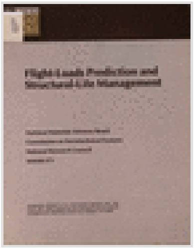

Flight-Loads Prediction and Structural-Life Management (1981)

Pages
37

Size
8.5 x 10

ISBN
030933120X

Committee on Loads Measurement and Life Prediction of Aircraft; National Materials Advisory Board; Commission on Sociotechnical Systems; National Research Council

TL 570 .F54 1981

Flight-loads prediction and
structural-life management

NATIONAL RESEARCH COUNCIL
MISSION ON SOCIOTECHNICAL SYSTEMS
NATIONAL MATERIALS ADVISORY BOARD

Chairman

Mr. William D. Manly
Senior Vice President
Cabot Corporation
125 High Street
Boston, MA 02110

PAST CHAIRMAN

Mr. Julius J. Harwood
Director, Materials Science Lab
Engineering and Research Staff
Ford Motor Company
P.O. Box 2053
Dearborn, MI 48121

Members

Dr. H. Kent Bowen
Professor, Ceramic and
Electrical Engineering
Massachusetts Institute
of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

Dr. William J. Burlant
Manager, Materials Technology
Operations
General Electric Company
Engineered Materials Group
500 W. Wilson Bridge Road
Columbus, OH 43285

Dr. George E. Dieter, Jr.
Dean, College of Engineering
University of Maryland
College Park, MD 20742

Dr. Larry L. Hench
Professor and Head
Ceramics Division
Department of Materials
Science & Engineering
University of Florida
Gainesville, FL 32601

Dr. Nick Holonyak, Jr.
Professor Electronic Engineering
University of Illinois-Urbana
Department of Electrical Engineering
Urbana, IL 61801

Dr. John R. Hutchins III
Senior Vice President and Director
Research and Development Division
Corning Glass Works
Sullivan Park
Corning, NY 14830

Dr. Sheldon E. Isakoff
Director, Engineering Research
and Development Division
E. I. du Pont de Nemours
& Company, Inc.
Wilmington, DE 19898

Dr. Frank E. Jaumot, Jr.
Director of Advanced
Engineering
Delco Electronics Division
General Motors Corporation
P.O. Box 1104
Kokomo, IN 46901

Dr. Alan Lawley
Professor Metallurgical Engineering
& Chairman, Materials Engineering
Department
Drexel University
Department of Materials Engineering
Philadelphia, PA 19104

Dr. James W. Mar
Professor, Aeronautics and
Astronautics, Bldg. 33-307
Massachusetts Institute
of Technology
Cambridge, MA 02139

Dr. Raymond F. Mikesell
W. E. Miner Professor of Economics
University of Oregon
Department of Economics
Eugene, OR 97403

Dr. R. Byron Pipes
Director, Center for
Composite Materials
Department of Mechanical &
Aerospace Engineering
University of Delaware
Newark, DE 19711

Dr. Brian M. Rushton
Vice President, Technology
Celanese
1211 Avenue of the Americas
New York, NY 10036

Dr. Allen S. Russell
Vice President, Science
& Technology
Aluminum Company of
America
1501 Alcoa Building
Pittsburgh, PA 15219

Dr. John J. Schanz, Jr.
Senior Specialist
Congressional Research
Service-ENR
Library of Congress
Washington, DC 20540

Dr. Arnold J. Silverman
Professor
Department of Geology
University of Montana
Missoula, MT 59801

Dr. Dorothy M. Simon
Vice President & Director
of Research
AVCO Corporation
1275 King Street
Greenwich, CT 06830

Dr. Roger A. Strehlow
Professor, Aeronautical and
Astronautical Engineering
University of Illinois
Urbana
101 Transportation Building
Urbana, IL 61801

Dr. Michael Tenenbaum
1644 Cambridge
Flossmoor, IL 60422

Dr. William A. Vogely
Professor and Head
Department of Mineral Economics
Pennsylvania State University
University Park, PA 16802

Dr. Albert R. C. Westwood
Director, Martin Marietta Labs
Martin Marietta Corporation
1450 South Rolling Road
Baltimore, MD 21227

NMAB Staff

R. V. Hemm, Acting Executive Director

2-81

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		**READ INSTRUCTIONS BEFORE COMPLETING FORM**
1. REPORT NUMBER NMAB-373	2. GOVT ACCESSION NO. --	3. RECIPIENT'S CATALOG NUMBER --
4. TITLE *(and Subtitle)* Flight-Loads Prediction and Structural-Life Management		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER NMAB-373
7. AUTHOR(s) Committee on Loads Measurement and Life Prediction of Aircraft		8. CONTRACT OR GRANT NUMBER(s) MDA 903-78-C-0038
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Materials Advisory Board National Academy of Sciences 2101 Constitution Ave., N.W. Washington, D.C. 20418		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS --
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 1981
		13. NUMBER OF PAGES 31
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Distribution limited to U.S. Government organizations only; T&E April 1981. Other requests for this document must be referred to DARPA, 1400 Wilson Boulevard, Arlington, VA 22209.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Aircraft design
Airframe life
Fleet behavior
Fracture mechanics
Inspections
Life prediction
Loads measurement
Predictive methods
Preliminary design
Stress analysis
Structural design
Structural life
Tracking
Wind-tunnel testing

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

This report emphasizes the importance of accurate predictions of design loads early in an aircraft development program. Early wind-tunnel loads testing and generic research programs aimed at improving load-prediction capabilities are encouraged. The report also emphasizes the need for improved methods for predicting airframe life. The development and status of fleet management and tracking programs are summarized. The report notes that the

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

20. continued

quantity of usable data now collected is low, which affects the quality of predictions, and that the adjustment of predictions using fleet-experience data is neglected. The utilization of improved data-recording and processing methods and equipment and the development of quantitative methods for effectively utilizing inspection-feedback information are recommended.

FLIGHT-LOADS PREDICTION AND STRUCTURAL-LIFE MANAGEMENT

Report of the

Committee on Loads Measurement and
Life Prediction of Aircraft

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

Publication NMAB-373
National Academy Press
Washington, D.C.
1981

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which established the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

The Commission on Sociotechnical Systems is one of the major components of the National Research Council and has general responsibility for and cognizance over those program areas concerned with physical, technological, and industrial systems that are or may be deployed in the public or private sector to serve societal needs.

The National Materials Advisory Board is a unit of the Commission on Sociotechnical Systems of the National Research Council. Organized in 1951 as the Metallurgical Advisory Board, through a series of changes and expansion of scope, it became the National Materials Advisory Board in 1969. Its general purpose is the advancement of materials science and engineering in the national interest. It fulfills that purpose by providing advice and assistance to government agencies and private organizations on matters of materials science and technology affecting the national interest, by focusing attention on the materials aspects of national problems and opportunities, and by making appropriate recommendations for the solution of such problems and the exploitation of the opportunities.

This study by the National Materials Advisory Board was conducted under Contract No. MDA 903-78-C-0038 with the Department of Defense and the National Aeronautics and Space Administration.

Printed in the United States of America.

ABSTRACT

This report emphasizes the importance of accurate predictions of design loads early in an aircraft development program. Early wind-tunnel loads testing and generic research programs aimed at improving load-prediction capabilities are encouraged. The report also emphasizes the need for improved methods for predicting airframe life. The development and status of fleet management and tracking programs are summarized. The report notes that the quantity of usable data now collected is low, which affects the quality of predictions, and that the adjustment of predictions using fleet-experience data is neglected. The utilization of improved data-recording and processing methods and equipment and the development of quantitative methods for effectively utilizing inspection-feedback information are recommended.

NATIONAL MATERIALS ADVISORY BOARD

Committee on Loads Measurement and Life Prediction of Aircraft

Chairman

GEORGE P. HAVILAND, Retired (formerly Director, Structures Systems, Rockwell International, Los Angeles, California)

Members

WILLIAM D. BUNTIN, Director, Structures and Design, General Dynamics, Fort Worth, Texas

KEITH HERTZENBERG, Flight Load Specialist, McDonnell Douglas-Corporation, St. Louis, Missouri

DARRELL F. SOCIE, Professor, Department of Mechanical Engineering, University of Illinois at Urbana-Champaign

E. KENNETH WALKER, Structures Division Staff, Lockheed Aircraft Corporation, Burbank, California

JOHN E. WHERRY, Chief of Structures Staff, Boeing Wichita Company, Wichita, Kansas

Liaison Representatives

FRED H. IMMEN, U.S. Army Aviation Research and Development Command, Ames Research Center, Moffet Field, California

FRANK BARATTA, U.S. Army Materials and Mechanics Research Center, Watertown, Massachusetts

ALLAN R. SOMEROFF, Naval Air Systems Command, Washington, D.C.

JACK LINCOLN, Aircraft Subsystems, Wright-Patterson Air Force Base, Ohio

JEROME PERSH, Staff Specialist for Materials and Structures, Office of Deputy Under Secretary of Defense for Research and Engineering, Washington, D.C.

HERBERT F. HARDRATH, Assistant Chief, Materials Division, National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia

GEORGE BATES, Program Manager, Airframes, Aircraft Design Criteria Branch, Federal Aviation Administration, Washington, D.C.

NMAB Staff

JOSEPH R. LANE, Staff Metallurgist

Chapter 1

CONCLUSIONS AND RECOMMENDATIONS

FLIGHT-LOADS PREDICTION

Conclusions

1. Although the accurate prediction of design loads is central to successful aircraft structural development, very little generic research and development effort has been devoted to improving design-load-prediction methods.

2. Instrumented flight-test aircraft can be most useful in establishing the loading characteristics of an aircraft and the load trends over the entire envelope, but they are not always used effectively.

Recommendations

1. Given the schedule and financial constraints on aircraft development programs, emphasis should be placed on maximizing the opportunities for early wind-tunnel loads testing.

2. Higher Department of Defense (DoD) and National Aeronautics and Space Administration (NASA) priority should be given to generic research and development programs aimed at improving load-prediction capabilities. Such programs should focus on improving wind-tunnel loads testing methods and should involve iterative comparisons of test data with analytical results and existing aircraft program flight data.

3. Full-scale flight-loads programs should include loads surveys to allow the extraction of data to be integrated into a structural-life-management program.

STRUCTURAL-LIFE MANAGEMENT

Conclusions

1. The accuracy of analyses used to predict the onset of airframe fatigue cracks in a fleet depends solely on the data base used. No major improvement in analytical capacity is likely.

2. The quantity of usable usage data from loads/environment spectra survey (L/ESS) programs is unacceptably low.

3. Methods for quantitatively using fleet-inspection-experience data to enhance estimates of fleet condition are lacking.

4. Unless the trend toward more complex individual aircraft tracking (IAT) data-collecting systems is accompanied by improvements in equipment reliability, the yield of usable IAT data will be as low as it now is from L/ESS programs.

Recommendations

1. A program to improve the acquisition and processing of fleet-usage data should be implemented immediately. This program should provide for on-board logic or aerospace ground equipment (AGE) to recognize data error or equipment malfunction, increased attention to the maintenance of needed spare parts in base inventories, and continued emphasis on the development of on-board microprocessors to selectively compile data and therefore reduce the amount to be processed.

2. The Department of Defense (DoD) services should institute requirements that will improve efforts to track older aircraft and to identify aircraft condition with respect to general cracking that would limit usable life. Aircraft users should be required to compile data on all aircraft structural inspections and to forward these data to the life-monitoring agency. The life-monitoring agency should be required to define the significant structural details and the nature of the data to be reported.

Research effort also is needed to provide quantitative means of using inspection-feedback data. (These recommendations anticipate the need for improved capabilities to sustain existing fleets through projected future use beyond initial design life.)

Chapter 2

INTRODUCTION

Acting on a request from the Department of Defense (DoD), the National Materials Advisory Board formed a committee of recognized experts in the fields of loads, stress analysis, fracture mechanics, and aircraft structural design to study aircraft flight-loads measurement and life prediction. Initially the committee was to examine airframe structural integrity from the preliminary design phase through final removal of the airframe from service use; however, it determined that both the U.S. Air Force and U.S. Navy already had initiated studies of the same general subject. Thus, after a complete review of existing information, the committee decided to concentrate primarily on the solution of critical structural problems at the management level by focusing on the need for early external-loads prediction and the need for more information concerning fleet behavior.

Informal discussions on the need for accurate and early loads estimates were held with Navy and airframe contractor representatives. Data on case studies were made available to the committee, but these data are not detailed in the report due to their proprietary nature. The committee received considerable information on the fleet-usage-data issue during briefings by service personnel (October 1979 presentations by B. Archer, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio; W. Hippenmeyer, Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio; R. Wallis, Air Force Logistics Center, Tinker Air Force Base, Oklahoma; F. Baratta, Army Materials and Mechanics Research Center, Watertown, Massachusetts; and R. Catenese and R. Virga, Naval Air Development Center, Warminster, Pennsylvania).

Chapter 3

FLIGHT-LOADS PREDICTION

Economic and time constraints dictate that program resources be used efficiently on the development of modern military aircraft. One area of engineering technology having a significant impact on the development cycle is that of aircraft flight-loads prediction.

With aircraft full-scale development programs continually being squeezed into shorter and shorter time frames, it is imperative that loads predictions be made available to the designers as early as possible if costly design iterations and schedule delays are to be avoided. The accuracy and dependability of such predictions are essential. The need for dealing early with external-loads predictions, sometimes in advance of contract award, has been pointed out by Troughton (1979).

PROGRAM CONSIDERATIONS

It should be recognized that a good estimation of external loads must be made early in any structural-design and fabrication program. It is understood, of course, that iterative refinements are made in many technical areas of design during the early stages of a new air-vehicle development program. For example, basic lines, aerodynamic data, weights, and control system parameters will be refined as the design progresses and have a bearing on structural-design loads as reflected in the design of models for wind-tunnel testing and in the details of analytical methodology. However, in view of the shortcomings of analytical techniques, methods to use wind-tunnel test data earlier in the structural-design-loads development cycle to model the loading should be studied.

ANALYTICAL PREDICTIONS

The ideal solution to the problem of early prediction of design loads would be to develop analytical capability to the point at which loads and aeroelastic effects could be calculated to the accuracy and dependability required in the design. Although great strides have been made in this direction, much work still remains to be done (Liaugminas, 1978). For example, during the 1976 AGARD symposium on fluid dynamics, many unresolved problems encountered during flight were described as were the significant improvements being made in analytical techniques.

Present Capability

Currently used methods for predicting airplane structural-design loads have emphasized digital-computer modeling of aircraft structural and aerodynamic characteristics including aeroelastic interactions. This approach generally makes use of finite-element models to represent the airframe structure and small-panel-buildup representations of external-surface contours to implement the aerodynamic theory. Several different aerodynamic theories, all generally based on potential flow, are available for use in structural-loads analysis.

Over time, aerodynamic theory has evolved from early two-dimensional flow representations on a single infinite-span lifting surface to more complex three-dimensional flow capabilities. This latter capability enables one to recognize differences in flow along the finite span of a lifting surface such as a wing. It also accounts for the effects of aerodynamic interference on wing-body-tail combinations. In addition to interference effects on a body shape caused by the presence of lifting surfaces (i.e., wing, horizontal tail, and vertical tail), body-alone airloads may be predicted. For example, this may be done based on slender-body theory using short-body segments having circular-shaped cross sections of different radii to build up representations of a fuselage or engine nacelle. For purposes of simplification, small-panel-buildup representations of a fuselage often may be used to get good approximations for total airplane lift and pitching moment and generally good load distributions for exposed wing and horizontal tail surfaces. However, this simplification is not considered to give adequate airloads data for structural design of the major fuselage components.

Some great strides have been made in the development of theory. Practical application of theory in the design process for airframe structures now may be accomplished through its use in an integrated computer system. For example, the FLEXLODS Program undertaken by General Dynamics for the Air Force offers the following options of aerodynamic theory: doublet-lattice, kernal function, piston, and modified Newtonian. These options, together with others for modeling structural characteristics, provide powerful tools for making analytical predictions of design loads for both preliminary and detailed design phases.

Shortcomings

Several areas of shortcomings in the current, more generally used, theory are recognized. For example: there is a lack of practical theory for the transonic speed range in which flow conditions are influenced by local shock formations, and questionable load predictions for small structural components such as the wing leading edge (slat) or trailing edge flap can result from nonrecognition of flow separation. In addition potential-flow theory does not recognize the effects of flow separation related to high incidence angles, which resolves into nonlinear aerodynamic effects, and no practical theory has been developed to predict the effects of lift generators such as a vortex-flow field over a wing.

One of the problems that became apparent during the extensive load studies accomplished on the C-5 aircraft is that of turbulence modeling for large aircraft. Several difficulties were encountered. It was found that a significant portion of the gust input was asymmetrical; specifically, there were unsymmetrical inputs from vertical gusts that must be accounted for. This is of concern because all regulatory agencies allow analyses based on symmetrical gusts only. Further, the data base needed to define the three-dimensional nature of the turbulence does not exist. It also was found that phasing of the load components (e.g., bending moment and shear in the wing) was extremely important, especially for the growth of cracks out of fastener holes. The phasing problem also is very significant for the loading computation for a wing-mounted engine pylon. It is believed that the state of the art is inadequate to develop these loads analytically with sufficient accuracy. The airframe manufacturers have compensated for this deficiency by designing conservatively.

Current Development Efforts

There are ongoing efforts to develop improved theoretical methods at several research centers across the nation. The major efforts are summarized below.

The Bailey/Ballhaus Procedure is a three-dimensional transonic wing/body analysis procedure being developed at NASA-Ames. This procedure accounts for the effects of shock formation on local-flow characteristics. In comparison with subsonic or supersonic-potential-flow procedures, it is relatively complex and expensive to use (i.e., it requires considerable setup and computer run time); however, it does provide a means for realistic modeling of nonseparated, mixed-flow conditions and can be considerably less costly than a wind-tunnel test program of comparable coverage.

The Pan Air Program is a three-dimensional potential-flow program being developed by Boeing for NASA-Ames. Subsonic and supersonic steady-flow conditions are covered. Thick-airfoil and general-configuration shapes can be modeled using arbitrary as well as rectangular shapes for aerodynamic panel buildup.

A Boeing program is under development for NASA-Langley. It is similar in its theoretical complexity to the Pan Air Program but with the additional capability of handling nonlinear and vortex flow. This program may be used for transonic flow problems.

The Subsonic-Supersonic-Steady-Unsteady Aerodynamic Technique is under development by Morino at Boston University for NASA-Langley. It is based on potential-flow theory and is similar to the Pan Air Program in complexity. General-configuration shapes may be modeled using panels of arbitrary shape; however, rectangular panels are recommended. This program is being extended to cover transonic flow.

As these efforts emerge from development, they should be evaluated against flight data. If found valid, they should be incorporated into integrated computer systems for airframe design to upgrade and enhance the methodology in areas that are presently deficient because of shortcomings in the current theory.

In any given development program or study, probably only a portion of the capability of the theoretical procedure will be used because the detailed effort usually focuses on a relatively narrow range of configuration variables. Therefore, correlation with test results for a given development program probably will be concentrated only on the procedural capability called on for that program. Shortcomings in the theory may be made evident by correlation analysis while others may remain undetected in the unused portion of the procedure. Further, knowledge of shortcomings that are brought to light may not be made available to other users of the procedure and therefore may do little to enhance further development and more efficient use of the methodology.

WIND-TUNNEL TESTING

Unless analytical methods can be improved to the accuracy required for design-loads prediction, wind-tunnel testing of loads must be relied on to give the most accurate assessment of the loads distributions that can be expected to occur on a new aircraft when it reaches flight status. Improvements in this area, along with testing early in the development cycle, will lead to a much higher certainty factor in the aircraft design.

Researchers have investigated specific wind-tunnel-testing problems, but very little effort has been expended on the overall concept of wind-tunnel loads testing. What is needed are parametric wind-tunnel investigations aimed solely at determining the influences of various aircraft design parameters on the choice of model (type, size, etc.) and the types of instrumentation available (optimum strain-gauge bridges, optimum pressure-tap grids, etc.). If the work is done on a general basis, without regard for specific aircraft, the results can be used in all future programs to define specific needs. In the past, as each new aircraft development program was begun, the approach to wind-tunnel loads testing that was adopted reflected budget constraints, and little time or money was available for research to determine the best method to use for a particular aircraft under consideration.

FLIGHT LOADS

The measurement of loads in flight on an appropriately instrumented aircraft, in consonance with full-scale static and fatigue tests, represents a major step in verifying that the airframe is structurally adequate for the design requirements as defined by procurement specifications. In an ideal flight-loads program, all load components considered significant in design of the airframe would be measured in flight. Furthermore, the schedule would be such that any adverse variation between measured and predicted loads could be accounted for early enough to make appropriate manufacturing changes in the program.

Present Capability

The ultimate test of the quality of a loads program is how well the actual flight-measured loads correlate with the predicted loads used in the design. This is true whether the method used is a discrete point demonstration (Navy) or multipoint flight survey (Air Force). For this reason, the main thrust of full-scale flight-loads-measurement programs has been the verification of design loads to determine the adequacy of the aircraft structure. Instrumentation consists mainly of overall airplane kinematic devices (i.e., accelerometers and rate sensors), flight-condition sensors (such as pitot tubes), and calibrated structural-strain measurements.

Outlook

A complete and thorough flight-loads survey can supply data that can be used throughout the lifetime of the aircraft to simplify and enhance the tracking and monitoring programs. With increased emphasis on durability and service-life monitoring procedures for operational aircraft, the verification of maximum design conditions is no longer adequate in itself. Rather, loads also must be verified at subcritical flight conditions that, because of the mission requirements of a particular aircraft, may result in more significant airframe damage in terms of fatigue and crack growth than the static design load conditions. The ground-air-ground cycle needs to be defined for all airframe members including the landing gear. The effects of actuator loads also should be evaluated and defined. Sufficient data need to be acquired to permit the development of equations that relate basic aircraft parameters as recorded on service-loads recorders to loads or stresses at the various fatigue- or fracture-analysis control points. The more thorough and extensive the initial flight-loads survey, the more valid will be the decision on the limited number of parameters to record in tracking and monitoring each aircraft to determine such things as life expended and changes in usage.

SUMMARY

The general approach to determination of flight loads for use in the design of aircraft structure involves three basic phases: analytical predictions, wind-tunnel testing, and flight-loads measurement.

Although current capabilities and development under way in the area of analytical prediction are adequate for the foreseeable future, improvements, particularly in the area of wind-tunnel testing, could substantially reduce uncertainties in loads prediction and reduce costs of the loads effort. However, the loads-determination methods, regardless of their sophistication, will have little or no effect on aircraft design unless they are initiated in the development process at a very early stage.

Loads flight testing, in addition to being the final verification of design flight loads, also should be expanded to include loads surveys at other than critical design conditions. The data from these surveys then can be used to update aircraft-life predictions and establish inspections. When derived from a fully instrumented aircraft, information of this type can simplify the fleet-monitoring and tracking program required for a specific aircraft by reducing the number of measurements needed to adequately describe the flight loads acting on the aircraft during actual fleet usage.

REFERENCES

Liaugminas, R. Technical Evaluation Report on Fluid Dynamics. Panel on Prediction of Aerodynamic Loading, Report No. AGARD-AR-125, NASA-Ames Research Center, 1978.

Troughton, A. Plantema Memorial Lecture. International Congress on Air Fatigue. Brussels, Belgium, 1979.

Chapter 4

STRUCTURAL-LIFE MANAGEMENT

Military aircraft are a vital resource of the United States. Because the cost of aircraft replacement is great and requires advanced planning, the structural integrity of these aircraft must be continuously monitored and maintained. Various programs for monitoring fleet use and tracking the structural condition of military aircraft have evolved through the years (Clay et al., 1978; McDonnell Aircraft Company and Vought Corporation, 1979). The objectives of these programs vary with aircraft type, use, and age. Among the more common are loads/environment spectra survey (L/ESS) and individual aircraft tracking (IAT) programs.

LOADS/ENVIRONMENT SPECTRA SURVEY PROGRAMS

One L/ESS program approach is to instrument extensively one or two aircraft of a given type and to subject them to special systematic flight tests. The purpose is to obtain or revise estimates of the load distribution for given maneuver, gust, landing, and other specific flight conditions. The use of flight-loads data to verify design is an example of this approach. and it was reported to the committee that the U.S. Navy uses this approach when there is an apparent need (October 1979 presentation by B. Archer, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio; W. Hippenmeyer, Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio; and R. Wallis, Air Force Logistics Center, Tinker Air Force Base, Oklahoma). This need can arise when there is an obvious change in mission requirements, an increase in structural problems in the fleet, or observable changes in measurements by relatively simple on-board IAT equipment. Usually this IAT equipment is a counting accelerometer that records the number of times normal load factors (n_z) are exceeded. When more complex monitoring is required, either more complex monitoring equipment needs to be installed or some external means must be employed (e.g., filming of carrier landings of the aircraft or flying over a specially instrumented range). Although a high percentage of usable data most likely can be obtained, the number of aircraft monitored and the amount of information obtained is limited.

Another L/ESS program approach is to install special instrumentation on 10 to 20 percent of a fleet of aircraft and monitor this instrumentation continually, along with less complex IAT instruments. The special instrumentation varies from relatively simple VGH recorders that measure air speed, acceleration, and altitude to multichannel recorders that, in addition to VGH, record such factors as roll rate, control surface positions, and strains at select locations in the structure. Newer aircraft generally have the more complex instrumentation. This approach is used by the U.S. Air Force.

In addition to being used to monitor and update loads assumptions associated with IAT data, continuously recorded L/ESS data are used to provide historical loads information that enhances assumptions made for planning future aircraft systems. Experience to date with monitoring L/ESS instrumentation during routine aircraft use shows a low (about 10 percent) recovery of usable data (October 1979 presentation by B. Archer, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio; W. Hippenmeyer, Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio; and R. Wallis, Air Force Logistics Center, Tinker Air Force Base, Oklahoma).

In many if not most instances, in-service use changes from that defined as baseline during the life of an aircraft fleet (e.g., because of changes in threat or tactics, the introduction of new weapons, modernization of older aircraft to improve performance, or a combination of these). Because of the substantial impact these changes can have on expected service life, structural-inspection and maintenance requirements and the safety of the aircraft, it is essential that any significant usage change be identified as early as possible and its effects quantified. Thus, continual, or at least frequent, re-evaluation of operational-load spectra or load-time history is mandatory. Neither of the current approaches has been totally satisfactory for accomplishing these re-evaluations.

INDIVIDUAL AIRCRAFT TRACKING PROGRAMS

Information from which loads may be derived, with the support of L/ESS data, is monitored for every aircraft of a fleet throughout the life of each aircraft. On older fighter aircraft the monitoring equipment is a counting accelerometer. Additional details of missions flown are recorded in a pilot log. For transport aircraft, individual aircraft tracking has been by pilot log. All newer transport aircraft (C-5) have on-board equipment available for detailed monitoring but only a sample is monitored continuously. Newer fighter aircraft such as the F-14 and F-16 have relatively complex instrumentation that is monitored on all such aircraft. On these aircraft, the differences between L/ESS and IAT programs become less significant.

The IAT data in conjunction with more detailed data obtained in the L/ESS program and special aircraft-condition inspections are used to estimate the accumulated fatigue damage in aircraft of a given type in order to schedule major modifications and replacement. The Air Force uses these data to estimate crack growth in order to schedule inspections and safely detect cracks in critical structure.

The information from the IAT program also is used to determine how aircraft should be flown and rotated through various assignments to conserve the fleet, to guide inspection intervals and procedures, to maintain safety, to schedule repairs at the most cost-effective time, and to advise squadron commanders about unusual life and safety penalties accruing for individual aircraft in their squadrons. IAT information also is used in scheduling special or early inspections and modifications to a specific aircraft in the light of its specific load experience.

IAT programs achieve their objectives by providing estimates of the time at which fatigue cracks initiate and/or the time it takes for cracks to grow. These estimates are obtained by relating estimates of the number of stress cycles and their severities at sensitive locations in the structure to prior cracking experience or fatigue test results through a suitable analysis scheme.

Numerous analysis schemes are available to support IAT programs. These programs will vary in methodologies used, complexity, and scope. However, regardless of these differences, each program should perform the same identifiable tasks:

1. Estimate baseline use.

2. Define the probable condition (number, size, locations and growth rates of cracks) in the structure in terms of the number of hours, missions, or flights of a reference (baseline) use.

3. Develop a relationship between the reference use and actual use so that the probable condition of an aircraft can be determined.

4. Perform inspections of the aircraft when its estimated condition warrants and perform the maintenance, repairs, or replacements dictated by inspection findings.

5. Compare anticipated conditions of the aircraft with those actually observed and adjust the relationship between baseline use and actual use accordingly. This task sometimes also includes development of new baseline information, improved fleet-monitoring procedures, or even revision of basic approach.

BASELINE USE

There are basic differences between the Air Force and Navy philosophies with respect to the baseline stress spectra or stress-time history used to design and qualify new aircraft. These baseline stress spectra and subsequent modifications thereof by L/ESS information are fundamental to estimating individual aircraft damage conditions. In a broad sense for purposes of design, the Air Force attempts to define the average use of an aircraft while the Navy attempts to define a relatively conservative use, which is identifiably true for fighter and attack aircraft. For other aircraft, such as large patrol aircraft, the probable conservatism is less identifiable.

Historically, neither of these baseline design test spectra have been truly representative of actual service spectra as discussed previously with respect to L/ESS programs. Thus, there is a real need for the collection and analysis of L/ESS information. This information can be used to update the baseline spectra and to develop a baseline for future aircraft.

Once the baseline loads spectra or load-time history has been defined, the stress spectra or stress-time history is generated for areas of structure where experience and/or analyses have indicated a potential safety or durability problem. Specific methods vary for accomplishing this translation of a load-time history into internal stresses at select locations. With the exception of the problems associated with the development of external loads discussed in chapter 3, the methods are straightforward and mathematically relatively accurate. The overriding variable is estimating the local stress-time history.

PREDICTIVE METHODS

There are two basic approaches to conducting durability and/or damage tolerance analyses: fatigue initiation and fatigue crack growth.

The fatigue-initiation approach is the older of the two and involves determining the time for cracks to "initiate." There are, however, various interpretations of the term "initiate." In aircraft use, "initiate" can be interpreted as the time for cracks to become of sufficient size so as to be safe yet detectable in the structure (inspection threshold), to be undetectable yet compromise safety (safe line), or to be an economic burden (economic limit). Most frequently, the conditions associated with "initiation" are not well defined. The index of whether or not the time for "initiation" has been reached is expressed as a damage fraction with the "initiation" time as unity. In its most familiar form, linear cumulative damage, stress-time history effects (sequence effects) are only considered indirectly through correlation with service experience. This indirect consideration of load-history effects is accomplished by making trial linear cumulative-damage calculations (i.e., summing up the fraction of total damage attributable to each stress level independently). The trials start with the selection of a set of constant-amplitude stress versus cycles-to-failure curves (S-N curves) for a notch geometry K_T that, for a given type of structure and fabrication procedure, prior experience has shown provides good agreement between a linear cumulative-damage fraction of unity and observed test and/or service cracking under variable-amplitude load conditions. In design, these S-N curves and the anticipated load history are used to adjust stress levels in the structure until design objectives (in terms of a design-target damage fraction) are met. In aircraft-use monitoring, these S-N curves and the estimated service load history are used to obtain a damage fraction that is then compared to the design-target damage fraction and indirectly to the condition of cracking it is supposed to represent. Presumably, when this design-target damage fraction is reached in service, the state of cracking will be similar to that for the test or service experience base at the same design-target damage fraction. This approach was used in the design of all aircraft through the 1960s and is still in some use today for fleet tracking, particularly for older Navy aircraft.

The second approach, crack growth, assumes that cracks of some size or sizes exist in a structure from the onset. The sizes of these are determined, usually by analysis, so that when "grown" mathematically they correspond at some point in time to cracks observed in service or test. A relatively large initial size (typically a 0.05 in. semicircular corner crack) is assumed to exist and is "grown" in the structure in the U.S. Air Force approach to define a safety limit. This limit is reached when the grown crack has reached a size that would cause fracture under a specified load level. Most frequently, stress-time-history effects are considered directly, using a calculation procedure in which the influence of prior large tensile or compressive loads alters the subsequent growth contribution for smaller load cycles until the crack has grown beyond the area influenced by the larger load. This requires estimating the actual sequence of stress levels in the stress-time history. Usually there is some "tuning" of the analysis (by varying constants within the calculation procedure) to match predicted and measured crack growth.

Some form of sequence-sensitive crack-growth methodology has been used to estimate crack-growth behavior in critical elements of structure for the B-1 aircraft and later the F-14, F-15, and A-10 aircraft. In design, baseline constant-amplitude crack-growth data and expected load history are used to adjust stress levels until design crack-growth rates are obtained. These calculations and design objectives are in addition to the previously described linear cumulative-damage calculations and objectives. The latter have been retained to satisfy economic objectives with respect to fleet cracking.

In aircraft-use monitoring, these same crack-growth calculation procedures (or some simplified derivative) are used with an estimated service-load history to obtain a crack size at each sensitive location. These crack sizes and projected growth rates are used to establish times for inspections for structure that can be inspected or to measure remaining "safe" life for uninspectable structure. The Air Force has revised the tracking programs for the majority of its aircraft to include crack-growth estimates.

There are proponents of both methods of analysis, and both have technical difficulties and inherent inaccuracies. Thus, the picture one obtains concerning the consequences of a given aircraft use varies with approach depending on details of methodology. Both methods are, to a great extent, dependent on correlation with test and service experience for meaningful application. Of most concern, even after state-of-the-art correlation with test and service experience, is that the two methods can yield the same time to a given damage state while showing different contributions to this condition for the same elements of aircraft use.

In a practical sense, the crack-growth approach, at least through the detectable size range, is essential because it provides positive information concerning what to look for during inspection. However, it does not provide data on the likelihood of cracking in a given location. This information must come from tests and/or service experience. To the detectable level, corresponding to crack "initiation," prior experience and data base would determine the choice of approach.

When evaluating structure from the viewpoint of long-term durability, it is questionable whether the growth of very small defects can be modeled properly using state-of-the-art crack-growth methods. The development of the initial growth of very small cracks may be along principal shear planes (stage I cracks.) They can be influenced by the full range of shear stress even when a major portion of the load cycle is compressive. This influence can be seen in the effect of compressive loads in typical fatigue-life (S-N) tests. Later in service life, these cracks become oriented normal to the applied tension loadings and are predictable by crack-growth methods. Current crack-growth methods tend to severely truncate the influence of compressive loading. Thus, particularly for estimating the long-term durability of structures such as upper surfaces of wings, the crack-growth approach may be significantly unconservative.

INSPECTIONS

Inspections or other maintenance actions are initiated whenever the estimated condition of an aircraft warrants. Ideally, the findings from inspections should be compared to conditions estimated beforehand so that adjustments can be made in the analyses and in the projections for future inspections. This feedback and re-evaluation task is the most neglected aspect of tracking programs.

First, it is necessary to establish, by a combination of analyses, experience, and testing, what sizes of cracks could be present, what size must be found (safety), and/or the numbers and sizes of cracks that may be present requiring repair (economics). These statistical evaluations then can be used to assess inspection results.

It is possible to arrive at such statistical assessments using either the fatigue-initiation or crack-growth approach or a combination of the two, but such assessments often are not made. When these assessments are made, a feedback of inspection results can then be used to adjust the analysis approach to agree with fleet cracking experience. This adjustment process may be slow or ineffectual when dealing with cracks of low probability of existence in a structure such as is normally associated with safety limits for single-load-path structure. Nevertheless, the adjustment can be extremely important when dealing with aircraft that may be approaching the economic limit of a damage-tolerant structure due to multiple cracking.

Both the Air Force and the Navy now recognize the importance of service-experience feedback. However, analytical tools for relating expectations of cracking and service experience are not well developed, and confidence in existing methods is low.

HARDWARE AND SOFTWARE FOR TRACKING

The equipment used in IAT programs varies from aircraft to aircraft. In general, 20 percent of the Air Force fleet is equipped with multichannel recorders that accumulate data describing aircraft usage by recording many parameters. The balance of the fleet is equipped with minimal instrumentation (e.g., acceleration-exceedance counters). For example, 15 to 20 percent of the A-10 fleet is scheduled to get multichannel recorders while the balance of the fleet will be equipped with counting accelerometers with g levels of 0.3, 2.5, 3.4, 5.5, and 7.0. A pilot log also will be used.

It is important to note that the number of parameters to be recorded vary with aircraft type and missions. A swing-wing bomber with a rolling tail will require more parameters to be recorded than a fixed-wing, conventional-tail trainer. Recording needless data, however, is expensive and counterproductive because the data must then be processed and stored. Thus, the number of channels being recorded should be chosen carefully so that only the pertinent data are taken.

The Air Force uses a centralized agency, located at the Oklahoma Air Logistics Center, to process IAT data. The program is called the Air Force Structural Integrity Management Information System (ASIMIS). It receives and stores all fleet-usage data. Damage calculations for individual aircraft are usually made by the airframe contractor.

The U.S. Navy primarily uses counting accelerometers to generate data for its Structural Appraisal of Fatigue Effects (SAFE) program. More than 3000 Navy and Marine aircraft are included in the quarterly SAFE report. The accelerometer data are used to calculate fatigue-life (initiation) data every three months. Pilot logs and special surveys also are used. The Navy now is tending toward the use of more sophisticated recording devices that will process the data on-board through logic and edit routines resulting in more usable data.

SHORTCOMINGS IN DATA ACQUISITION

As discussed above, the current approach to tracking is to use a few measurements on all aircraft (IAT) and many measurements on a few aircraft (L/ESS). The L/ESS data are used to augment the IAT data to improve the accuracy of damage calculations made from IAT. One of the main problems with the current approach is the obtaining of usable tracking data from the system. Although it varies from aircraft to aircraft, the data return from the continuous service-use monitoring L/ESS programs is typically 10 percent of the possible data return (October 1979 presentation by B. Archer, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio; W. Hippenmeyer, Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio; and R. Wallis, Air Force Logistics Center, Tinker Air Force Base, Oklahoma). There are several reasons for this poor return, including the following:

1. Delayed recognition of data error due to time span between data recording and editing.

2. Improperly installed sensing elements (e.g., strain gages).

3. Delays in repair of recording equipment due to normal procurement-cycle inefficiencies and the lack of spare parts in base inventories.

4. Lack of motivation of personnel because of lack of understanding of the need for the data.

5. Aerospace ground equipment not available or not adequate to detect problems with recording systems.

Based on the experience of dedicated contractor field teams, the usable data return from L/ESS is approximately 75 percent of the possible return. This figure is probably the best that can be achieved, and it is unlikely that returns of over 50 percent will be realized in practice.

The data return from IAT is typically much higher than from L/ESS. The reason for this is that IAT instrumentation is inherently simpler than that of L/ESS. Therefore, the goal of IAT data return should be approximately 90 percent of the total flight time.

There is a trend toward use of more complex instrumentation for IAT programs on newer aircraft. The goal of 90 percent IAT data return should be recognized along with the maximum demonstrated yield for L/ESS programs of 75 percent. In this light, the trend toward more complex IAT instrumentation may need to be re-examined as system-reliability data reach an acceptable level.

Another shortcoming involves the disposition of the data after it has been reduced. On some systems it was found that no maintenance action is taken based on the tracking-program output and that the basis for maintenance action was, in many cases, unverified by inspection results (October 1979 presentation by B. Archer, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio; W. Hippenmeyer, Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio; and R. Wallis, Air Force Logistics Center, Tinker Air Force Base, Oklahoma). One of the reasons for this is inconsistency in the definition of a fatigue failure ("initiation"). This problem has largely been eliminated through the durability and damage-tolerance assessments that have been made on older aircraft in the inventory. These assessments establish crack sizes and growth rates for critical structure on the basis of inspections. The tracking data have been used directly in these assessments to help develop the baseline spectrum and to provide a basis for spectra-sensitivity tests and analyses. So far these assessments have not been updated using new data, and no criteria exist for determining when an update should be accomplished. This is a problem that should be examined carefully.

Still another consideration in the use of tracking data for computing damage to the aircraft structure is the role of the airframe contractor. The durability and damage-tolerance assessments previously mentioned generally have been accomplished at the contractor's facility with mainly contractor personnel. The reason for this is that the contractor has the data base and the experience to perform this assessment efficiently. It would appear reasonable then for the contractor to remain involved with the aircraft tracking program to the extent of updating the assessment periodically and reviewing the published tracking reports.

OUTLOOK

The lack of new airframe designs has focused attention on preserving the life of existing fleets. The programs to extend the service life of the B-52, C-5A, C-141, C-130, A-10, and other fleets have been significant in extent.

It seems that despite speculation about a new group of aircraft, the replacement of existing airframes with new ones is well in the future. This means that present methodologies for tracking usage and life prediction will necessarily have to serve for the foreseeable future. The present methods are both sound and effective when used with a correct data base. It is the latter that needs major attention because much of the data collected from the operating commands cannot be used effectively (October 1979 presentation by B. Archer, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio; W. Hippenmeyer, Air Force Logistics Command, Wright-Patterson Air Force Base, Ohio; and R. Wallis, Air Force Logistics Center, Tinker Air Force Base, Oklahoma).

The task of data collection from fleets in service often is considered to be an unnecessary burden on the maintenance personnel. However, all levels within the operating organization must be made to realize that no meaningful prediction of the life of the fleet can be made without good, usable data.

SUMMARY

L/ESS and IAT are two basic types of loads- and usage-data programs associated with structural-life management. The L/ESS programs conducted by the Air Force continually monitor complex instrumentation on 10 to 20 percent of a fleet. The yield of usable data from these programs is on the order of 10 percent. Navy L/ESS programs are conducted when considered necessary and usually require installation of the special instrumentation on a few aircraft. Although the yield of usable data is higher, the amount of data obtainable is smaller. Continual, or at least frequent, re-evaluation of operational data is mandatory. Existing L/ESS programs need improvement.

Individual aircraft tracking programs use simple instrumentation on all aircraft in the fleet. Yield of usable data is acceptable. There is a trend toward the use of more complex instrumentation in IAT programs. Greater complexity in IAT instrumentation must be accompanied by improved system reliability.

Aircraft inspections and feedback of inspection information for use in adjusting tracking methods is as essential as the collection of loads and usage information. As existing fleets get older, there will be an increased need for inspection feedback to track the fleet with respect to the onset of general cracking. Methods need to be developed to use fleet-inspection data quantitatively.

REFERENCES

Clay, L.E.; Sandlin, N.H.; Morcock, D.S.; Brown, K.E. and Johnson, R.L. Force Management Methods. Prepared at the University of Dayton (Ohio) Research Institute under Contract F33615-77-C-3122 from the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, 1978.

McDonnell Aircraft Company and Vought Corporation. 1979. Improved Structural Life Tracking Procedures for Navy Aircraft. Prepared for the U.S. Navy.