New Air Force Requirements for Structural Safety, Durability, and Life Management

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The past five years have seen significant changes in the Air Force philosophy and approach in achieving structural safety and durability in military aircraft. These changes have been motivated by problems of high cost, late system development programs, with a high level of in-service structural maintenance and modification costs (poor durability) and, in some cases, less than desired fracture resistance (poor damage tolerance/safety). The problem area has been attacked along a number of avenues; one major thrust has been a thorough examination and revision of the structural design and test specifications, the MIL-A-8860 series. In this paper, certain aspects of the overall problem are discussed; an overview of the pre-1969/70 Air Force approach is presented, along with its short-comings; and, finally, significant aspects of current policy are listed, giving comparisons with the old requirements.

I. Introduction

SINCE the 1969/1970 time period, there have been significant changes in the Air Force philosophy for achieving structural safety and durability in military aircraft. These changes have been influenced strongly by serious structural problems that were encountered in several new system development programs as well as severe cracking problems in older "in-service" aircraft. Within the past year, a critical examination has been made of the entire "cradle-to-the-grave" cycle of aircraft development and life management in an effort to embody this new philosophy into an overall consistent policy, and then to develop properly documented requirements to enforce this policy.

This overall structural problem area has been attacked along a number of avenues such as 1) encouraging contractor participation in developing system requirements through such means as prototype programs, 2) requiring detailed design trade studies, and 3) improving the Air Force capability to recognize and penalize high structural risk proposals. In addition, a major thrust has been to examine thoroughly and to revise structural design and test specifications, in particular, the MIL-A-8860 series. The goal has been to minimize arbitrary requirements, to eliminate unsuccessful requirements, to relax overly stringent, high-cost requirements, and to develop new requirements that address the specific causes of past problems. The following paragraphs will first discuss certain aspects of the overall problem, give an overview of the pre-1969/70 Air Force approach, and finally present a brief statement of current policy and requirements, giving comparisons with the old approach.

II. Problem

Several of the basic causes of past structural problems can be identified readily. Figure 1 depicts a possible sequence of events that can lead to such problems in a development program. In certain cases, programs were defined on a very success-oriented basis embodying high performance estimates as well as very optimistic cost and schedule projections. Unrealistic program milestone and budget constraints did not allow adequate engineering design trade studies. The fixed performance and functional requirements resulted in low weight allowances, which, in turn, forced the selection of high-strength fracture-sensitive materials and use of design stress levels. In an effort to prevent initial manufacturing flaws, which would be catastrophic when combined with high stress levels, it was necessary to adopt high-cost materials and manufacturing processes and quality control programs. Such efforts drive up program costs, and experience has shown that even the most careful manufacturing and quality control program will not eliminate all initial manufacturing flaws. In fact, studies have confirmed that a predominance of structural failures are due to fatigue and corrosion-induced fatigue, with pre-existing material and fabrication quality deficiencies being the primary crack initiation source.[1,2]

In summary, the overall problem addressed is one of high-cost development programs, with higher than desired in-service structural maintenance and modification costs (poor durability) and in some cases less than desired fracture resistance (poor damage tolerance and/or safety).

III. Pre-1969/70 Approach and Its Shortcomings

An examination of the pre-1969/70 approach to durability and safety reveals that in the design phase there was emphasis on initial static strength, and a "safe-life" fatigue design approach was utilized with the assumption of an initially flaw-free structure. Analyses leading to mean life estimates were conducted with a scatter factor introduced to account for such factors as environmental effects, material property variations, and initial quality variations. There were no damage tolerance design requirements for protection of the aircraft structure from flaws either induced from in-service oepration or existing in the as-delivered new structure.

Regarding full-scale testing in the development phase, there was considerable emphasis on the static ultimate test. In the full-scale fatigue test, there was emphasis on utilization of a representative production aircraft. There were no schedule requirements that keyed the start or completion of fatigue testing to major program milestones. There were no firm requirements for use of flight-by-flight test load spectra; block test spectra often were used. Test duration normally was limited to four design lifetimes, unless catastrophic failure occurred earlier, and there were very limited post-test inspections and analyses conducted after completion of the test.

In the force management phase, the operational force was assumed to have a "safe life" equivalent to one-fourth of the safe life demonstrated in the fatigue test. The timing of force maintenance and modification actions indicated from the

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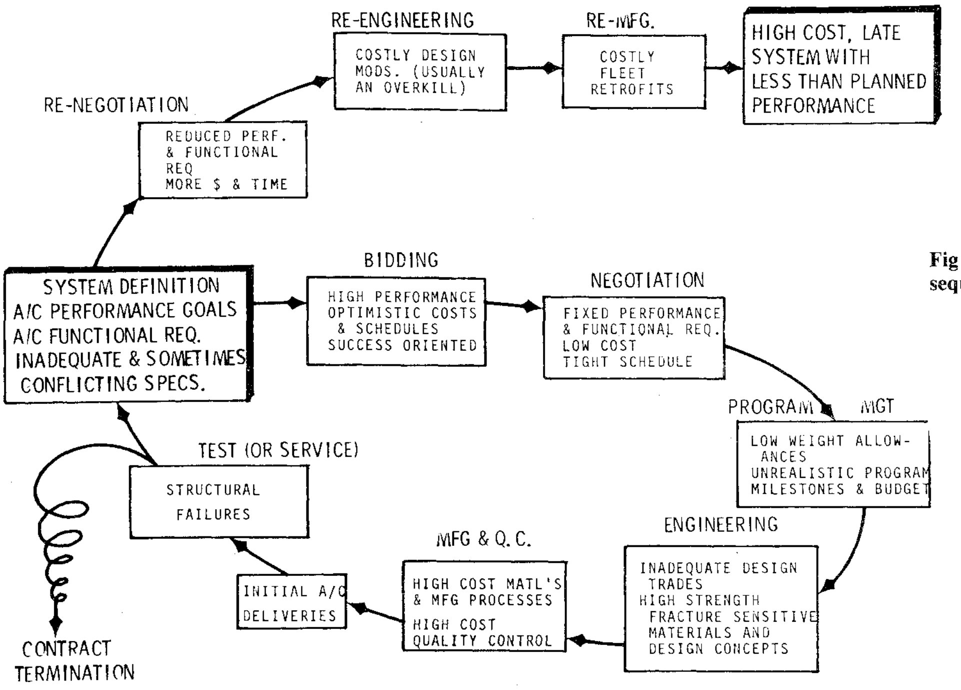

Fig. 1 Some past procurement/development sequences (spirals?).

fatigue test also was governed by the scatter factor of four. For example, if a failure requiring modification occurred at the 8000-hr point in testing, the in-service modification would be planned at the 2000-flying-hour-point. In most cases, these maintenance times were adjusted for severity of usage based on force tracking data and conventional cumulative damage fatigue analysis (i.e., Miner's rule). It thus was assumed that restricting oeprational use to one-fourth of the test life limit along with an in-service inspection program would protect force safety.

A number of shortcomings in the pre-1969/70 approach have surfaced. First, there are numerous examples where the "safe life" design and test approach did not assure structural safety. In particular, an initial flaw in a critical structural area could cause very early operational failure even though the fatigue test article domonstrated acceptable durability throughout the four lifetimes of fatigue testing. A second shortcoming was the existence of uninspectable structure which was not protected by the inspection program. Typically, because design allowed very small critical flaws, flaws under the fasteners could grow to critical size before emanating from under the fastener, thus allowing no chance for detection. A third problem was that fatigue test results generally came much too late in the development program. This allowed little if any opportunity to correct deficiencies in the production phase, but resulted in costly downstream redesigns and in-service retrofits. Lastly, the overall force managment approach lacked credibility in that, in many cases, critical structural areas were neither identified nor found, and there was a very poor basis for selecting maintenance times and for establishing life estimates.

IV. Current Air Force Approach

A. Overview

The "safe life" approach of using fatigue test results and a scatter factor to maintain structural safety has been abandoned. Instead, structural safety is obtained by requiring damage-tolerant structure that is capable of accommodating flaws induced either in manufacture or in service. Damage Tolerance Design Policy is reflected in a specification issued in 1974, MIL-A-83444,[3] which establishes requirements for all safety of flight structures. Durability Design Requirements are reflected in a recently revised specification, MIL-A-8866B,[4] which requires that the economic life of the airframe exceed the specified design service life of the airplane when flown to the design loads/environment spectra. Ground test policy to assure compliance with safety and durability requirements is stated in a newly revised MIL-A-8867B.[5] These three specifications contain the key elements of the current Air Force Structural Integrity Program (ASIP). An overall governing document, MIL-STD-1530,[6] gives a general ASIP description. A number of supporting handbooks are either completed, in preparation, or planned.[7,8]

B. Requirements to Assure Damage Tolerance

In the pre-1969/70 period, safety design philosophy was based on a predicted mean life divided by a scatter factor of four, assuming an initially unflawed structure. Currently, flight safety is obtained by requiring a damage-tolerant design with identification are careful control of critical safety of flight structural components. Certain other key elements contained in MIL-A-83444 are as follows: 1) flaw size assumptions based on NDI capability, proof test, and/or initial quality data; 2) minimum residual strength requirements based on probability of load occurrence in specified minimum periods of unrepaired service useage; 3) minimum periods of unrepaired service usage based on inspectability of the structure and the probability of detection; 4) damage growth limits in terms of flight time to grow an initial flaw to critical crack size; and 5) a fastener policy that encourages use of flaw growth retarding, cost-effective fastener systems but precludes assuming that they are 100% effective.

C. Requirements for Durability

As previously noted, the old durability design philosophy was based on a "safe life" design concept. The current approach requires that the economic life be equal to or greater than the specified design service life when subjected to the design loads/environment spectra. The economic life is defined as that operational life indicated by the results of the durability test program (i.e., test performance, interpretation, and evaluation per MIL-A-8867B) to be available with the incorporation of Air Force approval and committed production and/or retrofit changes and the supporting application of the force structural maintenance plan per MIL-STD-1530. In general, production and/or retrofit changes will be incorporated to correct local design and/or manufacturing deficiencies disclosed by the test, and it will be assumed that the economic life of the test article has been attained with the

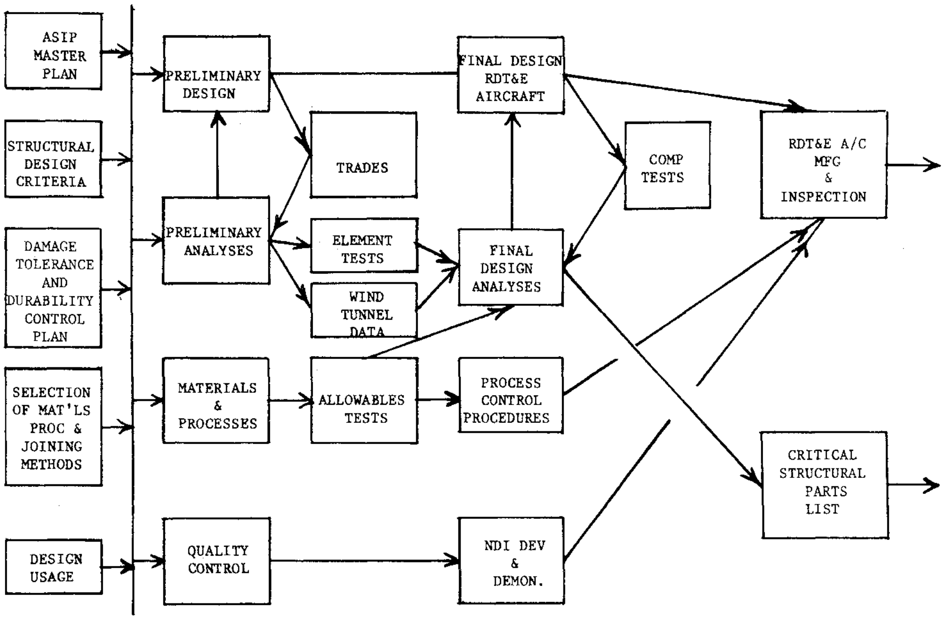

Fig. 2 Design analysis and development tests.

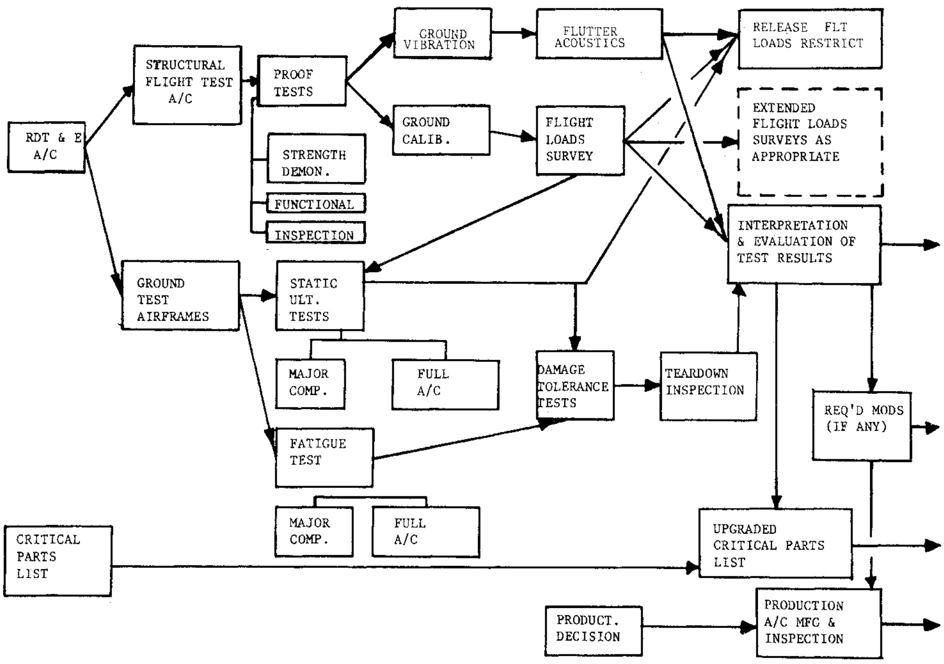

Fig. 3 Design verification tests.

occurrence of widespread damage that is uneconomical to repair and, if not repaired, could cause functional problems affecting operational readiness. This generally can be characterized by a rapid increase in number of damage locations (or repair costs) as a function of cyclic test time.

Achievement of the design economic life requirement will be accomplished through the use of rational analysis, disciplined design procedures, and strict control over design, manufacturing, and service maintenance procedures that affect durability. Each area of the airframe will be analyzed to show that cracks or other damage will not reach sizes large enough to necessitate repair, modification, or unplanned replacement of structure within the required design life when subjected to the design loads/environment spectra. In addition, it will be required that the analysis procedure account for those factors affecting the time for damages to attain unacceptable sizes. These factors include initial quality distribution, environment, load sequence and environmental interaction effects, material property variations, and analytical uncertainties. In addition, it will be necessary to demonstrate that cracks that may exist in the structure will not grow due to 1-*g* steady-state sustained stresses throughout the life of the airframe.

Disciplined durability design procedures are required to minimize the probability of incorporating local design details, adverse residual stresses, materials, processing, and fabrication practices into the airplane design and manufacture which could lead to early unexpected cracking or failure problems. Effective managerial actions will be required to insure that the durability detail design activities are maintained and controlled properly.

D. Requirements for Design Development and Design Verification Testing

Testing programs will be required in Air Force aircraft development programs to assure that durability and safety requirements are met. Figures 2 and 3, respectively, depict key elements of design development testing and design verification testing.

1. Design development test policy and guidelines

In establishing material and joint allowables, maximum use of existing handbook data will be expected so as to minimize cost. Where existing data are insufficient, new data will be developed per the handbook guidelines. Small element tests will be performed to flight-by-flight spectra in simulated service environments to verify flaw growth and life analysis procedures and to obtain early verification of allowable stress levels, material selections, fastener systems, etc. Design development tests will be performed on selected critical full-size components to conform damage tolerance and durability.

2. *Full-scale test policy and guidelines*

Some of the most significant changes in the new requirements are in the area of full-scale static ultimate testing, full-scale fatigue testing, and the introduction and recognition of full-scale proof test as an acceptable alternative in certain cases. No significant changes are contemplated in flight loads survey testing or in vibrations, flutter and acoustics testing.

a) Static Ultimate Tests. In the previous specifications, static ultimate and failure tests were stated as a firm requirement prior to release of 80% flight load restrictions. The new specifications recognize that there are certain cases where the cost of a static test to destruction might not be justifiable. An example might be in the adaptation of a commercial transport to a military purpose.

Static ultimate tests are envisioned as a requirement in most Air Force development programs, but provisions are made for waiving this requirement if the design has been verified previously or if adequate component tests have been performed on critical structure. If the static ultimate test is not performed, then a strength demonstration proof test must be performed. The principal concern in waiving a static test to destruction is with regard to compression and shear stability critical structure. The rationale is that deficiencies in tension critical structure will surface early in the full-scale fatigue test; however, compression and shear stability deficiencies may not be disclosed by a proof test of a single aircraft to the maximum expected flight load, and, if not, neither would they be disclosed by full-scale fatigue test. Without test verification of minimum stability strength margins, there is a risk that the variation in these strengths due to manufacturing and material variations could be sufficient to cause service problems. This risk is, of course, highest for new structural concepts or materials where the buckling and crippling analysis procedures are not well established.

b) Proof Tests. In previous specifications, proof tests were recognized only as a functional test requirement on pressurized cabins and movable structures such as flight control surfaces. The new specifications retain the requirement for functional proof testing of pressurized compartments. The requirement for such tests on movable structures is left as a program decision based on engineering judgment as to the necessity for such tests. The new specifications also recognize the possibility of utilizing proof tests for strength demonstrations (applied to a single aircraft in lieu of the static ultimate test) and as an inspection technique that would be applied to each aircraft or component being inspected.

In using a proof test for strength demonstration, the proof test load level would be at least as great as the maximum design spectrum load and in no case less than the design limit. Critical design conditions would be tested, and this testing would be prerequisite to the release of flight load restrictions. In using proof testing as an inspection technique, the specifications allow the use of specific component (and, if justified, the full aircraft) proof testing for the purpose of defining maximum possible initial flaw sizes where design constraints make the use of conventional NDI impractical or not cost effective. The proof test load level, test temperature, and reproof requirements must be established analytically and verified experimentally. It is envisioned that proof test inspections might play a more prominent role in the inspection of advanced composite and bonded structures.

c) Fatigue tests – general. Establishing optimum requirements for cyclic fatigue testing led to more deliberation than any other single area. The authors have confidence that the resulting specification is technically sound, that it optimizes program cost and schedule considerations, and that it is flexible enough to apply to most Air Force programs without major deviations. In formulating this policy, the rationale is that the most important purpose of a full-scale fatigue test is the identification of critical fatigue areas ("hot spots") not previously identified by analysis or component testing. It is thus important to conduct fatigue testing as early as possible in a development program, so that design deficiencies can be identified and corrected as soon as possible in production, to avoid costly downstream modification and retrofit programs. The fatigue test serves a number of other useful functions, such as demonstrating compliance to the requirement that the economical operational lifetime exceeds the design service lifetime when subjected to the design loads/environment spectra, providing a basis for establishing *when* and *what* special (i.e., previously unplanned) inspections and/or modifications are required for force‡ aircraft, providing a basis for verifying initial quality (flaw distribution) estimates used in the original design, verifying flaw growth analysis procedures, and providing partial (and possibly total) compliance to full-scale damage tolerance testing requirements. In addition, the new policy recognizes the value of a teardown inspection of the test article at the conclusion of cyclic testing. The following paragraphs outline current full-scale fatigue test policies and point out differences from previous policy.

Selection of test articles. It will be a program option whether or not the testing will be performed on a full aircraft or separately on the major assemblies thereof such as the wing, fuselage, or empennage. Potential schedule and cost advantages favor major assembly tests, although airframe/jig interface problems may outweigh schedule and cost advantages of assembly testing for some aircraft. The test article should be an early Research, Development, Test, and Evaluation (RDT&E) aircraft so as to comply with the "scheduling policy" discussed later, but be as representative of the probable operational configuration as the schedule will allow. If there are significant design, material, or manufacturing changes between the RDT&E test article(s) and production aircraft, then test of an additional fatigue test article or selected components thereof will be required. The old policy emphasized fatigue testing of a full aircraft selected from a stable production configuration, thus leading to very late fatigue test results.

Fatigue test scheduling. One lifetime of fatigue testing will be completed prior to the decision for full production go-ahead and should be supported by initial flight loads survey data. Two lifetimes of fatigue testing plus a close visual inspection will be completed prior to the first production aircraft delivery. In the event that the economic life is reached prior to two lifetimes, a sufficient portion of the teardown inspection and data evaluation will be completed so as to establish whether or not production changes are required prior to the first production aircraft delivery. Previous policy did not address test scheduling as related to production scheduling.

Test spectrum and environment. The design flight by flight loads spectrum, with rationally distributed positive and negative loads and flights, will be used in full-scale fatigue tests. Truncation of the design spectrum (i.e., elimination of certain load cycles) to reduce test times and costs will be allowed provided that the effect is defined, by analysis and laboratory experiment, and accounted for. Air Force approval of the test spectrum will be required. Where it is judged by the System Program Office (SPO) that chemical and/or thermal environment could affect test results significantly, the

‡Use of the word "force" refers to "the force of operational aircraft." The word "fleet" often is used in this context.

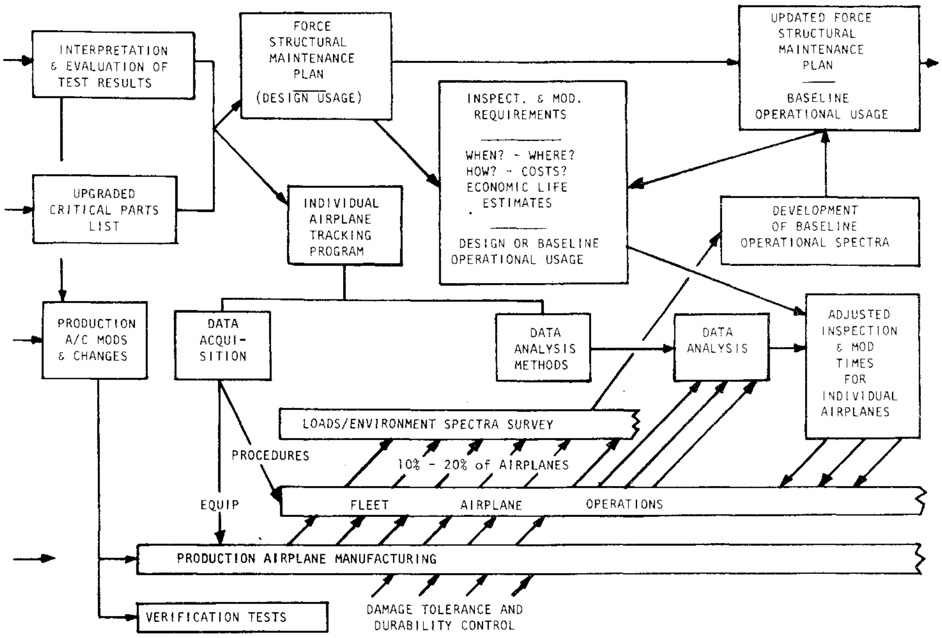

Fig. 4 Force management.

design environment spectra will be simulated during fatigue testing. Previous policy did not emphasize chemical environmental simulation. It is anticipated that in most cases material selections can be made which will minimize the requirement for and the cost of chemical environmental simulation.

In-progress inspections. The required inspection procedures and intervals applied to full-scale fatigue test articles will be the same as those assumed in the design of the aircraft. Where such problems as loading pads and test fixtures make inspection of certain areas of the structure impractical, the possible deletion of the inspections of these areas will be reviewed and, as deemed to be justified, submitted to the SPO for approval. Additional engineering inspections considered necessary or helpful to the achievement of the test objectives will be established by the contractor and/or the SPO.

Test duration. A number of conflicting considerations require that a compromise policy be establshed in the area of test duration. Technically, there is a good agreement for continuing cyclic testing until the economic life is attained in order to determine life extension capabilities of the aircraft. There are other compelling reasons to terminate testing as early as possible to minimize costs, to allow possible further damage-tolerance testing, and to provide timely data for subsequent force management tasks. At least one lifetime of testing certainly is needed to demonstrate compliance with the durability design requirement that economic life exceeds the design life for the design usage spectra. It generally is agreed that more than one lifetime of testing is desirable to enhance detection of possible "hot spot" areas during test and teardown inspection. The current established policy is that a minimum of two lifetimes of testing will be conducted except in such case the economic life is reached prior to two lifetimes. If the economic life is not reached in two lifetimes, the decision to continue or discontinue testing will be made on an individual program basis. Primary factors in this decision include funding requirements, development and production schedules, possible force life extension needs, effects of possible usage extremes on life, and the magnitude of cracking problems encountered in two lifetimes of testing. The old policy required four lifetimes of testing to support the "safe life" approach of mean life prediction and use of a scatter factor of four.

Damage tolerance testing. Tests to demonstrate compliance with the damage tolerance design requirements will be performed. These will be slow crack growth tests and/or fail-safe tests, depending on how the structure was qualified as damage tolerant. The test program will be flexible and tailored to specific systems. Extent of the program will depend on the number of fracture critical parts or areas in the airframe and the extent of verification already obtained during the full-scale fatigue tests and previous component tests. Existing hardware will be used to include the static test aircraft, the fatigue test aircraft, and component test articles. Detailed test requirements such as type of tests, number of tests, choice of specimens, and precrack locations will be established by the System Program Office. Corrective actions to include modifications, special inspections, and process changes will be required for deficiencies disclosed during these tests because the damage-tolerance requirements are to protect safety of flight.

Teardown inspection. A teardown inspection and, as deemed necessary, fractographic examinations will be performed for the purposes of 1) locating critical structural areas (hot spots) not previously identified, 2) verifying analytical crack growth predictions and compliance with damage tolerance requirements, 3) assessing the adequacy of the design inspection procedures and intervals, and 4) assessing the initial quality of the structure. The scope of the teardown inspection, the specific inspection procedures used, and the extent of the fractographic examinations will vary depending on 1) the specific aircraft design, including materials, critical flaw sizes, and number of critical parts, 2) the duration of testing and the extent of cracking noted during the test, and 3) the correlation between predicted stresses and those determined from strain gage measurements.

E. Test Evaluation and Acceptance Criteria

A major test data review will be conducted to interpret and evaluate results from static tests, fatigue tests, damage tolerance tests, and the flight loads survey. Each structural problem will be analyzed individually to determine the cause, corrective action, operational force implications, and estimated costs. A total program then will be defined to correct deficiencies that could include any or all of the following: production modifications, revisions to operational inspection requirements, force modifications, and post-modification inspection requirements.

This test data evaluation review will provide a measure of the success achieved in the design of a safe and durable airframe, will scope the magnitude of program production and operational impacts, and will serve as the basis for establishing the Force Structural Maintenance Plan. The results of this review will give a good basis for program decisions on redesign requirements, contractual awards or penalties, and number of aircraft to be produced.

The old acceptance criteria required a demonstration of 150% of limit load capability for critical conditions in the static ultimate test and four lifetimes without fatigue failure in the fatigue test. There was, however, no generally accepted definition of fatigue failure.

F. Force Management Policy

Force management encompasses two major activities: the development of a Force Structural Maintenance Plan and the Individual Airplane Tracking Program. This is illustrated in Fig. 4, and comments on each activity follow.

1. Force structural maintenance plan

As illustrated in Fig. 4, the results of the full-scale test data interpretation and evaluation task will provide the basis for the development of a total Force Structural Maintenance Plan. The development of this plan will be a contractor responsibility and will assume initially that the operational airplanes will be flying to the design usage spectra. The maintenance plan will define the airplane inspection and modification requirements including when, where, how, and estimated costs.

It is intended that this plan will provide the Air Force with overall visibility as to the probable future maintenance cost obligation for the force as well as data that will allow an assessment of operational impacts associated with the maintenance actions, assuming that the airplanes will be flown to the design usage spectra.These data are needed for future force structure and budgetary planning. As indicated previously, the extent of this maintenance plan provides a measure of the contractor's success (or lack thereof) in designing a safe and durable airframe.

Recognizing that the actual usage of military airplanes often differs significantly from the design usage spectra, a loads/environment spectra survey will be conducted for the purpose of obtaining sufficient data to define the actual service usage and allow an update of the design loads/environment spectra. These updated spectra are called the baseline operational spectra. The loads/environment spectra survey generally will consist of installing multichannel recorders on 10% to 20% of the force airplanes and monitoring operational usage for a period of about 3 yr. At the end of about 3 yr the contractor will be responsible for developing the baseline operational spectra and updating the Force Structural Maintenance Plan. It then is anticipated that the Air Force will continue to monitor usage throughout the service life of the airplane and, as necessary, obtain additional updates to the Force Structural Maintenance Plan.

2. Individual airplane tracking program

In addition to the typical operational usage spectra often being different from the original design usage spectra, it also is recognized that any individual airplane usage may be either more or less severe than that represented by the typical spectra. Accordingly, there is generally a need for an Individual Airplane Tracking Program. The Individual Airplane Tracking Program consists of two major elements, as illustrated in Fig. 4. These are definition of data acquisition requirements and the development of data analysis methods. The data acquisition requirements encompass both the definition of recording equipment and the detailed procedures for obtaining the data from the force aircraft and getting them transmitted in a timely manner to the data reduction and analysis facility (i.e., the ASIMIS facility) at the Oklahoma City Air Logistics Center. The recorded data may include load factor exceedance data, flight logs, mechanical strain data, or a combination thereof. It will be an objective to keep the data acquisition as simple and limited as possible to minimize costs.

The data analysis methods will have the capability to estimate the potential flaw growth in each of the critical areas of the airframe and will be keyed to the damage growth limits of MIL-A-83444. The individual airplane usage data will be analyzed using these analysis methods and the inspection and modification times (included in the Force Maintenance Plan) adjusted for each airplane. These data then will be provided to the appropriate air logistics center for use in maintenance planning.

V. Summary

In summary, it can be seen that a major overhaul of the Air Force philosophy and approach to obtaining safe and durable airframe structure is being accomplished. With the incorporation of the changes discussed, it is anticipated that many of the structural problems that have been encountered on past systems will be diminished substantially in the future. The current status with regard to upgrading the controlling Air Force standards and specifications is as follows: MIL-A-83444 was published in 1974; MIL-A-8866B and MIL-A-8867B are presently in publication: MIL-STD-1530 currently is being reviewed at U.S. Air Force Headquarters. All of these documents have been coordinated with the Materials and Structures Committee of the Aerospace Industry Association. Certain concerns have been expressed by that committee, primarily relating to the cost and schedule implications of the new requirements.

The philosophy and policies discussed currently are being incorporated in the development of our newer military aircraft, for example, the F-16. They also are being used as a guide in a number of assessment activities on older Air Force aircraft. The Aeronautical Systems Division (ASD) of the Air Force Systems Command is working closely with other organizations such as the Air Force Logistics Command and the Air Force Laboratories to attack problems of structural durability and safety on a wide front. Although considerable progress has been made to date, much remains to be accomplished in continuing future efforts. As an example, continuing handbook development activity is required. A Durability Handbook is in preparation by ASD to reflect lessons learned and "do's and don'ts" in the area of design for durability. A specification, and possibly a handbook, is needed in the area of force structural management to govern aircraft tracking programs. Continued major research and development supporting activity by the Air Force Flight Dynamics Laboratory and Air Force Materials Laboratory is essential; considerable opportunity exists to effect improvement and to remedy technical deficiencies in current analysis methods and in the existing data base. Also, regarding new developments such as advanced composite and bonded structures, although current policy applies in general, joint efforts are underway to develop unique certification procedures where required.

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