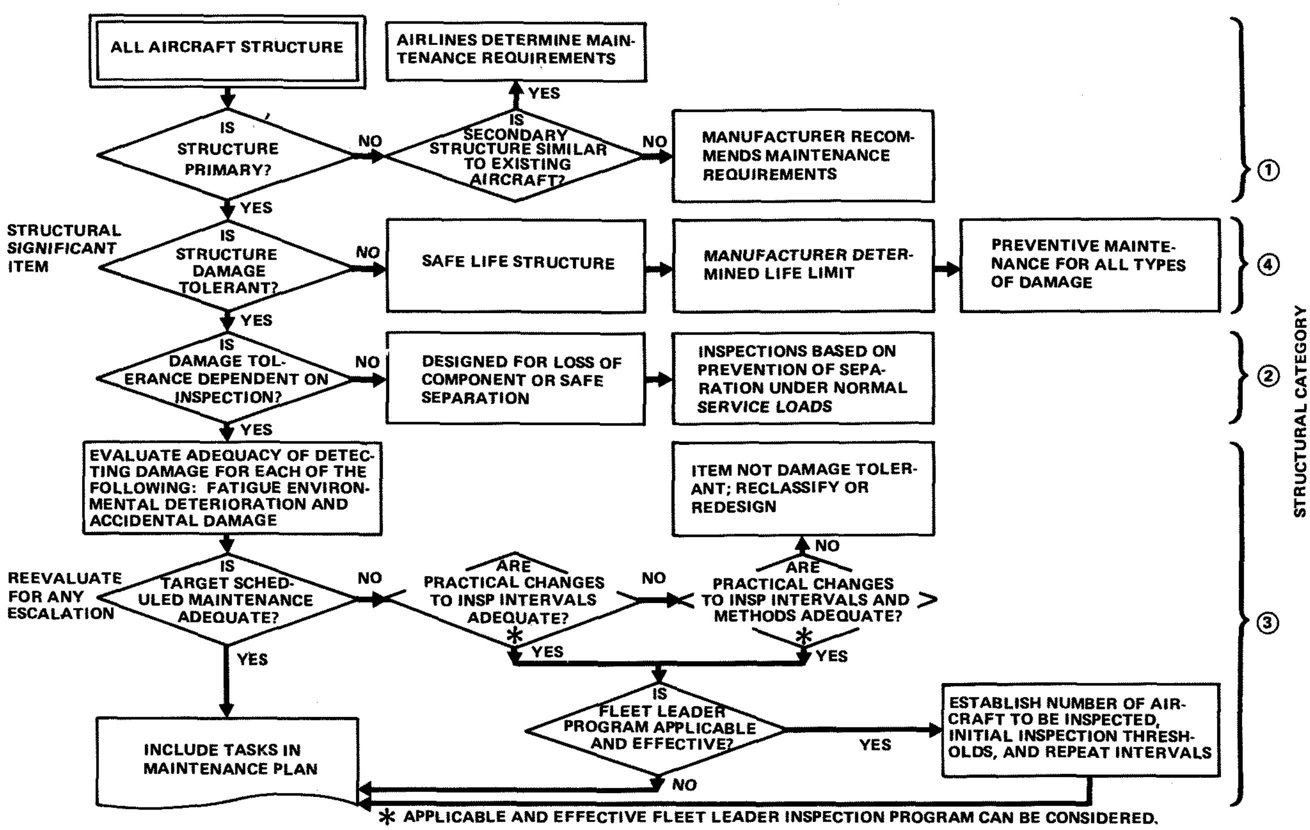


Figure 7. Maintenance Decision Process

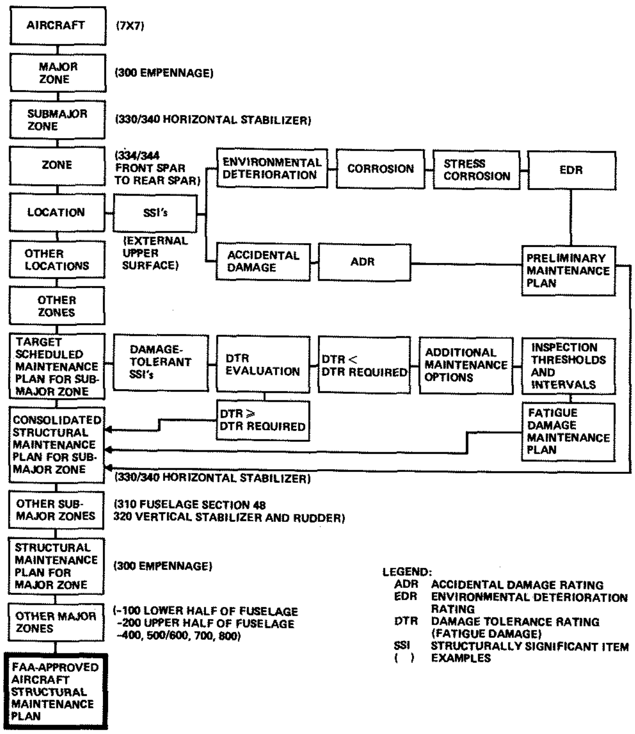


Figure 8. Maintenance Planning Procedure

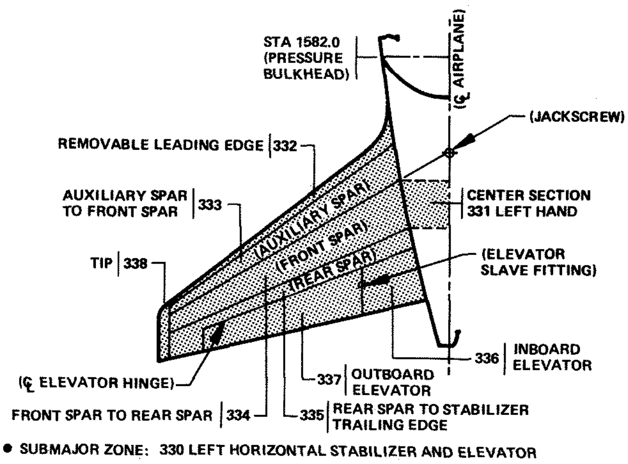


Figure 9. 767 Zone Diagram Example

Corrosion, stress corrosion, and accidental damage defy precise analysis. Therefore, evaluations rely heavily on related service experience and engineering judgment of the relative criticality of the structure to damage. Simple rating systems are used to combine the various parameters used in the evaluations. These provide the reference standard for the initial program and can be referred to for future program development.

Environmental Deterioration Rating System. In the environmental deterioration rating (EDR) system (fig. 10), requirements are based on susceptibility to and timely detection of both corrosion and stress corrosion, considered independently. Susceptibility to corrosion is assessed on the basis of probable exposure to an adverse environment and adequacy of the protective system. Material characteristics, coupled with the likelihood of sustained tensile stress that may be caused by such things as improper shimming, are used to assess susceptibility to stress

• EDR = SUSCEPTIBILITY INDEX + TIMELY DETECTION INDEX

SUSCEPTIBILITY INDEX		EXPOSURE TO ADVERSE ENVIRONMENT		
		PROBABLE	POSSIBLE	UNLIKELY
ENVIRONMENTAL PROTECTION	STANDARD	0	1	2
	PROVEN/ IMPROVED	1	2	3
	SPECIAL ATTENTION	2	3	4

TIMELY DETECTION INDEX		SENSITIVITY TO DAMAGE SIZE		
		HIGH	MEDIUM	LOW
VISIBILITY OF THE SSI FOR INSPECTION DURING SCHEDULED MAINTENANCE CHECKS	POOR	0	1	2
	ADEQUATE	1	2	3
	GOOD	2	3	4

Figure 10. Environmental Deterioration Rating (EDR) System

corrosion. Service experience for the same or similar structure is a primary ingredient.

On the susceptibility index, the term "standard" is used when the protective system is the same as, or similar to, that of previous airplanes and some direct or related service problems have occurred. "Proven" or "improved" is used when the system has had no reported service problems or an improvement has been made to rectify a known problem. "Special attention" is used when significant improvements have been made compared to previous airplanes.

Timely detection is determined by sensitivity to relative size of damage and visibility of the structure for inspection. Suitable access must be provided for the required level of visual inspection during scheduled maintenance. Manufacturer and operator experience is a key ingredient for this type of evaluation.

Figure 10 shows the simple numerical rating system used to combine the above independent assessments in a relative manner. The lowest rating values indicate the structure requiring the most stringent inspections during maintenance visits.

Accidental Damage Rating System. Maintenance requirements are based on an evaluation of susceptibility to, residual strength after, and timely detection of AD; figure 11 shows the accidental damage rating (ADR) system. Susceptibility is determined by the likelihood of the structure sustaining AD. Residual strength is based on the likely size of AD relative to critical damage size.

• ADR = SUSCEPTIBILITY INDEX + TIMELY DETECTION INDEX

SUSCEPTIBILITY AND RESIDUAL STRENGTH INDEX		LIKELIHOOD OF ACCIDENTAL DAMAGE		
		PROBABLE	POSSIBLE	UNLIKELY
ESTIMATED RESIDUAL STRENGTH AFTER ACCIDENTAL DAMAGE	LOW	0	1	2
	MEDIUM	1	2	3
	HIGH	2	3	4

TIMELY DETECTION INDEX		SENSITIVITY TO DAMAGE GROWTH		
		HIGH	MEDIUM	LOW
VISIBILITY OF THE SSI FOR INSPECTION DURING SCHEDULED MAINTENANCE CHECKS	POOR	0	1	2
	ADEQUATE	1	2	3
	GOOD	2	3	4

Figure 11. Accidental Damage Rating (ADR) System

Timely detection is based on the rate of growth after AD and the visibility of the structure to inspection. Suitable access must be provided for the required level of visual inspection during scheduled maintenance. As with the EDR, a simple numerical rating system is used to combine the individual assessments.

Some of the parameters used to determine the EDR and the ADR are derived on essentially the same basis. Many decisions used to determine these ratings are based on previous experience. In some cases, operators have the background knowledge for the assessments and in other cases it is the manufacturer who has that knowledge. Although each decision will involve inputs from both, the primary responsibility for determining the relative values is shown in figure 12. The key considerations are for SSI's in general. Some types of structure require special treatment because of unusual circumstances. In all cases, specialists are consulted when additional clarification on relative changes from past practices is required. Structure is inspected externally more frequently than internally. Therefore, when assessing sensitivity to damage size or growth, external damage is assumed to be associated with significant internal damage. Conversely, internal damage is assumed to have no associated significant external damage.

RATING CATEGORY	APPLICATION		PRIMARY RESPONSIBILITY		KEY CONSIDERATIONS
	EDR	ADR	OPERATOR	BOEING	
VISIBILITY	●	●	●		VISIBILITY FOR INSPECTION AFTER ACCESS
SENSITIVITY TO DAMAGE SIZE OR GROWTH	●	●		●	• RELATIVE SENSITIVITY WITHIN ZONE CONSIDERED • EXTERNAL: MULTIPLE ELEMENT DAMAGE • INTERNAL: SINGLE ELEMENT DAMAGE
ENVIRONMENTAL PROTECTION	●		●	●	COMPARISON WITH PREVIOUS PROTECTION SYSTEMS AND RECENT SERVICE HISTORY
EXPOSURE TO ADVERSE ENVIRONMENT	●		●		CORROSION EXPERIENCE IN SAME ZONE
				●	MATERIAL SUSCEPTIBILITY TO STRESS CORROSION AND POTENTIAL FOR PRELOAD
LIKELIHOOD OF ACCIDENTAL DAMAGE		●	●		OPERATOR EXPERIENCE IN THE SAME ZONE
STRENGTH AFTER ACCIDENTAL DAMAGE		●		●	LIKELY SIZE OF DAMAGE RELATIVE TO CRITICAL DAMAGE SIZE

Figure 12. Summary of Key Considerations and Responsibilities for EDR and ADR Evaluations

Use of EDR and ADR Systems. The worksheet shown in figure 13 is used to determine the EDR's and ADR's of all SSI's in the same general location. Because both corrosion and stress corrosion contribute to the EDR, each SSI will have three ratings. The remarks section on the worksheet is used to note, when necessary, information pertinent to the decisions. The completed worksheet provides a convenient overview of ratings so that appropriate inspection tasks can be defined for the SSI's.

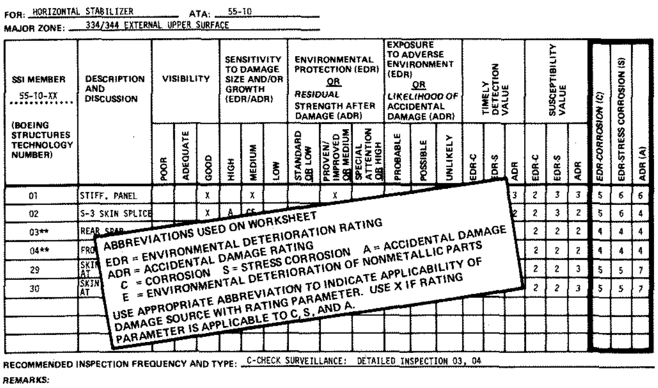


Figure 13. Environmental Deterioration and Accidental Damage Rating Work Sheet

Because the rating assessments pertain to a given zone, no specific rating-versus-inspection interval can be established. Each zone will have an acceptable service-proven level for external or internal surveillance. For example, external inspections at C-check intervals (or multiples of C-check, typically 2C) and internal at 4C are used in many locations. These typical surveillance levels, which will generally be defined by the operators, are established for structure in the midportion of the rating scale (fig. 14). A rating of zero is unacceptable, and added protection or redesign is required. The lowest acceptable rating, 1, generally corresponds to the minimum interval at which operators are willing to inspect a few critical details in the zone. Accessibility of these details is a prime consideration.

RATING	GROUND RULES FOR ESTABLISHING STRUCTURAL INSPECTION INTERVALS.
1	LOWEST PRACTICAL INTERVAL FOR INSPECTING A FEW CRITICAL SSI's IN THE ZONE CONSIDERED.
2	INTERMEDIATE INTERVALS EQUALLY SPACED BETWEEN INTERVALS ESTABLISHED FOR 1 AND 4.
3	
4	SERVICE-PROVEN ACCEPTABLE INTERVALS FOR EXTERNAL OR INTERNAL SURVEILLANCE OF THE ZONE CONSIDERED.
5	INTERMEDIATE INTERVALS EQUALLY SPACED BETWEEN INTERVALS ESTABLISHED FOR 4 AND 7/8.
6	
7	MAXIMUM INTERVAL CONSIDERED ADEQUATE FOR DETECTING DAMAGE FROM UNFORESEEN CIRCUMSTANCES. INTERVALS ARE GENERALLY BASED ON ECONOMIC CONSIDERATIONS FOR ACCESSIBILITY AND REPAIR. AN AGE EXPLORATION PROGRAM IS USED FOR INTERNAL STRUCTURE WITH DIFFICULT ACCESS.
8	

Figure 14. Relationship Between ED/AD Ratings and Inspection Intervals

To account for damage from unforeseen circumstances, a maximum interval for general surveillance should be determined for each zone. These intervals are generally quite short for a new airplane model until experience is gained in the fleet.

On the new airplane models, access has generally been provided to all internal areas where previous experience has shown structural damage may occur. In other internal areas to which access is difficult, an age-exploration program is normally used; that is, at the maximum interval prescribed for internal inspections, each operator will inspect some part of his fleet on a rotational basis. The sample sizes used for age exploration are generally 20% for tension-loaded structure and 10% for compression-loaded structure. At the first sign of distress, the internal inspection area is increased to find the extent of damage. This is followed by full-fleet inspections and/or preventive action.

Inspection Levels and Methods. The possible choices for routine inspection levels and methods are given in MSG-3, section 2.4.5.1, and described in figure 15. The initial structural inspection program is based on the use of these choices during applicable scheduled maintenance checks.

Ground-level observation, made by personnel whose primary function may not be structural inspection, frequently finds defects such as fuel leaks. This kind of observation is an essential part of the total capability for timely detection of damage in the fleet and is part of the routine structural maintenance plan. Other inspections by qualified personnel are conducted less frequently.

INSPECTION METHOD	DESCRIPTION (BOEING)
WALKAROUND	OBSERVATIONS FROM THE GROUND TO DETECT OBVIOUS DISCREPANCIES SUCH AS FUEL LEAKS (SEE CATEGORY 2 STRUCTURE)
GENERAL VISUAL	VISUAL CHECK OF EXPOSED AREAS OF WING LOWER SURFACE, LOWER FUSELAGE, DOORS AND DOOR CUTOUTS, AND LANDING-GEAR BAYS
SURVEILLANCE	VISUAL EXAMINATION OF DEFINED INTERNAL OR EXTERNAL STRUCTURAL AREAS FROM A DISTANCE CONSIDERED NECESSARY TO CARRY OUT AN ADEQUATE CHECK. EXTERNAL INCLUDES STRUCTURE VISIBLE THROUGH QUICK-OPENING ACCESS PANELS OR DOORS. INTERNAL APPLIES TO OBSCURED STRUCTURE REQUIRING REMOVAL OF FILLETS, FAIRINGS, ACCESS PANELS OR DOORS, ETC., FOR VISIBILITY [1]
DETAILED	CLOSE INTENSIVE VISUAL INSPECTIONS OF HIGHLY DEFINED STRUCTURAL DETAILS OR LOCATIONS SEARCHING FOR EVIDENCE OF STRUCTURAL IRREGULARITY [1]
SPECIAL	INSPECTIONS OF SPECIFIC LOCATIONS OR HIDDEN DETAILS [2] USING SPECIFIED NONDESTRUCTIVE INSPECTION (NDI) PROCEDURES. ALSO USED FOR INTENSIVE INSPECTION OF DETAILS WITH A KNOWN HISTORY OF SERVICE DISCREPANCIES

[1] USING ADEQUATE LIGHTING AND WHERE NECESSARY, INSPECTION AIDS SUCH AS MIRRORS, HAND LENSES, ETC. SURFACE CLEANING AND ACCESS PROCEDURES MAY BE REQUIRED TO GAIN PROXIMITY.

[2] DETAILS WHERE INTERNAL OR EXTERNAL VISUAL INSPECTIONS DO NOT PROVIDE ADEQUATE OPPORTUNITY FOR TIMELY DETECTION OF DAMAGE.

Figure 15. Structural Inspection Methods

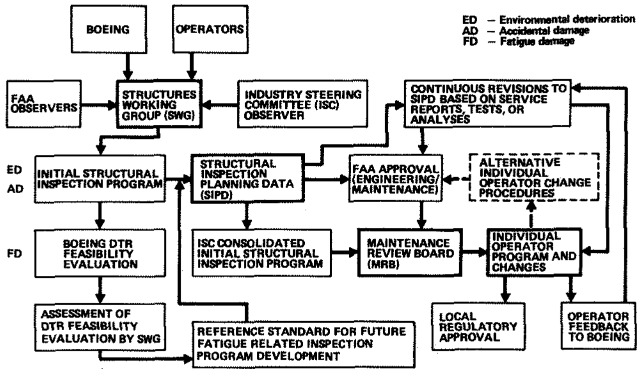


Figure 16. Development and Approval of Initial Inspection Program and Change Procedure

However, under special circumstances, any inspection method may be used at any frequency if operators deem such an inspection feasible.

Initial Structural Maintenance Plan. The initial structural maintenance plan for a new airplane model is developed by overlaying the tasks from the corrosion, stress corrosion, and AD evaluations. The tasks are based on the most critical requirements for each SSI or part of SSI considered externally or internally within a given zone. The resulting maintenance plan provides the minimum maintenance for ensuring continued structural airworthiness.

The total maintenance plan includes many other activities, such as systems servicing or checking. Access to areas for nonstructural tasks may in some cases provide additional opportunities for structural inspection.

The initiation of corrosion or stress corrosion is generally a function of calendar time. In both cases, it is possible for damage to occur with few or no flight operations. Therefore, inspection for timely detection of this type of damage occurs at specified calendar intervals. Fatigue crack growth following any form of damage initiation is a result of variations of cyclic stress. In most cases, growth is caused principally by the major ground-air-ground load variation occurring once per flight. Flight cycles are therefore used as the basis for determining the frequency of inspection for fatigue crack growth. The combination of calendar and flight cycle determinations results in a double limitation on the frequency of structural inspection. For example, the initial 757 and 767 structural inspection programs were developed with a C-check frequency of 3,000 flight cycles or 15 months, whichever comes first.

The initial structural maintenance plan is developed by a joint operator and Boeing structures working group (SWG) (fig. 16). Representatives from the FAA and other regulatory agencies are invited to attend the meetings as observers to gain a more comprehensive understanding of the procedures and decisions used by the SWG before it submits the program for approval. Similarly, an observer from the industry steering committee (ISC) monitors progress, checks that the procedures follow MSG-3 guidelines, and correlates development of the structural program with other maintenance activities.

The EDR and ADR systems are used by the SWG to evaluate the structural items in each zone. Results are combined with an assessment of current maintenance practice in the same zone to develop initial inspection intervals and tasks. The resulting inspection program will indicate structure within each zone requiring special attention. Structural descriptions, including material and corrosion protection, are included with the EDR and ADR worksheets in a structural inspection planning data (SIPD) document.

Boeing evaluates the adequacy of the initial structural maintenance program for timely detection of FD with a damage tolerance rating (DTR) system. (This procedure is described under "Mature Airplane Program.") If the initial program is inadequate, various additional inspection options are evaluated. These evaluations are conducted to show the feasibility of the inspection options only. Typical inspection options considered are:

a. More intensive visual inspection.
b. Increased frequency of inspection.
c. Use of various nondestructive inspection (NDI) procedures, such as ultrasonic or low-frequency eddy current.
d. Fleet-leader sampling program.
e. Any combination of the above.

Actual detectability standards, inspection tasks, repeat intervals, and other factors will be determined before they are required in the mature airplane program.

A supplemental inspection program based on DTR feasibility evaluations by Boeing is presented to the SWG, which determines which inspection options, if any, are practical. If no options are considered feasible, some redesign may be necessary to improve inspectability or the structure must be reclassified as safe life. Boeing uses the SWG's decisions as a reference standard for future fatigue-related inspection program development. All pertinent information is included in the SIPD document.

The most stringent inspection requirements from three independent damage-detection assessments (corrosion, stress corrosion, and AD) are used to determine the initial structural inspection program. This program is reviewed by the ISC and combined with inspection assessments for systems and power plant in a zonal review. The combined maintenance plan is submitted by the ISC to the MRB for approval. The requirements in the MRB document are also included in the maintenance planning document (MPD) published for each model by the manufacturer. Each operator uses the guidelines in these documents to develop a maintenance program to meet its specific environmental conditions, route structure, and scheduling requirements. In the United States, local FAA principal maintenance inspectors (PMI) approve each individual operator's program, before a new model is introduced into service, and any subsequent changes.

A key element in maintaining disciplined control of the total fleet maintenance program is operator feedback to Boeing. Information is required about inspection completions as well as about discrepancies found. This information and any new test or analysis results are used to continually update the SIPD document. The MPD may then be revised to reflect the changes after they are approved. Individual operators can also use the revised SIPD document to support changes to their own programs.

Program Escalation. The initial frequency for a new airplane inspection program is based on previous experience with similar models. An early age-exploration program is used in conjunction with a full-scale airplane fatigue test to search for unanticipated damage in the new model. Once this initial period has passed, the inspection program can gradually be escalated based upon operator experience.

Each operator's inspection program is monitored by its PMI's and reports and findings are assessed before any escalation is approved. The information given on the EDR and ADR worksheets provides additional background for these assessments.

The variation of U.S. fleet average C-check interval with year is shown in figure 17. Considered in terms of hours, there is a reasonable correlation between the different models, with the latest model 747 having the highest frequency. This changes completely when the repeat frequency is considered in terms of flight cycles (fig. 18). The procedure for escalating inspection frequency has been established for many years and will continue to be used for the 757 and 767 fleets.

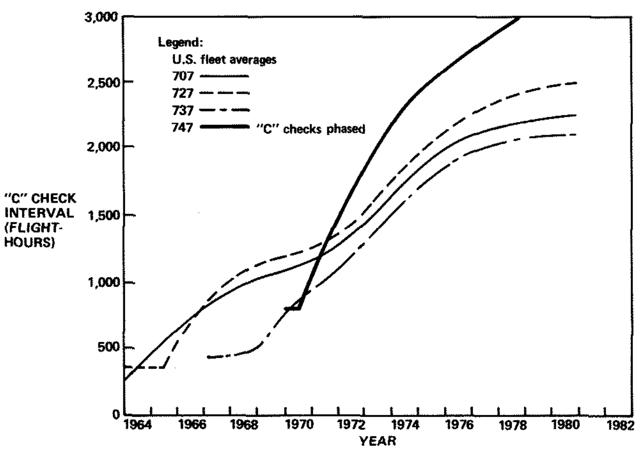


Figure 17. "C" Check Average Interval History in Hours

As the fleet matures, fatigue cracks of detectable size may occur in the SSI's. Any change to the inspection program must now take into account requirements for timely detection of these cracks.

Mature Airplane Program. Boeing airplanes are designed with an economic structural life objective of 20 years of service with 95% reliability. Assumptions about the number of flights to be completed during this period are based on anticipated use for short, medium, or long flights, whichever is most critical. An additional fatigue reliability factor (FRF) is used to account for the economic consequences of cracking.

A high FRF is used for structure that is difficult to repair or replace, such as a wing joint at the side of the

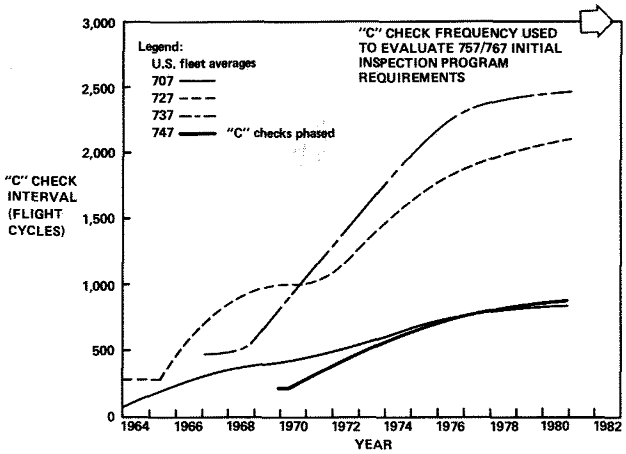


Figure 18. "C" Check Average Interval History—Flights

body. No additional factor is used for structure that is easy to repair or replace, such as a trailing-edge panel. All these considerations are aimed at providing an economically acceptable structural service life. Higher levels of reliability would require reductions in operating stress and corresponding increases in operating weight. This in turn would mean an increase in fuel costs throughout the operational life of the airplane. With today's fuel prices, a small increase in airframe weight can mean a significant increase in operating cost over a 20-year period. This increase must be balanced against the reduction in maintenance cost that can be expected with an increased level of structural reliability.

The economic life objective is for 19 out of 20 airplanes to exceed 20 years of operation without major fatigue cracking in the primary structure. For structure that just meets the design objective, 1 out of 20 airplanes may crack prior to 20 years of service. In a large fleet of airplanes, the earliest fatigue cracking could occur as early as midway through the design life, even though most of the fleet will exceed the full design-life objective without cracking.

For most structure, the inspection program established for detecting corrosion, stress corrosion, and AD provides adequate opportunity for detecting FD. Any required additional inspections will begin after a suitable threshold (fig. 19). The threshold should correspond to the time fatigue damage of detectable size is anticipated. For the most critical structure, this is expected to correspond to at least 10 years of service, 50% of the economic fatigue-life objective.

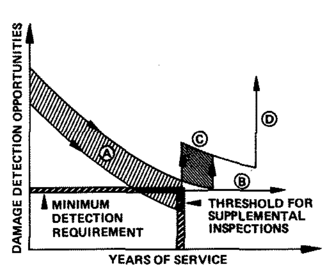


Figure 19. Structural Maintenance Options

Damage Tolerance Rating System. A quantitative fatigue-damage-detection rating system has been developed to determine the adequacy of the EDR and ADR program and optional fatigue-related inspection methods. Although this system is applicable only to fatigue cracking, it is known as a damage tolerance rating (DTR) system.

Damage detection is normally a function of damage size at the time of an inspection and the inspection method or procedure used. A number of events significantly influence the probability of detecting FD that has occurred in a fleet of aircraft (fig. 20).

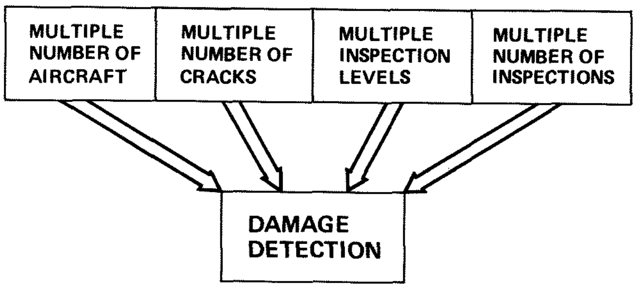


Figure 20. Damage Detection in a Fleet of Aircraft

The probability of detecting FD on a specific detail in a fleet of aircraft is a function of three independent probabilities (fig. 21). The probability, P_1, of inspecting an aircraft with a damaged detail is a function of the number of aircraft inspected and their position in the fleet relative to a given fatigue life. With the assumption that damage has occurred, $P_1 = 1$ when the full fleet is inspected. Sampling programs will have P_1 values of less than 1. Aircraft with the most flight cycles are most likely to experience the earliest fatigue cracking. Therefore, fleet-leader aircraft provide the highest value of P_1 for a given sample size. The probability, P_2, of inspecting the detail considered will generally be 1 or 0 for an individual airline. This value determines which maintenance levels are used to inspect the detail. Typical fleet values are used for design-checking purposes. For a single inspection of the detail considered ($P_2 = 1$) on an aircraft with damage ($P_1 = 1$), the probability of detecting damage, $\hat{P}_3$, is a function of crack length, inspection check level, and detection method (such as visual, ultrasonic). $\hat{P}_3$ is written in terms of a three-parameter Weibull distribution (equation 1),

$$\hat{P}_3 = 1 - \mathrm{EXP}\left[-\left(\frac{L - L_o}{\lambda - L_o}\right)^{\alpha}\right] \qquad (1)$$

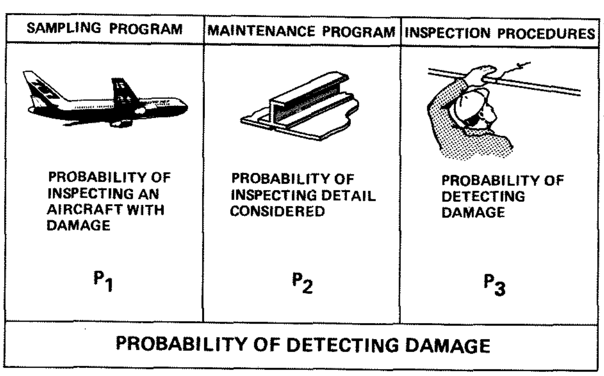


Figure 21. Damage Detection Parameters

in which the three parameters are: L_o, the threshold below which cracks are assumed undetectable; λ, the characteristic crack length of the distribution; and α, the shape function. L is the inspectable crack length at the time of inspection. It may be significantly different from the total crack length, depending on several factors, including location of cracks and method of inspection.

For example, consider the inspectable crack length for the detail shown in figure 22. 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.

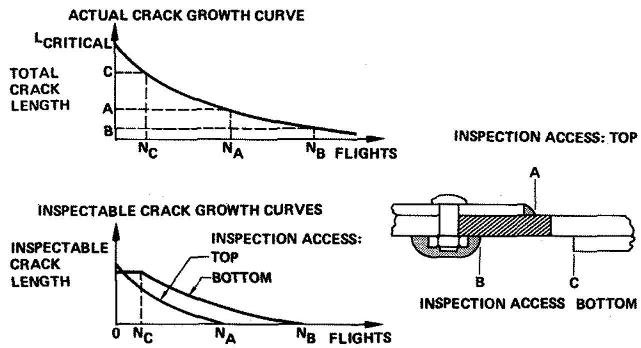


Figure 22. Inspectable Crack Length

Use of nondestructive inspection (NDI) procedures such as ultrasonic or high-frequency eddy current may significantly increase the damage-detection period (fig. 23). These procedures will not only detect smaller surface cracks than visual inspections but provide opportunities for detecting subsurface cracks. Therefore, an equivalent probability of detecting damage can be achieved with a reduced inspection frequency. Alternatively, detection of small cracks allows more economic repair.

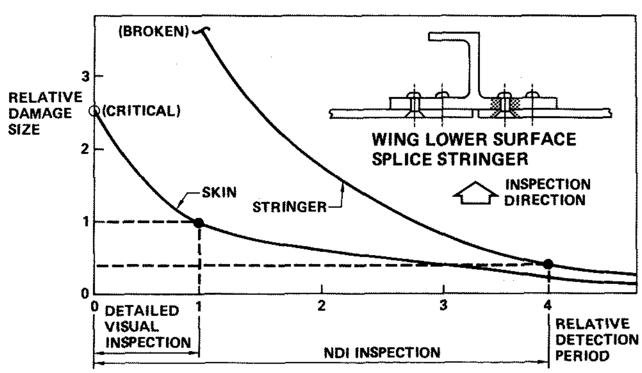


Figure 23. Visual Versus NDI Damage Detection

$\hat{P}_3$ is derived from service cracking data. A large data base of reported service cracking is used to determine the distribution of cracks at detection. Average inspection intervals and a simplified crack-growth curve are used to estimate the length of cracks missed during previous inspections (fig. 24). Allowance is made for cracks currently being missed that will be detected in the future. Each inspection that fails to discover an assumed crack is termed a "nondetection event." The total number of nondetection events is usually 20 to 50 times larger than the number of detection events and influences detection probabilities significantly (fig. 25). Data bases are continuously updated and provide valuable information about operator maintenance practice in terms of damage-detection statistics.

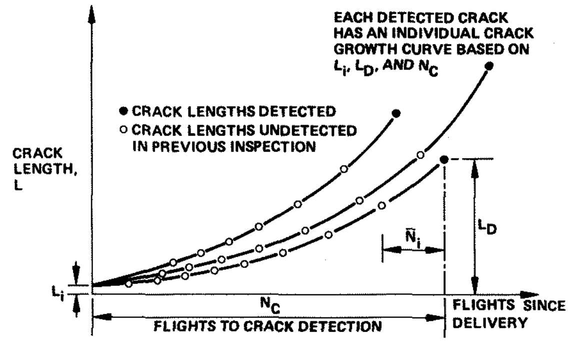


Figure 24. Detection and Nondetection Events

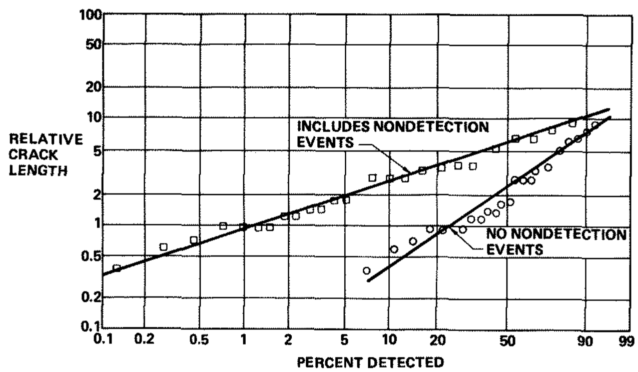


Figure 25. Effect of Nondetection Events

To ensure continued safe operation of aircraft, there must be a high probability of detecting fatigue damage in the fleet before any damage exceeds applicable regulatory requirements. The safe damage detection period, therefore, ranges from a detectable crack threshold to critical damage size for fail-safe load (fig. 26). It is important to note that failure to detect damage before it exceeds critical size does not automatically mean loss of an aircraft. Catastrophic failure will occur only if the damaged aircraft experiences the design fail-safe load while the critical-size crack remains undetected, an extremely unlikely event.

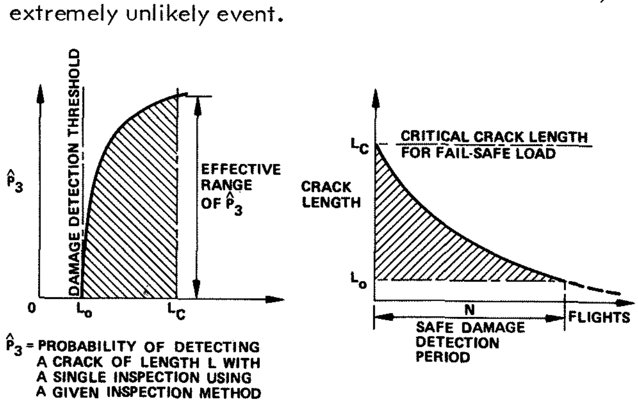


Figure 26. Safe Damage Detection Period—N

Crack length at the time of an inspection is random. The last inspection during the damage detection period, N, occurs at some point during the final inspection interval, $\bar{N}$ (fig. 27). A typical location for the final inspection corresponds to the average $\hat{P}_3$ value during the interval $\bar{N}$. With the position of the final inspection established, previous inspections are spaced at intervals of $\bar{N}$, prior to this. A crack length and $\hat{P}_3$ value can now be associated with each inspection. Assuming $P_1 = P_2 = 1.0$, the cumulative probability of detection for a single airplane during the period N is derived from the product of the nondetections in equation 2;

$$P_3 = 1 - \prod_{i=1}^{n} (1 - \hat{P}_{3i}) \tag{2}$$

where n is the number of inspections (integer).

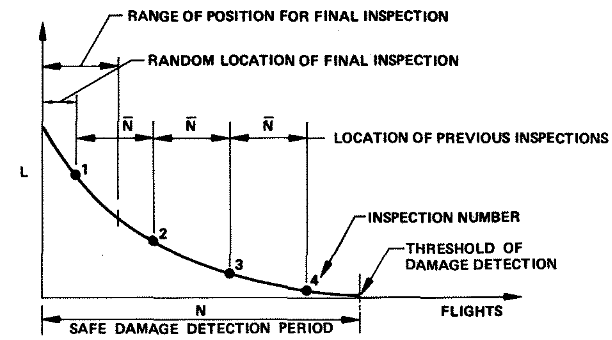


Figure 27. Multiple Inspections

In some cases the inspection interval $\bar{N}$ is equal to or greater than the damage detection period. For these cases, an average probability $\hat{P}_3$ is determined for $\bar{N} = N$. The probability that this inspection will occur during the period N, is accounted for by equation 3;

$$P_3 = \hat{P}_3 \cdot N/\bar{N} \tag{3}$$

Experience has shown that when damage is detected in the fleet, further inspections generally reveal additional damage in the same detail on other aircraft and/or on a similar detail at another location. Additional damage in the fleet increases the probability of detecting at least one crack. The number of flights between occurrences in the fleet of FD 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 $N_1 + 2\Delta N$ (fig. 28).

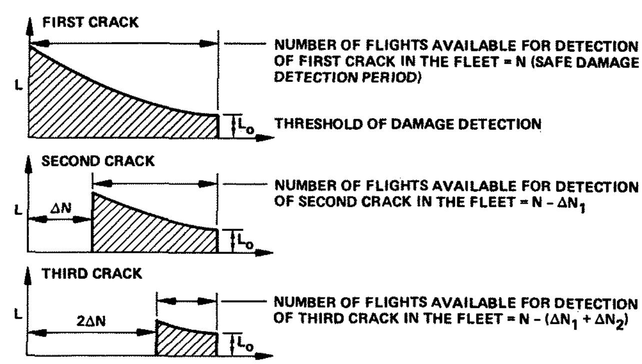


Figure 28. Multiple Cracking in the Fleet

Each successive crack occurring during the period N has a reduced interval for detection and a shorter crack length. 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, using a given inspection method and frequency, is given by equation 4;

$$P_3 = 1 - \prod_{i=1}^{m} \prod_{i=1}^{n} (1 - \hat{P}_{3_{ij}}) \tag{4}$$

where $\hat{P}_{3ij}$ is the probability of detection during the ith inspection of the jth cracked airplane. During the damage-detection period N, m is the number of cracked aircraft, 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;

$$\bar{P}_3 = 1 - (1 - P_3)^{\bar{N}/N} \tag{5}$$

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

$$P_D = 1 - \Pi (1 - P_{d_i}) \qquad \text{where } P_d = P_1 \cdot P_2 \cdot P_3 \tag{6}$$

i = applicable inspections

Values of P_D such as 0.999 and 0.998 appear to be very close. If the probability of not detecting damage ($1 - P_D$) is considered, it can be seen that there is actually a 2-to-1 difference in these values. This provides a better comparison between P_D levels. To provide a direct qualitative measure of design and/or maintenance planning actions, an equivalent number of 50/50 opportunities of detection is used to define a DTR (fig. 29).

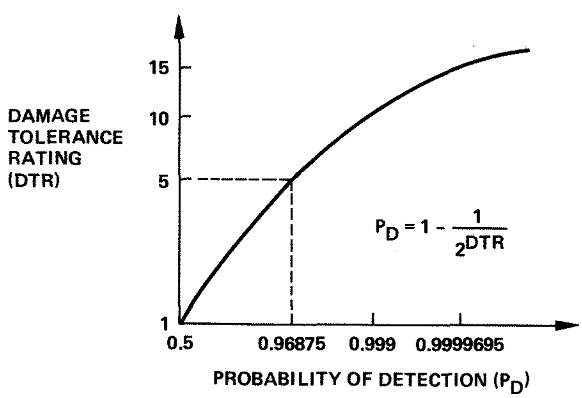


Figure 29. Damage Tolerance Rating Definition

Use of DTR System. The maintenance planning requirements for new design, or existing structure where damage has not been detected, can be evaluated by the DTR system. The actual DTR for a maintenance plan is derived by using fleet-demonstrated detectability standards in conjunction with typical crack-growth and residual-strength characteristics. Detectability is adequate if the actual DTR is equal to or greater than the required DTR (fig. 30).

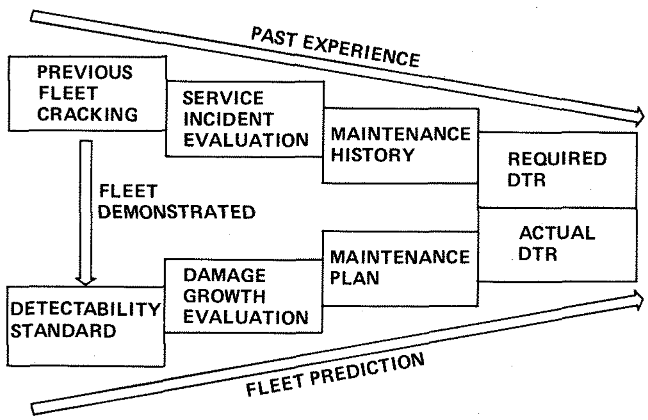
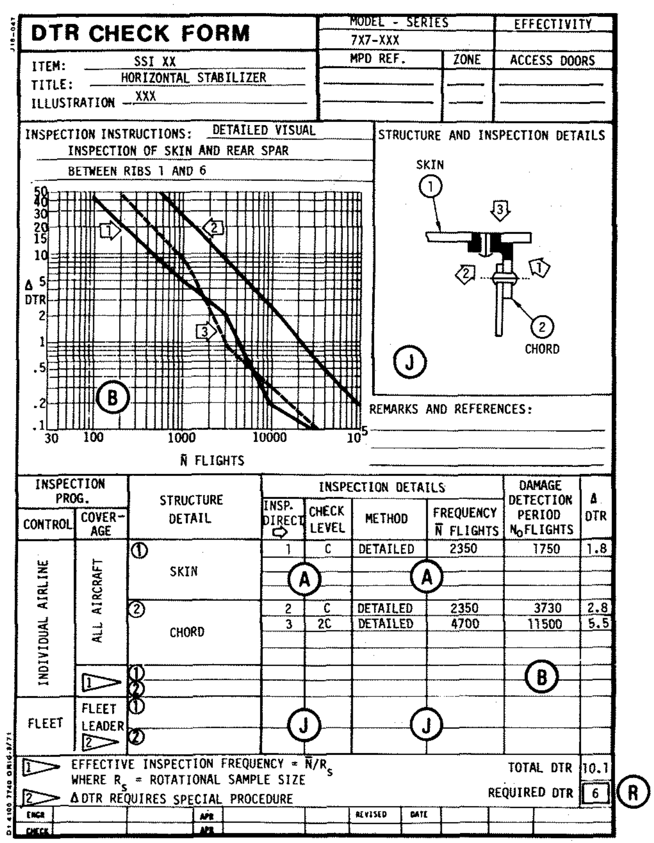


Figure 30. Comparative Detectability Evaluation for Fatigue Cracking

For maximum operating efficiency, each individual airline requires a certain degree of flexibility in its maintenance operations. Allowance for such flexibility must be included in any structural maintenance plan. To take this flexibility into account, the DTR system is used to evaluate a typical maintenance plan, but options for varying this plan are provided. The DTR check form completed for each SSI (fig. 31) must show the effect of varying inspec-



Data control

A — Individual airline

B — Boeing

J — Joint Boeing/All airlines

R — Joint Boeing/Regulatory

Figure 31. Data Control in DTR System

tion interval and/or method. This allows operators, if they so desire, to select more convenient intervals or methods for their individual inspection programs, with an approved procedure. In all cases the total DTR must equal or exceed the FAA-approved required DTR after the aircraft has exceeded the detectable damage threshold, and continue to satisfy the ED and AD inspection requirements. Any significant changes in the maintenance program or DTR system parameters must be reflected by an update of the appropriate DTR check forms.

Required DTR. The most consistent method of establishing acceptable detectability levels is to evaluate previous service cracking history (fig. 30). Actual crack-growth curves are required, as well as details of the inspection level and method used, previous inspection history, and crack length detected. Although a large computerized service cracking history is available at Boeing, in most cases some or all of the information required for DTR evaluations has not been recorded. Therefore, an improved reporting procedure is being initiated for the new airplane programs and supplemental inspection programs currently being developed for the existing aging fleets.

Until these additional data are available, required DTR levels have been established using engineering judgment of cracking circumstances and probability of actually having a safety-critical crack. The normally highly visible crack lengths exceeding critical, and prior to high risk of airplane loss are not included in the DTR evaluations. In addition, it is assumed that fatigue cracks always start in the worst location for detection. A study of reported cracking data shows that many cracks are detected during activities not directly related to structural inspection. These additional opportunities for detection are not used in the DTR evaluations. This background was used to establish a basic required DTR value of 4. Increments to the basic required DTR (fig. 32) were established by a qualitative assessment of opportunity detections and the level and frequency of fail-safe stress compared with normal operating stress.

STRUCTURE			REQUIRED DTR		
			BASIC	INCREMENTAL	TOTAL
WING AND NACELLES	EXTERNALLY VISIBLE AREAS		4	0	4
	AREAS NOT EXTERNALLY VISIBLE		4	2	6
	PRIMARY FLAP STRUCTURE		4	4	8
EMPENNAGE	PRIMARY STRUCTURE		4	2	6
FUSELAGE	CONTRIBUTION OF CABIN DIFFERENTIAL PRESSURE TO TOTAL FAIL-SAFE STRESS	< 50%	4	2	6
		≥ 50%	4	6	10

Figure 32. Required DTR

Schedule for Fatigue-Related Inspections. As stated earlier, fatigue cracking of detectable size is not anticipated in the fleet for a period corresponding to at least 50% of the economic-life objective. Beyond this threshold, there is a small but finite probability that a crack has occurred. Although there will be no sudden increase in fatigue cracking, the probability will continually increase as airplanes accumulate flights.

The most critical structural details are those for which routine maintenance for ED and AD provides little or no opportunity for timely detection of FD. An example is a detail on which the crack up to its critical length is hidden, allowing no opportunity for visual detection unless associated external signs of distress occur. The criticality is compounded when the damage-detection period is short. It is essential, therefore, to start fatigue-related inspections of the most critical structure as soon after the threshold as practical.

When routine inspections provide some opportunity for detection, less reliance need be placed on fatigue-related inspections for maintaining structural integrity. For structural items in this category, it is appropriate to phase in the initial inspections over a period of time that is a function of the damage-detection period and the extent of normal maintenance. This philosophy is shown schematically in figures 33 and 34 in terms of calendar time and relative damage detection period. These must be converted into an equivalent number of flight cycles to reflect the primary influence on fatigue and crack growth.

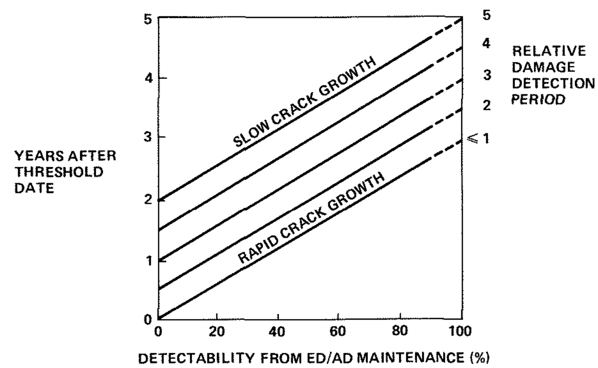


Figure 33. Initial Fatigue-Related Inspection Schedule

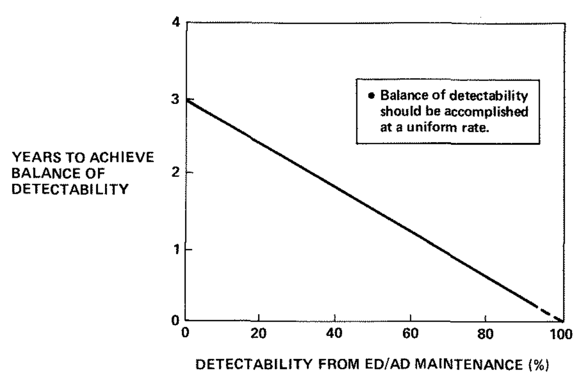


Figure 34. Buildup Rate for Fatigue-Related Inspections

Conclusions

Flexible structural maintenance programs have been developed for the Boeing 757 and 767 aircraft using new technology and procedures that meet damage tolerance regulations. The programs are designed to maintain structural airworthiness in the event of environmental deterioration, accidental damage, or fatigue damage. Inspection requirements for timely detection of these types of damage are determined by a structures working group using rating systems that--

a. Utilize available maintenance resources most efficiently to ensure timely detection or prevention of structural damage.
b. Combine damage-tolerance evaluation with service experience and engineering judgment.
c. Allow an individual operator the flexibility to change programs without complex procedures requiring specialized knowledge.
d. Maintain, as far as practical, existing procedures for approving changes to the maintenance program.
e. Reflect continuing service experience.

The initial inspection program is based on evaluations for detection of corrosion, stress corrosion, and accidental damage. Inspection tasks are based primarily on current maintenance practice for each major zone. Two rating systems are used to determine the relative criticality of the structurally significant items in each zone or partial zone. The resulting inspection program will indicate the structure requiring special attention within each zone.

Boeing uses a third rating system to determine the adequacy of the initial program for timely detection of fatigue damage. A feasibility study is made to define additional inspection options for items for which the initial program is inadequate. The options are presented to the structures working group for approval as a reference standard for future development of a fatigue-related inspection program. This program applies to a mature or aging fleet and is implemented gradually after a predetermined threshold.

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