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Overview of NASA Research Related to the Aging Commercial Transport Fleet

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This article describes the research activities of the NASA airframe structural integrity program for the aging commercial transport fleet. Advanced analysis methods are under development to predict the fatigue crack growth in complex built-up shell structures. Innovative nondestructive examination technologies are under development to provide large-area inspection capability to detect corrosion, disbonds, and fatigue cracks. The ultimate goal of this interdisciplinary program is to develop and transfer advanced technology to the airline operators and airframe manufacturers. This program is being conducted cooperatively with the FAA and the U.S. industry.

Introduction

ON April 28, 1988, an Aloha Airlines Boeing 737 experienced an in-flight structural failure when the upper fuselage ripped open and a large section of the skin peeled away. This failure was precipitated by the link-up of small fatigue cracks extending from adjacent rivet holes in a fuselage lap-splice joint. This event, brought about by multisite damage (MSD), helped focus the attention of the industry on the problems of operating an aging commercial transport fleet. Currently, approximately 46% of the jet airplanes in the fleet are over 15-yr old, with 26% being over 20-yr old. During the past 4 yr the industry has acted to ensure the continued safe operation of the aging fleet. These activities included increased emphasis on maintenance, inspection, and repair, as well as mandatory modifications to various models in the fleet. Additional ways of ensuring safety are being vigorously pursued for both the current fleet and aircraft for the next-generation fleet. This article describes the research activities of the NASA airframe structural integrity program (ASIP) which has the goal of developing improved technology to support the safe operation of the current fleet and the design of more damage-tolerant aircraft for the next-generation fleet.

Basic research related to the fatigue and fracture of metals, computational fracture mechanics, structural analysis methods, and nondestructive examination (NDE) methods for material defect characterization has been ongoing at NASA Langley for many years. All of these disciplines have been brought to bear on the problems facing the aging commercial transport fleet. NASA has developed the ASIP in coordination with the FAA and the U.S. airframe manufacturers. The ASIP has two key program elements. They are the development of advanced analysis methodology to predict the fatigue crack growth in complex built-up structure, and innovative NDE technologies to detect fatigue cracks, corrosion, and disbonds in adhesively bonded joints. The near-term focus of the program is MSD in lap-splice joints. However, the research is generic in nature and the developed methodology is expected to be applicable to many other structural components that may be fracture-critical.

Analysis Methodology

The objective of the analysis methodology program is to develop and verify advanced mechanics-based prediction methodology which can be used to determine inservice inspection intervals, quantitatively evaluate inspection findings, and design and certify damage tolerant structural repairs. This objective will be met by developing an analysis methodology that integrates global shell analysis with local fracture mechanics analysis to predict fatigue crack growth in a fuselage structure. This can best be accomplished by developing and exploiting global/local strategies for combining the necessary levels of modeling and analysis. These levels are shown schematically in Fig. 1. A sufficiently detailed local analysis is used to obtain the boundary conditions for a physically meaningful, yet computationally tractable, crack problem. Then a fracture mechanics analysis employing crack closure concepts is used to predict crack growth. The effects of the crack growth must then be integrated upward to the global structural level to insure that correct load transfer paths and internal load distributions are calculated. Of course, these analyses may have to be performed in an iterative fashion to achieve correct results.

The program logic is shown schematically in Fig. 2. The individual program elements are discussed in more detail in the following sections.

Fatigue Crack Growth Closure Model

The concept of crack closure to explain crack growth acceleration and retardation was pioneered at NASA Langley almost two decades ago.[1] The closure concept (illustrated

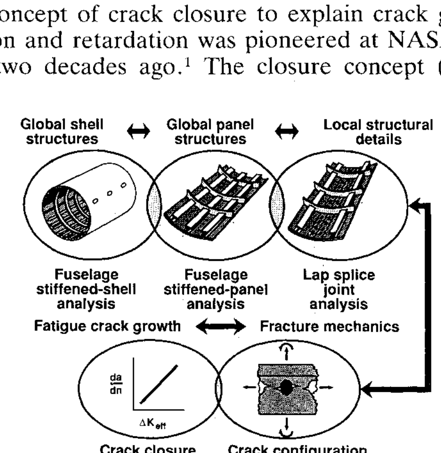

Fig. 1 Integrated shell analysis-fracture analysis methodology.

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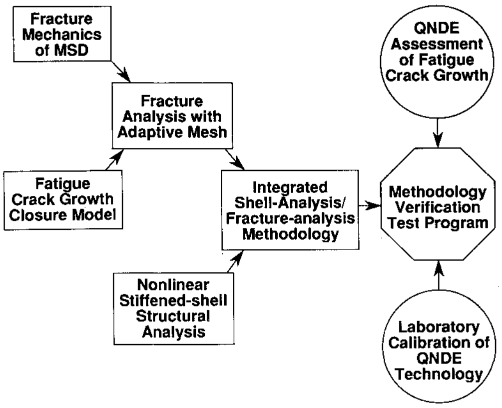

Fig. 2 Logic diagram for analysis methodology program.

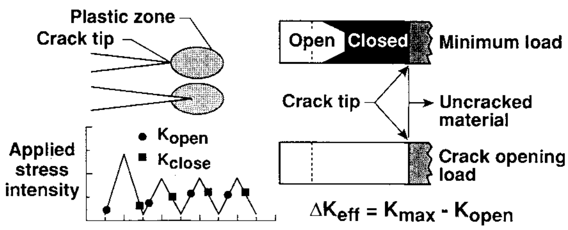

Fig. 3 Fatigue crack growth controlled by closure mechanism.

schematically in Fig. 3) is based on the postulate that the wake of plastically deformed material behind an advancing crack front may prevent the crack from being fully open during the complete loading cycle. Therefore, only part of the load cycle is effective in growing the crack. A plasticity-induced closure model[2] employing fracture mechanics principles was shown to be quite accurate in predicting the fatigue crack growth in aluminum alloys for a number of basic crack configurations for both constant amplitude and spectrum loadings. The closure model has also been successfully used to explain the small-crack phenomenon exhibited by many aluminum alloys. The crack growth rate data must be correlated with the effective stress-intensity factor range, rather than the full range, to yield meaningful predictions of total crack growth. The successful coupling of the closure methodology with the small-crack growth rate data base has resulted in a total life prediction methodology which treats initiation by predicting the growth of micron-size cracks initiating at inclusion particles in the subgrain boundary microstructure.[3] This type of methodology is necessary to predict the fatigue crack growth of small cracks initiating at a rivet hole before they grow to a detectable size. Furthermore, this methodology may be used to predict the necessary inspection intervals to monitor crack growth before critical sizes are reached and before link-up of adjacent cracks occur.

Fracture Mechanics of MSD

A rigorous fracture mechanics treatment of cracks initiating at rivet holes and MSD will require stress-intensity factor solutions to several basic crack configurations. NASA has developed several computational methods for computing stress intensity factor solutions to complex crack configurations. The boundary force method (BFM)[4] is well-suited to two-dimensional problems such as a through-crack in thin sheet material. For more complex problems, the finite-element method and the virtual-crack-closure technique (VCCT)[5] have been successfully employed to obtain solutions to three-dimensional crack configurations such as a surface crack emanating from a semicircular notch. These techniques will be used to generate the solutions to crack configurations such as those shown in Fig. 4. Because MSD linkup is likely to be governed by net section yielding, an elastic-plastic analysis of the loaded rivet hole and a typical splice joint will also be required.

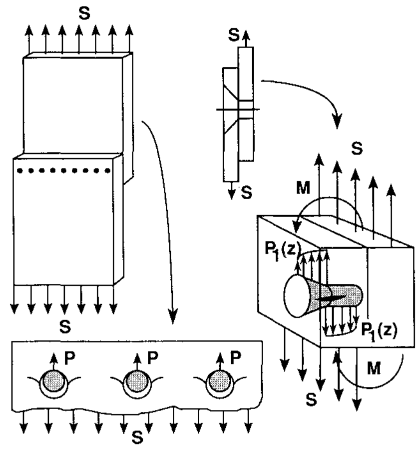

Fig. 4 Fracture mechanics analyses of multiple-site cracks.

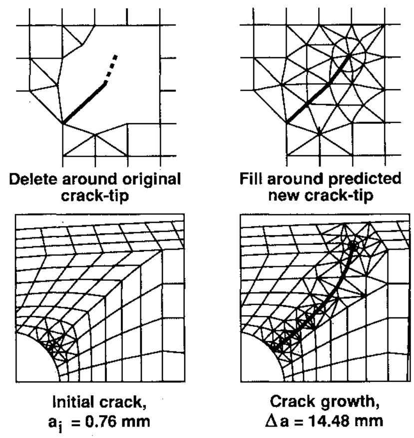

Fig. 5 Crack propagation by adaptive remeshing. Finite element and boundary element methods.[6]

Nonlinear Stiffened-Shell Structural Analysis

The behavior of large cracks in fuselage structures such as midbay cracks or splice-joint cracks after MSD link-up are strongly influenced by the stiffening effects of the circumferential frames and longitudinal stiffeners. It is not practical to model all of the structural details in a finite-element analysis. Greater efficiency can be achieved by exploiting a global/local strategy where local details that produce stress gradients can be treated in a companion analysis to the global structural analysis. The structural analysis methodology will have to account for geometric nonlinear behavior as well as large deformation behavior. Effects such as pressure pillowing and the outward bulge of the skin between stiffeners must also be accounted for in the analysis. This is necessary to predict the crack-growth direction and crack opening of large cracks that may result in a rapid decompression rather than a catastrophic in-flight failure.

Fracture Analysis with Adaptive Mesh

To accurately predict the behavior of a growing crack in a stiffened shell structure, the global/local methodology must be extended to include an adaptive mesh concept so that the local refined mesh can change in a manner dictated by the growing crack. This concept is illustrated schematically in Fig. 5 taken from the work of Wawrzynek and Ingraffea.[6] The path of the growing crack is represented by the heavy dark line in Fig. 5. The top two schematics illustrate the element deletion and refill concept while the lower two schematics illustrate a crack-growth example problem.

Methodology Verification Test Program

The integrated fracture mechanics and fuselage structural analysis methodology must be verified by a test program. As

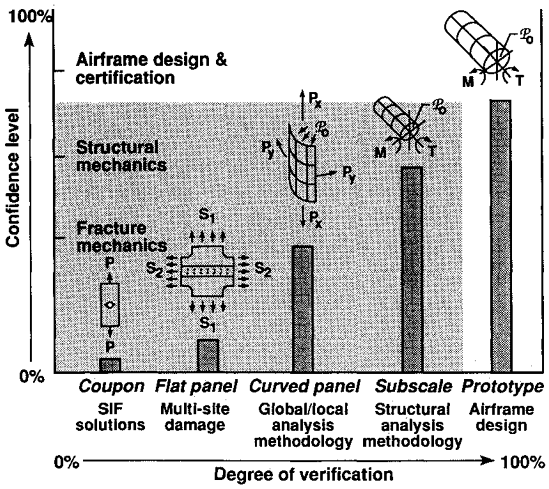

Fig. 6 Prediction methodology verification program.

shown in Fig. 6, there are various levels of testing required to achieve a full verification of a structural analysis methodology. The goal of the ASIP program is to achieve verification through the curved panel and subscale barrel-test article level. This program element will be conducted in cooperation with Boeing Commercial Airplane Company and Douglas Aircraft Company. Each airframe manufacturer will contribute panels with riveted splice joints typical of their manufacturing practices. Furthermore, data from previous fatigue and damage-tolerance test programs conducted by the airframers will serve as bench marks for the analysis methodology verification.

Quantitative Nondestructive Examination Technology (QNDE)

The objective of the QNDE program is to develop and demonstrate advanced NDE technologies that can reliably and economically detect disbonds, fatigue cracks, and corrosion of airframe structures. This objective will be met by developing NDE techniques with large-area inspection capability. A number of NDE techniques are under development by NASA which show great promise for application to airframe structural inspection. These techniques include thermography, ultrasonics, coherent optics, magnetics, and radiography. The science of these techniques must be combined with computational models to insure that the resulting measurements are physically meaningful and interpretable. Finite-element models will be developed to computationally simulate the response of the structure to the sensor input energy. Advanced algorithms will be developed to process the measurements data to extract the most meaningful information. Computational models will then be used to provide a physical interpretation of the data.

The QNDE program logic is shown in Fig. 7. For each technique under development, laboratory demonstrations of the basic measurement science and the proof of concept will be followed by prototype instrumentation development and field-service demonstrations. The large area inspection techniques currently under development are briefly discussed in the following sections.

Thermal Methods

Perhaps the most promising technique in the near-term is an advanced thermal imaging method which is based on heat flux rather than absolute temperature.[7,8] Recalling the one-dimensional Fourier heat conduction equation, the second spatial derivative of the temperature field is proportional to the heat flux. This method is sensitive to any discontinuity in the heat flowfield resulting from features such as a local disbond between mating surfaces. The thermal flux method has been used successfully in the laboratory to detect disbonds in

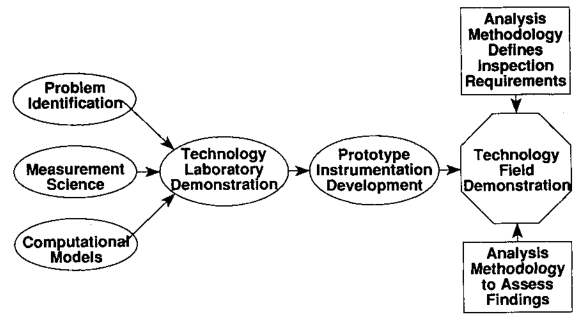

Fig. 7 Logic diagram for NDE technology program.

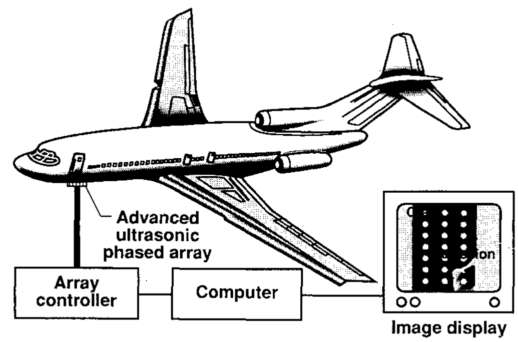

Fig. 8 Processed thermal image of the LaRC Research Boeing 737.

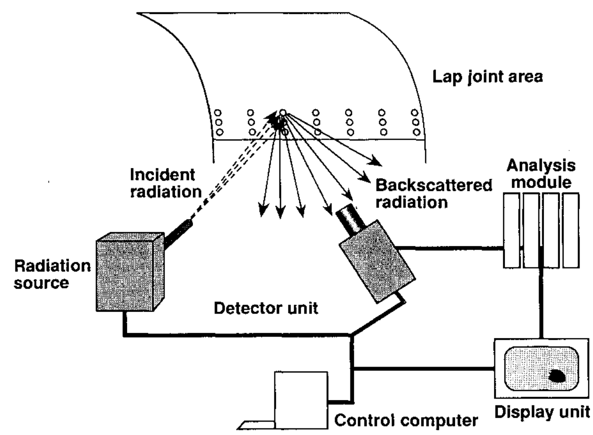

Fig. 9 Application of ultrasonic-phased array imaging of aging aircraft.

the lap-splice joints of test articles. The technique has also been shown to be applicable to actual fuselage structure as illustrated in Fig. 8. This figure shows a resolution of the waffle-doubler pattern of the Boeing 737 fuselage. (No disbonds are present in this pattern.) This technique shows such great promise for detecting disbonds, that NASA and the FAA have developed a technology transfer program and are planning a full-scale field demonstration on an airplane at a field rework facility within the next year.

Ultrasonics

Ultrasonic-phased array techniques,[9] currently under development, also show promise as a candidate for field applications. The technique is similar to phased array RADAR and provides high-resolution detection, image aberration correction, and quantitative characterization through signal processing.[10] As suggested in Fig. 9, this technique has the potential to detect fatigue cracks and corrosion by scanning a relatively large field-of-vision during the inspection. A water spray system will also be developed which will reduce inspection time and permit noncontacting access to the airframe.

Radiographic Methods

Large-area radiographic methods are under development which offer the potential for detecting the presence of corrosion products.[11] As illustrated in Fig. 10, NASA is investigating the feasibility of time-resolved neutron activation. It is anticipated that this technique would be very effective for identifying regions where corrosion exists. These local regions would then be subjected to a more detailed inspection to quantify the type and extent of corrosion.

Magnetic Methods

NASA research is focusing on large-area magnetic technologies rather than conventional eddy current probes.[12] One such concept is illustrated schematically in Fig. 11. This approach would use an array of sensors embedded in a "shield" which is shaped to match the curvature of the fuselage so that the magnetic input energy could be obtained through induction coupling. This shield would then travel along the airframe by way of robotics. Using nonlinear computational techniques, the amplitude and frequency of the first and second harmonics in the ouput signals would be processed to resolve fatigue cracks and severely corroded regions. This technique may also use other sensors, such as acoustics in conjunction with magnetics, to increase the probability of detection.

Optical Methods

Optical techniques offer an alternative technology for large-area inspection. For example, the shearography technique,[13] shown schematically in Fig. 12, does not require special surface treatment such as techniques like moire interferometry, but offers more-or-less equal sensitivity for resolving strain gradient fields produced by structural discontinuities. The optical image displayed in Fig. 12 is the constructive/destructive (light/dark) fringe pattern produced by the displacement gradients in a riveted splice joint. NASA is developing an integrated optics approach including shearography, speckle interferometry,[14] and thermal quantitative diffusivity in conjunction with three-dimensional computational models. The combination of measurements and analysis to convert the optical data into engineering strains is critical to assess the structural condition.

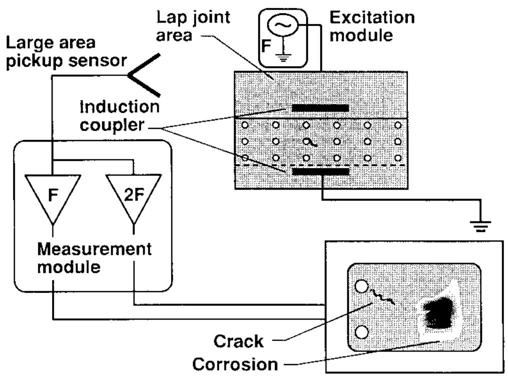

Fig. 10 Backscattering radiographic NDE for corrosion detection.

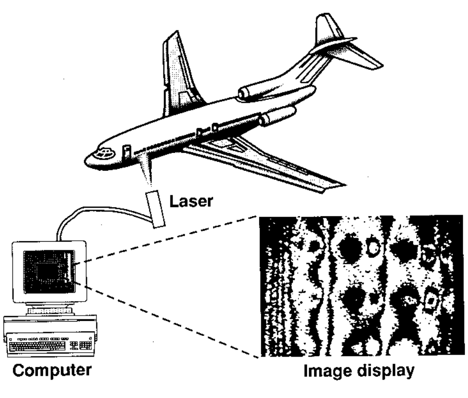

Fig. 11 Application of advanced electromagnetic NDE for aircraft inspection.

Fig. 12 Optical NDE inspection of aging aircraft.

Integrated NDE and Fracture Mechanics

An additional goal of the ASIP program is to couple the disciplines of physics and mechanics to obtain a more thorough understanding of the crack growth process and more reliable experimental maps of the stress gradient fields[15] produced by a crack. The coupon and panel tests planned to verify the fracture mechanics solutions will include NDE techniques. For example, the high-resolution thermal method will be used to provide maps of the local stress gradient fields produced by a crack. This technique relies on a mathematical algorithm derived from thermoelasticity that relates the stress field to the temperature gradients obtained from the infrared radiation emitted by the elastic body undergoing cyclic deformation. This information will provide a useful benchmark to the stress fields predicted by the fracture mechanics analyses. Also, a special facility with an x-ray CAT-scanner system mounted to a servo-hydraulic loading frame will provide three-dimensional images of microcracks in the 25–50 μ size. The three-dimensional image is constructed by processing x-ray exposures taken from various locations around the specimen. This technique will allow for the determination of both the orientation and crack-growth increments of small cracks in real time rather than inferring this information from an examination of the specimen after failure.

Summary

NASA is conducting interdisciplinary research combining the disciplines of fracture mechanics, structural mechanics, material science, physics, and nondestructive instrumentation sciences, for the purpose of developing an advanced integrated technology to support the continuing airworthiness of the aging commercial transport fleet. The objective of the NDE program is to develop and demonstrate advanced NDE technologies that can reliably and economically detect disbonds, fatigue cracks, and the corrosion of airframe structures. The objective of the analysis methodology program is to develop and verify advanced mechanics-based prediction methodology which can be used to determine inservice inspection intervals, quantitatively evaluate inspection findings, and design and certify damage-tolerant structural repairs. The program is coordinated with the FAA and is being worked cooperatively with the airframe manufacturers and airline operators.

References

[1]Elber, W., "The Significance of Fatigue Crack Closure," *Damage Tolerance in Aircraft Structures*, American Society for Testing and Materials STP 486, Philadelphia, PA, 1971, pp. 230–242.

[2]Newman, J. C., Jr., "A Crack Closure Model for Predicting Fatigue Crack Growth Under Aircraft Spectrum Loading," *Methods*

and Models for Predicting Fatigue Crack Growth Under Random Loading, American Society for Testing and Materials STP 748, Philadelphia, PA, 1981, pp. 53–84.

[3]Phillips, E. P., and Newman, J. C., Jr., "Impact of Small-Crack Effects on Design-Life Calculations," *Experimental Mechanics*, Vol. 29, No. 2, 1989, pp. 221–225.

[4]Tan, P. W., Raju, I. S., and Newman, J. C., Jr., "Boundary Force Method for Analyzing Two-Dimensional Cracked Bodies," NASA TM-87725, May 1986.

[5]Shivakumar, K. N., Tan, P. W., and Newman, J. C., Jr., "A Virtual Crack-Closure Technique for Calculating Stress Intensity Factors for Cracked Three Dimensional Bodies," *International Journal of Fracture*, Vol. 36, 1988, pp. R43–R50.

[6]Wawrzynek, P. A., and Ingraffea, A. R., "Interactive Finite Element Analysis of Fracture Processes: An Integrated Approach," *Theoretical and Applied Fracture Mechanics*, Vol. 8, 1987, pp. 137–150.

[7]Winfree, W. P., Welch, C. S., James, P. H., and Cramer, E., "Thermographic Detection of Delaminations in Laminated Structures," *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chementi, Vol. 8, Plenum Press, New York, 1988, pp. 1657–1662.

[8]Winfree, W. P., Crews, B. S., Syed, H., Cramer, E., and Howell, P., "Thermographic Detection of Disbonds in Riveted Lap Joints," *Proceedings of the 37th International Instrumentation Symposium*, Instrument Society of America, San Diego, CA, May 5–9, 1991, pp. 1097–1105.

[9]Johnson, P. H., and Madaras, E. I., "Modeling the Pulse-Echo Response of a Two-Dimensional Phase Insensitive Array for NDE of Layered Material," *Proceedings of the IEEE 1988 Ultrasonics Symposium*, 88CH2578-3, Chicago, IL, Oct. 2–5, 1988, pp. 1021–1025.

[10]Kishoni, D., "Pulse Shaping and Extraction of Information from Ultrasonic Reflections in Composite Materials," *Signal Processing and Pattern Recognition in Nondestructive Evaluation of Materials*, edited by C. H. Chen, Springer-Verlag, Berlin, Vol. 44, NATO ASI Series, 1988.

[11]Birt, E. A., Namkung, M., Vulcan, W., and Welsh, R. E., "Application of Neutron Interrogation Techniques to Corrosion Detection," *Proceedings of Review of Progress in Quantitative NDE*, Vol. 10, pp. 393–518.

[12]Blalock, T. N., and Yost, W. T., "Detection of Fiber Damage in Graphite Epoxy Composite Using Current Injection and Magnetic Field Mapping," *Review of Progress in Quantitative NDE*, Vol. 5B, edited by D. O. Thompson and D. E. Chimenti, 1986.

[13]Hung, Y. Y., *Optical Communications*, Vol. 11, No. 2, pp. 132–135, 1974.

[14]Jones, R., and Wykes, C. *Holographic and Speckle Interferometry*, Cambridge Univ. Press, Cambridge, England, UK, 1983, Chaps. 3 and 4.

[15]Belgen, M. H., "Infrared Radiometric Stress Instrumentation Application Range Study," NASA CR-1067, May 1968.