Durability and Damage Tolerance Control Plans for U.S. Air Force Aircraft

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A set of disciplined, integrated procedures involving a number of a contractor's functional organizations is necessary if the requirements for a durable and damage-tolerant structure are to be met. To this end, the Air Force requires that Durability and Damage Tolerance Control Plans (DADTCPs) be developed and implemented during aircraft development and manufacturing. DADTCPs define all tasks necessary to ensure that the final product meets the Air Force durability and damage tolerance requirements. Various aspects of DADTCPs will be discussed in this paper. The foundation for a generalized model outlining the tasks in a DADTCP will be presented. Examples from existing DADTCPs will be used to illustrate elements of the generalized model.

Introduction

NEW U.S. Air Force aircraft rely on the application of a durability and damage-tolerant structural design philosophy to protect fleet safety and ensure a long life structure. The durability and damage-tolerant design approach is interdisciplinary, involving engineering aspects of loads analysis, stress analysis, fracture mechanics, fatigue analysis, materials and processes, standards and producibility, and verification. Manufacturing and quality assurance become involved as the design becomes hardware. A set of disciplined, integrated procedures involving a number of a contractor's functional organizations is necessary if the requirements for a durable and damage-tolerant structure are to be met. To this end, the Air Force requires that Durability and Damage Tolerance Control Plans (DADTCPs) be developed and implemented during aircraft development and manufacturing. DADTCPs identify and define all tasks necessary to ensure that the final product meets the durability and damage tolerance requirements specified by the Air Force. The program that results from these plans, after approval by the Air Force, is maintained by the contractor without significant involvement by Air Force personnel.

The purpose of this paper is to discuss DADTCPs. Various aspects of the plan will be covered and explained. The foundation for a generalized model outlining the tasks in a DADTCP will be presented. Examples from existing DADTCPs will be used to illustrate elements of the generalized model.

Durability and Damage Tolerance Control

Structural integrity requirements for design and testing have long existed for Air Force aircraft.[1,2] The Air Force approach to the application of a durability and damage-tolerant structural design philosophy has been the subject of exhaustive study and numerous references are available.[3-5] Durability and damage tolerance control is the rigorous application of a set of design, test, and manufacturing requirements, based on the principle of controlling cracks (or crack-like defects) or the growth of cracks.[2,6-8] DADTCPs are an extension and formalization of these requirements.

Durability is defined as the ability of the aircraft to resist cracking, corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for the entire design service life. It is an economic consideration. The purpose of durability control is to ensure that the economic life of the aircraft is greater than the required design service life and that expensive maintenance actions or repairs will not be necessary.

Damage tolerance is defined as the ability of the aircraft to resist failure due to the presence of flaws, cracks, or other damage. The purpose of damage tolerance control is to ensure that flaws which may exist in safety-of-flight structure will not grow to a critical size which would cause catastrophic failure during the design or operational usage period and that a specified level of residual strength is maintained during this period.

The plans produce an intensified management approach to ensure the contractor's coordinated interdisciplinary functions design and produce a durable and damage-tolerant aircraft. In addition, the plans include the requirement to perform durability and damage tolerance trade studies early in the design phase. These studies are performed to determine the best choice of materials and structural configuration which meet the structural integrity requirements and provide the desired emphasis on cost/weight reduction within the performance requirements of the aircraft. DADTCPs have been required on all new Air Force aircraft and on major modifications to old aircraft since 1972. No major structural durability or safety problems have been encountered in test or operation on aircraft which have had the full benefit of durability and damage tolerance control procedures.

Air Force air vehicle system procurement standards and specifications are currently going through a major revision process.[9] However, it is anticipated that DADTCPs will be an integral part of all future Air Force development programs.

The DADTCP is often referred to as if it is one document. In actuality, current Air Force data requirements specify two separate plans: a Durability Control Plan and a Damage Tolerance Control Plan. In practice, however, one document that merges the two has been accepted. Most of the elements that make up each plan are, in fact, identical and it is reasonable to expect that one document will be acceptable for future development programs. In this paper, the plans will be examined as one and the few differences noted.

The concept of durability and damage tolerance control is not limited to aircraft development. Most industries that have to deal with structural design have found damage tolerance

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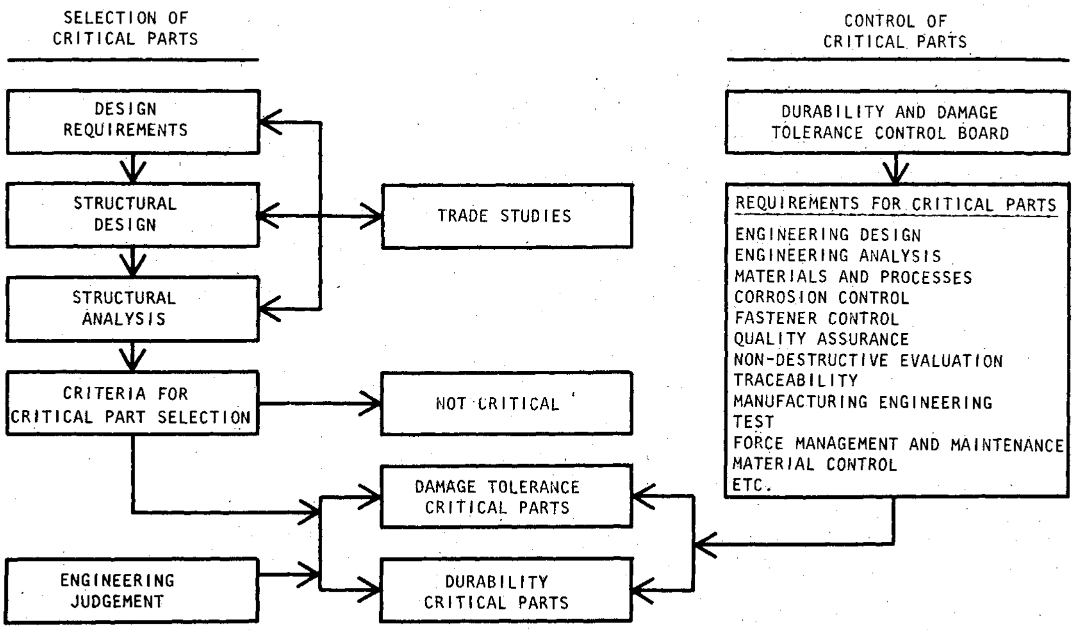


Fig. 1 Generalized durability and damage tolerance control plan.

control, also referred to as fracture control, programs to be beneficial. Examples include the nuclear industry, the marine industry, the railroads, and bridge builders, among others.[10] In fact, the National Aeronautics and Space Administration has been using formal fracture control programs to ensure structural integrity throughout the space program. Reference 11 describes the fracture control plan for the Space Shuttle Orbiter.

The use of DADTCPs to ensure compliance with Air Force durability and damage tolerance requirements is not restricted to airframe structures. Model plans have been written for other major assemblies such as landing gear.[12] Specifications now being written for engine structural integrity will also require a DADTCP. The model plan presented in this paper is applicable to other structural assemblies where safety and durability are concerns. It is likely that the only differences will be in the criteria for the identification of durability critical parts or damage tolerance critical parts.

The Durability and Damage Tolerance Control Plan

A generalized model of the DADTCP is shown in Fig. 1. For illustrative purposes, the plan can be divided into two major tasks: the selection of critical parts and the control of critical parts. Each task can be divided into subtasks as shown. While each subtask will be discussed in detail in subsequent sections, a brief discussion of the process in general is useful.

The selection of critical parts starts as system design requirements are translated into a design, and analyses are accomplished. Trade studies, formal and informal, are continuously performed to determine the most cost-effective lowest weight design. After a design is finalized, durability and damage tolerance critical parts are chosen according to a set of predetermined criteria. Design trade studies, continuing on at least an informal basis, may result in parts being added to or deleted from the critical parts list at any time. Critical parts can also be selected by engineering judgment. These parts, although not critical according to predetermined criteria, may be deemed critical because of economic consequences of failure (e.g., expensive to repair or replace) or by the aircraft not being mission capable, etc. Those parts that do not make the list are subject to normal controls.

The control of critical parts is administered by the Durability and Damage Tolerance Control Board. The board is comprised of a broad range of people that represent different functional areas within the company—engineering, manufacturing, quality assurance, etc. The board is responsible for establishing and overseeing the administration of the specific controls that will be applied to the critical parts. Typically, the board reports directly to the program manager.

The durability and damage tolerance control process is similar to what is normally accomplished in most companies during system development and manufacturing. It does, however, represent a significantly more rigorous application of controls and a directed interdisciplinary effort among the company's functional organizations. DADTCPs have been developed and used successfully on recent aircraft development programs. Air Force contractors have found durability and damage tolerance control to be a sound and reasonable approach to insuring structural integrity.[13]

Selection of Critical Parts

Design Requirements, Structural Design, Structural Analysis, and Trade Studies

These subtasks are basic elements of any development program. Their role within the context of a DADTCP is the source of hardware (Critical Parts List) that will be subject to specific durability and damage tolerance control procedures. Typically, only general references as to what is required in those subtasks are in the plan itself, the specific details being available in other sources such as the Design Criteria Report, Durability Analysis Report, Damage Tolerance Analysis Report, etc.

The trade studies are done throughout engineering development in order to balance design, material selection, and weight to achieve a cost-effective design. Although not shown pictorially, these studies are done with knowledge of what is required under the DADTCP. Trade studies have been a firm requirement in recent programs and it is reasonable to expect that they will be part of future programs.

Criteria for Critical Part Selection

A generalized model for durability and damage tolerance critical part selection is shown in Fig. 2. Different specific criteria are applied to select durability critical parts than to select damage tolerance critical parts. The process, however, is similar for both classifications. In general, the criteria are developed and the selection is done by the group responsible for durability and damage tolerance analysis.

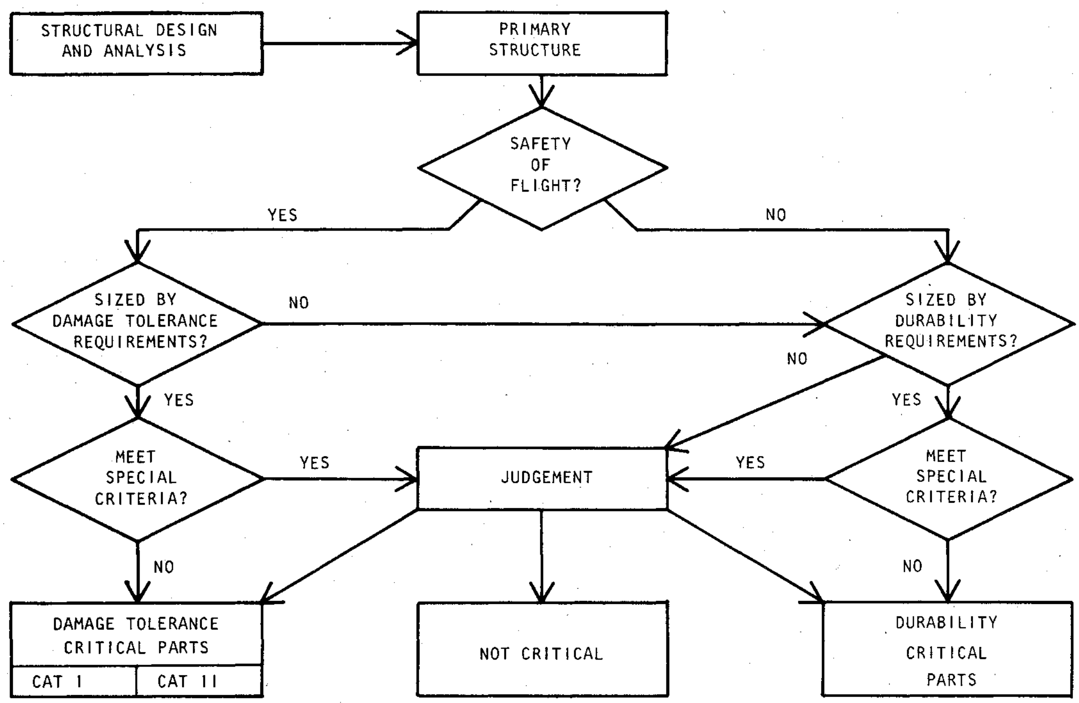


Fig. 2 Durability and damage tolerance critical part selection.

After preliminary design and analysis, the primary structure is classified as safety-of-flight or non-safety-of-flight. Safety-of-flight parts that are sized by damage tolerance requirements (i.e., design stress level set by damage tolerance requirements) become damage tolerance critical parts.

Special criteria, as shown in the block, "Meet Special Criteria," may be used at the contractor's option to delete items from the damage tolerance critical parts list. These criteria are subject to Air Force approval. For example, a special criteri on has been devised that allows a safety-of-flight part sized by damage tolerance requirements to be considered noncritical if the crack growth life is far in excess of that required. Note that even if the special criteri on is met, the part is subjected to a judgment decision.

The judgment block is the final step before a piece of primary structure can be called noncritical. This step is used to designate parts as critical that, by the criteria, are not critical, using sound engineering judgment. There will be instances in any development program where, regardless of predetermined criteria, experience and reason dictate that certain pieces of structure be subject to special controls. For example, in a recent program it was decided that every single load path, noninspectable structure would be on the damage tolerance critical parts list whether it was sized by damage tolerance requirements or not. Other similar types of decisions are made in the judgment block.

It is important to note that this step is *not* used to delete a part from the critical parts list, only to add them or make a final determination that a part is, in fact, noncritical. A safety-of-flight part, sized by damage tolerance requirements and *not* meeting any special criteria, will remain on the critical parts list.

Damage tolerance critical parts are classified into two categories. A category I damage tolerance critical part is one that is sized by damage tolerance requirements. A category II damage tolerance critical part is one that would be sized by damage tolerance requirements if damage tolerance controls were not used.[8] An example of a category II part would be one where it is necessary to maintain a high value for a material property, e.g., fracture toughness, to keep it from being sized by damage tolerance requirements (category I).

The selection of durability critical parts is similar. If the part is not safety-of-flight or not sized by damage tolerance requirements, the question is asked if it is sized by durability requirements. If it is, then it becomes a durability critical part. If not, it becomes subject to judgment. As with the damage tolerance critical parts, this step can be used to designate an otherwise noncritical part as durability critical if experience or reason justify such a decision. A part that is expensive or hard to replace, but not critical by special criteria, would likely be designated critical at this step. Sizing for the durability requirement, in the past, has been based on conventional crack initiation analysis techniques and/or crack growth analysis that determines the time for a very small flaw in the part, typically from 0.005 to 0.01 in., to grow large enough to cause functional impairment of the part.

Special criteria are also employed to systematically exclude parts from the durability critical parts list. In a manner analogous to that mentioned for damage tolerance critical parts, a part that is overdesigned by some predetermined amount may be deleted. The part is, however, still subject to a judgment.

Three examples of the critical part selection process are shown in Figs. 3-5. Figure 3, from a recent cargo/tanker modernization program, and Fig. 4, from a fighter development program, show the process in a fashion similar to Fig. 2.[14,15] Figure 5, from a bomber development program, shows the selection process for critical parts as an integral part of the durability and damage tolerance analysis worksheet.[16]

In summary, the damage tolerance and durability critical part selection process consists of two paths to a critical parts list. One path uses predetermined special criteria, and it is mandatory that any parts passing the appropriate tests be on the list. The other path is judgmental: the decision to designate as critical is based on experience and consideration of circumstances.

Control of Critical Parts

Durability and Damage Tolerance Control Board

To insure the success of the DADTCP, a strong board must be established by the contractor to assure compliance during design and production of the structure. The functional areas of engineering, manufacturing, and quality assurance are represented. The board should have the power to select and enforce the controls that must be placed on the critical parts as they progress from design through final manufacturing

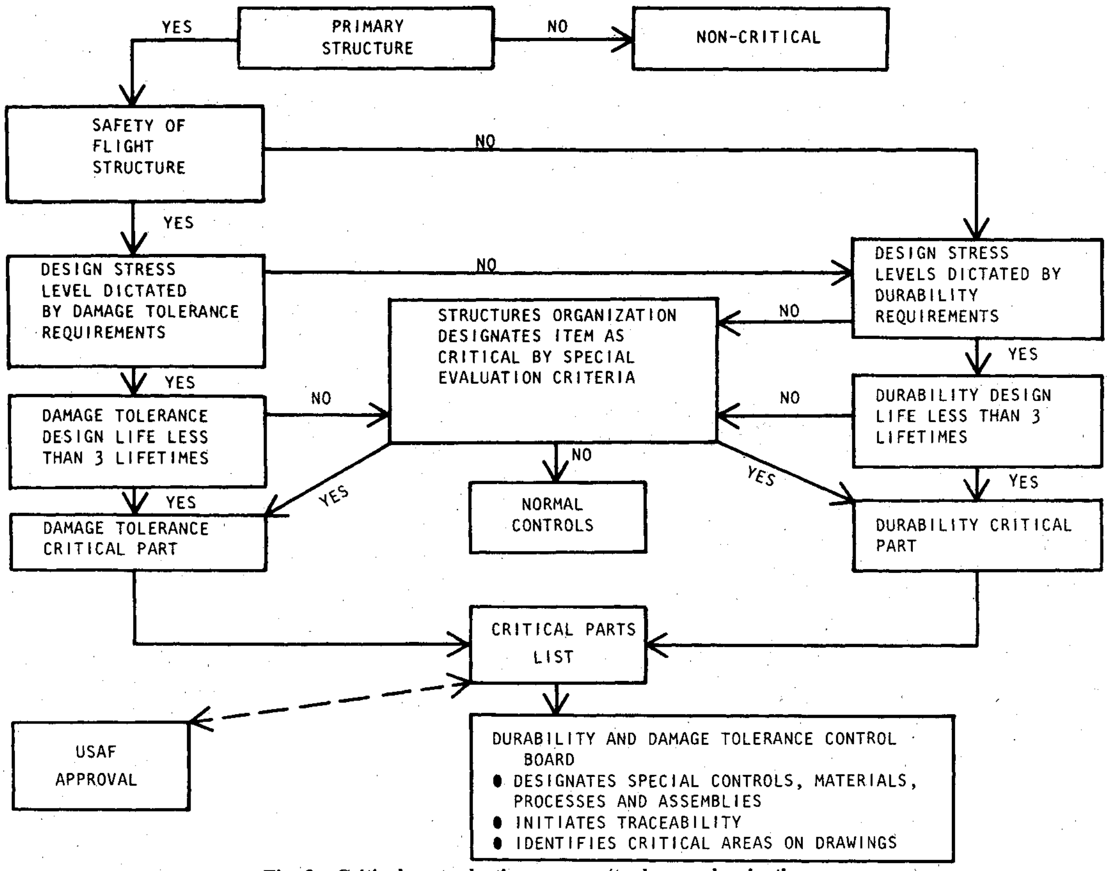


Fig. 3 Critical part selection—cargo/tanker modernization program.

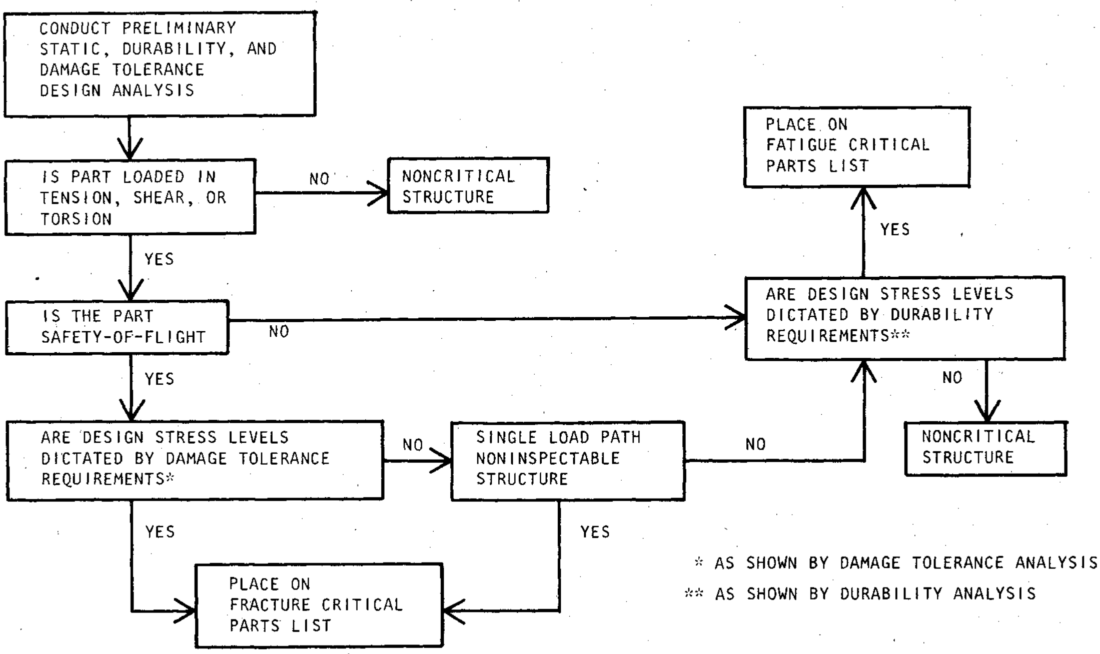


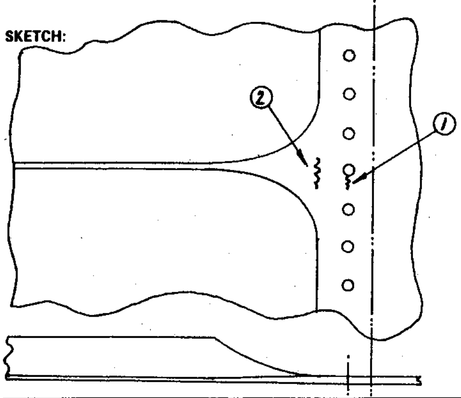
Fig. 4 Critical part selection—fighter development program.

stages. It is recognized that each company has its own organizational structural. It is not the intent of this paper to recommend any one organizational structure over another. Since the board must exercise control across functional lines, it is imperative that the Durability and Damage Tolerance Control Board (DADTCB) chairman has the authority to cross the functional lines of the organizational matrix, or that he be delegated the power and authority within the company. It is the job of the DADTCB chairman to ensure that each of the functional organizations implements the requirements of the DADTCP. The board must not be diffused by functional chains of command; its sole purpose in the organization is to enforce the DADTCP. Its responsibility is to identify, implement, and integrate the respective tasks and functions of all of the organizations involved in producing a durable and damage-tolerant structure.

An example of an organization's structure that has been effective is shown in Fig. 6. In this organizational structure, the DADTCB chairman has delegated authority from the program manager to coordinate, implement, and enforce the

DURABILITY AND DAMAGE TOLERANCE ANALYSIS SHEET

SKETCH:



PROG. RUN I.D. ______
SPECTRUM I.D. ______
ANALYST ______ DATE ______

SECTION OF AIRCRAFT: WING CARRY THRU

LOCATION X_P 38.5 Y_P 982 PART NO. ______
NAME LOWER COVER MATERIAL 6A1-4V T1
Ftu 130 KSI Fty 120 KSI
NOTES:

CRITERIA FOR DURABILITY AND DAMAGE TOLERANCE PARTS LIST SELECTION

		YES	NO
① Member of the primary structure		X	
② Failure would cause loss of the aircraft			X
③ Part is a member of a multi-load path component, failure of which would cause loss of aircraft		X	
④ Part can be replaced economically			X
⑤ Part initially designed (sized) by:	Durability requirement		X
	Damage tolerance requirement	X	
⑥ If without control, part would be designed (sized) by:	Durability requirement		
	Damage tolerance requirement		
⑦ Part known by experience to be sensitive and to benefit from control procedure:	Durability		
	Damage tolerance	X	

①	②	③	④	⑤	⑥	DURABILITY			DAMAGE TOLERANCE			⑬
Initial Crack Location	Design Condition	Limit Stress (KSI) Avg. Gross	Max Spect. Stress (KSI) Avg. Gross	Crack Type	K_{IC} and Kc (KSI $\sqrt{\text{In.}}$)	⑦ Initial Crack Length (In.)	⑧ Final Crack Length (In.)	⑨ Predicted Life	⑩ Initial Crack Length (In.)	⑪ Critical Crack Length at Limit Stress (In.)	⑫ Predicted Life	Crack Length After 1 Life (In.)
1	110122	78.4	54.4	CORNER	140	.01	THRU	5.0	.050	1.015	2.72	.112
2	110122	52.57	36.5	SURFACE	140				.125	1.925	5.95	.146

Fig. 5 Critical part selection—bomber development program.

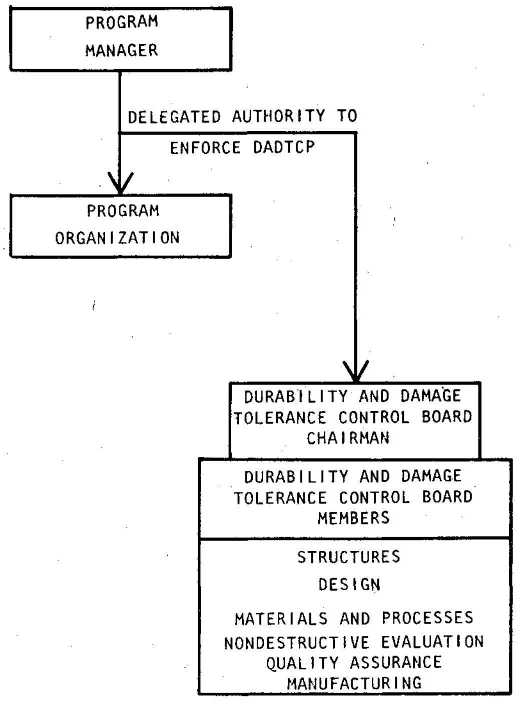


Fig. 6 Durability and Damage Tolerance Control Board organizational structure.

DADTCP. The board determines the special controls to be applied to critical parts and ensures that the controls are enforced.

Membership on the DADTCB should include representatives from all the functional areas directly involved in the design and production of the structure. Normally this will include, as a minimum, representatives from structural analysis, design, materials and processes, nondestructive evaluation, quality assurance, and manufacturing. The representatives should have the authority for their individual functional areas in exercising their responsibilities on the board. The exact membership is dictated by the company's own organizational structure.

As illustrated in Fig. 1, the board does not select the critical parts. Critical part selection is normally done by the structural analysis department. The board is responsible for selecting and enforcing the special requirements and controls on the critical parts. The actual tasks of applying the special requirements and controls are accomplished under the normal supervision and management of the program functional organizations.

Special Controls

The objective of the special controls imposed by the board is to produce a durable and damage-tolerant structure. This is achieved through special control of material properties and processes, special nondestructive evaluation (NDE) requirements, special manufacturing and assembly requirements, and special quality assurance requirements. Detailed requirements will not be presented in this paper since these requirements will vary from program to program and part to part. Instead, the tasks that need to be accomplished to ensure that all of the requirements of the DADTCP are met will be outlined.

It is again emphasized that the special procedures and tasks are accomplished under the normal management structure of the responsible functional organization. The board establishes the requirements and insures that the functional organizations follow them. Implementation of the requirements is the responsibility of the contractor. The Air Force's only involvement is approval of the requirements.

Basically, all of the special controls consist of two broad tasks: 1) special procedures for identifying durable or damage-tolerant critical parts and controls on each design drawing, and 2) special controls to assure that the quality of the produced parts and assemblies is no less than required by the design.

To accomplish the first task, the engineering drawings for the critical parts and assemblies should identify all critical parts and locations. If the entire drawing is not critical, it should be zoned to identify the critical areas. All special processing and inspection requirements should be identified. The DADTCB should coordinate the special procedures used to identify critical locations to ensure that all functional areas clearly understand the identification of a critical part and the requirements associated with that part. The engineering design organization retains the responsibility for the drawings.

The major task of the DADTCB should be the identification of specific material procurement, manufacturing processes, NDE, process control, corrosion control, and quality control requirements for each part on the critical parts list. Also, where it is deemed necessary because of the nature of the part, they should establish traceability requirements. These special controls *are* subject to the approval of the Air Force. The contractor's plan for monitoring subcontractor, vendor, and supplier controls for critical parts also is specifically required.

All special fatigue-enhancement processes, such as shot peening, cold working, stress coining, and the use of special fatigue-enhancing fasteners where used to meet durability and damage tolerance control, should be covered by the plan. Installation and inspection standards for using these techniques should be controlled by the board.

It may be necessary to develop special material procurements or manufacturing process specifications to ensure that the critical parts meet the requirements. Typically, category II critical parts require controlled material properties, e.g., fracture toughness, crack growth rates, etc. In the past, this requirement has made it necessary to have special material procurement specifications. However, recently, because of durability and damage tolerance requirements, the Aluminum Association has developed controlled toughness versions of most conventional high-strength aluminum alloys used in the aerospace industry.[17] Examples include 2124 Al plate for 2024 Al plate, 7175 Al plate for 7075 Al plate, etc. Special material processes also exist for controlled fracture properties for titanium and steel alloys.

Traceability requirements may be imposed on critical parts that are subject to contractor or subcontractor in-house processing or fabrication operations which may degrade the design or material properties. The traceability requirements should be defined for each level of activity as required. These requirements will vary depending upon the type of structure, the material, the process, and the assembly sequence. Traceability requires that the parts be serialized and the complete history of the part be kept as it progresses through the manufacturing process. Traceability may also include the requirement to set aside coupons from parts/stock for future testing.

The Air Force damage tolerance specification specifies initial flaw sizes that must be assumed in design.[8] When a design is based on initial flaw assumptions less than those specified, a special NDE demonstration program must be conducted. This NDE demonstration program is a part of the DADTCP. Manufacturing inspection requirements and procedures must be based on the demonstration program and must comply with Air Force NDE specifications.[18]

Corrosion prevention is an integral part of durability and damage tolerance control. Corrosion pits can be an initiation site for cracks. Current Air Force specifications require a corrosion prevention and control plan.[19] The requirements of the corrosion control plan apply to the entire structure, including all critical parts.

Perhaps the most important subtask of the control program is the development and enforcement of the special quality assurance (QA) techniques for critical parts. The QA department gives final certification that a critical part has met all special control requirements levied upon it. Any critical part found to be discrepant in any way must be referred back to the DADTCB for final disposition. Normally, the inputs of the structural analysis representatives are the most important in determining whether a discrepant part may be salvaged. The control board, however, must coordinate the inputs of all of the functional areas in dispositioning a discrepant part. Since the sole purpose of durability and damage tolerance control is to insure that all critical parts meet all of the stringent requirements, it is a major undertaking to salvage a discrepant part without compromising the basic requirements of durability and damage tolerance control.

Durability and Damage Tolerance Control Plan Organization

Presenting a generalized DADTCP is difficult due to differences among contractors in organizational structure and methodologies used and system differences. The generalized model presented here is not intended as a specification but rather as a guideline. Approval of any DADTCP will necessarily be the responsibility of the program office involved.

DADTCPs for recent development programs have had a number of different formats.[14,15,20] In general, all could have been organized with four major topics: I. Introduction, II. Organization and Implementation, III. Critical Part Selection, and IV. Tasks and Responsibilities.

I. Introduction

A. Objectives. A statement of purpose and of what is to be accomplished.

B. Scope. Defines the system, subsystems, or specific structural assembly to which the plan applies. Also noted here are the major functional organizations that will be affected by the requirements of this plan: design, analysis, test, quality assurance, manufacturing, etc.

C. Requirements. Contains, or references the source of, the durability and damage tolerance requirements that are being met. Typically, the detail requirements (initial flaw sizes, inspection intervals, etc.) are those in the appropriate military specifications.[2,6,8] The general requirements, such as service life, are specified by the procuring activity. Reference should be made to the design, analysis, and verification methodologies and results used in support of the durability and damage tolerance control effort. Such references include design criteria reports, trade studies, damage tolerance analyses reports, durability analyses reports, durability and damage tolerance test plans/procedures/reports, material properties sources/tests, etc.

II. Organization and Implementation

A. Durability and Damage Tolerance Control Board. Defines the structure and functions of the board.

B. Procedures/Directives/Standard Practices. Defines any relationship with or use of company standard practices, etc. In some cases, contractors have developed new directives to implement all or parts of durability and damage tolerance control.

C. Engineering Drawings. Details the use of the engineering drawings for durability and damage tolerance control. The drawings will likely be the primary means of communicating the necessary control procedures.

D. General Responsibilities. Outlines the basic responsibilities of the major organizations involved: engineering, quality assurance, and manufacturing. The detailed tasks are covered under topic IV, Tasks and Responsibilities.

III. Critical Part Selection

A. Selection of Critical Parts. A description of the process used for choosing critical parts, normally including a flow diagram.

B. Damage Tolerance Critical Parts. Used to define, in general, what will be done to damage tolerance critical parts, who will do the selecting, etc.

C. Durability Critical Parts. Used to define, in general, what will be done to durability critical parts, who will do the selection, etc.

IV. Tasks and Responsibilities

Subtopics under this heading should include any functional group that will be affected by durability and damage tolerance control. These can include but need not be limited to

A. Engineering Design
B. Engineering Analysis
C. Materials and Processes
D. Corrosion Control
E. Fastener Controls
F. Quality Assurance
G. Nondestructive Evaluation
H. Traceability
I. Manufacturing Engineering
J. Test
K. Force Management and Maintenance
L. Material Control, etc.

Each subtopic or function should define all specific tasks and the responsible group, under that function, necessary to achieve durability and damage tolerance control.

Summary and Conclusions

DADTCPs ensure that all requirements for a durable and damage-tolerant aircraft are met. Contractors who have implemented durability and damage tolerance control plans have found that the resulting program is a viable and useful part of system development. Cooperation and understanding among functional groups are strengthened due to the awareness that the plans provide of each other's procedures and problems. Durability and damage tolerance control can be a constructive part of other structural systems.

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