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# Evaluation and Verification of Advanced Methods to Assess Multiple-Site Damage of Aircraft Structure

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16. Abstract

Widespread fatigue damage (WFD) is a complex phenomenon that is extremely difficult to analyze with standard methods developed from first principles of linear elastic fracture mechanics (LEFM). Because of the limited applications of LEFM, more advanced methods have been explored and developed over the past decade. These include analytical tools to determine parameters governing the onset and growth of cracks and elastic-plastic fracture criterion for residual strength determinations. The tools also include the finite element alternating method (FEAM); a computationally efficient yet rigorous approach to calculate two- and three-dimensional stress-intensity factor solutions governing crack growth; FASTRAN, a fatigue crack growth analysis program using a crack-closure model; and STAGS, an advanced finite element program implemented with fracture mechanics and stable-tearing analysis capabilities for generalized shell structures. The elastic-plastic failure criterion includes the plastic zone touch, crack tip opening angle (CTOA), and the T*-integral. These computational tools must be verified and validated using experimental data to ensure successful transfer of useable and accurate technology to the industry.

The objectives of this study were to (1) take existing analysis tools and establish the processes required of using them as engineering tools to determine the effects of multiple-site damage (MSD) on the residual strength of representative aircraft structures and (2) investigate small crack behavior to better understand the formation of MSD in structures. These tools and criteria were used and verified in this study to analyze portions of the multiple-site crack initiation, growth, linkup, and catastrophic fracture process. For the development of MSD, the fundamental phenomenon of fatigue crack initiation in material and the rate of growth were addressed experimentally at the coupon level and analytically using FASTRAN. The initiation of MSD was addressed at the component level on flat panels that were representative of typical fuselage lap splices. Experimentally generated data and a closure-based crack growth code were used to develop equivalent initial flaw sizes. Residual strength analysis used the application of the T*-integral, CTOA, and plastic zone linkup criteria to predict the linkup and fast fracture of MSD in curved panels and aft pressure bulkhead. A procedure was developed that used elastic-plastic finite element analyses with STAGS and CTOA to perform the stable tearing and unstable fracture of MSD in aircraft structures.

From extensive experimental work, test data was generated and used for correlation and validation and verification of the various methodologies and criteria.

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| | |
|---|---|
| AAWG | Airworthiness Assurance Working Group |
| AFRL | Air Force Research Laboratory |
| AGARD | Aerospace Research and Development |
| BES | Boundary element system |
| BIAM | Beijing Institute of Aeronautical Materials |
| CAAC | Civil Aviation Authority of China |
| CTOA | Crack tip opening angle |
| C(T) | Compact Tension |
| DOF | Degree of Freedom |
| EIFS | Equivalent initial flaw size |
| EO | Engineering order |
| EPFEAM | Elastic-plastic finite element alternating method |
| FAA | Federal Aviation Administration |
| FASTER | Full-Scale Aircraft Structural Test Evaluation and Research |
| FEA | Finite element analysis |
| FEAM | Finite element alternating method |
| GUI | Graphical user interface |
| LaRC | Langley Research Center |
| LEFM | Linear elastic fracture mechanics |
| LVDT | Linear Variable Differential Transformer |
| MPC | Multiple-point constraint |
| MSD | Multiple-site damage |
| NAARP | National Aging Aircraft Research Program |
| NASA | National Aeronautics and Space Administration |
| NDI | Nondestructive inspection |
| NIST | National Institute of Standards and Technology |
| OEM | Original equipment manufacturer |
| POD | Probability of detection |
| PZL | Plastic zone linkup |
| SCG | Small crack growth |
| SEM | Scanning Electronic Microscope |
| SENT | Single-edge notch under tension |
| SIF | Stress-intensity factor |
| TCL | Tool command language |
| USAF | United States Air Force |
| WFD | Widespread fatigue damage |
| WPAFB | Wright-Patterson Air Force Base |

| | |
|---|---|
| $\alpha$ | Constraint factor |
| $K$ | Stress-intensity factor |
| $a_1/L$ | Dimensionless parameter |
| $a_{\text{eff}}$ | Effective crack length |
| $\beta_1$ | Total geometry correction factor for the lead crack |
| $\beta_2$ | Total geometry correction factor for the MSD crack |
| $\beta_u$ | Correction factors |
| $c/a$ | Crack depth to crack length |
| $da/dN$ | Crack growth rate |
| $\Delta K$ | Crack tip stress-intensity factor range |
| $\Delta K$ | Stress-intensity factor range |
| $\Delta K_{\text{eff}}$ | Effective stress-intensity factor range |
| $F_{TU}$ | The material allowable |
| $F_{\text{TY}}$ | Yield strength |
| $F_{TY}$ | Material yield strength |
| $\Gamma_\varepsilon$ | Crack tip contour |
| $M(T)$ | Middle-crack tension |
| $R$-ratio | Stress ratio (minimum stress/maximum stress) |
| $T^*_R$ | T*-integral resistance |
| $\Psi_c$ | Critical COTA |
| $\Psi_{c,}$ | Critical tearing angle |

# EXECUTIVE SUMMARY

This report summarizes the results from a study performed by The Boeing Company, Huntington Beach, CA, during August 1996 to February 2003. This study was undertaken to achieve two goals: (1) take existing analysis tools developed under government-funded research and establish the processes required to use them as engineering tools to determine the effects of multiple-site damage (MSD) on the residual strength in the representative aircraft structures and (2) investigate small crack behavior to better understand the formation of MSD in a structure.

WFD is a complex phenomenon that is extremely difficult to analyze with standard methods developed from first principles of linear elastic fracture mechanics (LEFM). Because of the limited applications of LEFM, more advanced methods have been explored and developed over the past decade with the support and sponsorship of the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration. This includes analytical tools to determine parameters governing the onset and growth of cracks and elastic-plastic fracture criterion for residual strength determinations. The tools include the finite element alternating method (FEAM); a computationally efficient yet rigorous approach to calculate two- and three-dimensional stress-intensity factor (SIF) solutions governing crack growth; FASTRAN, a fatigue crack growth analysis program using a crack-closure model; and STAGS, an advanced finite element program implemented with fracture mechanics and stable-tearing analysis capabilities for generalized shell structures. The elastic-plastic failure criterion include the plastic zone touch (PZT), crack tip opening angle (CTOA), and the T*-integral.

These tools and criteria were used and verified in this program to analyze portions of the multiple-site crack initiation, growth, linkup, and catastrophic fracture process. For the development of MSD, the fundamental phenomenon of fatigue crack initiation in material and the rate of growth were addressed at the coupon level experimentally and analytically using FASTRAN. The initiation of MSD was dealt with at the component level on flat panels that were representative of typical fuselage lap splices. Experimentally generated data and a closure-based crack growth code were used to develop equivalent initial flaw sizes (EIFS). For residual strength analysis, the approach taken was to apply the T*-integral, CTOA, and plastic zone linkup (PZL) criteria to predict the linkup and fast fracture of MSD. A procedure was developed that used elastic-plastic finite element analyses using STAGS and CTOA to perform the stable tearing and unstable fracture of MSD in aircraft structures.

Computational tools must be verified and validated using experimental data to ensure successful transfer of useable and accurate technology to industry. Extensive experimental work was carried out to generate test data for correlation and validation of the various methodologies and criteria. Testing was conducted collaboratively by five organizations: (1) The Boeing Company, Long Beach, CA; (2) United States Air Force (USAF), Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base; (3) Beijing Institute of Aeronautical Materials (BIAM); (4) Civil Aviation Authority of China (CAAC); and (5) the FAA William J. Hughes Technical Center.

This project was divided into six major tasks to analyze portions of the multiple-site crack initiation, growth, linkup, and catastrophic fracture process.

1. Crack Initiation. Cracks were initiated and developed from edge-notched coupons and analyzed using FASTRAN. Testing was conducted by BIAM and CAAC under several fatigue loading conditions, including constant-amplitude and spectrum loading. Good correlation between analysis and experimental data was demonstrated under constant-amplitude loading for crack sizes larger than 0.005 inch. However, under spectrum loading, there was poor correlation.

2. Equivalent Initial Flaw Size. A semiempirical procedure was developed for the determination of EIFS using FASTRAN. Tests were conducted by AFRL using large flat panels with four joint configurations representative of aircraft joint construction. The attempts to develop comprehensive SIF solutions by compounding or superpositioning for the individual effects derived from first principles were not effective. An iterative method was developed to empirically account for these factors for the prediction to match the experimental results. In this way, the EIFS was determined to fall between 0.0001 to 0.0015 inch for the four types of splice joints. However, whether the results can be applied to other structures under different loading conditions or using different crack growth models requires additional study.

3. Small Crack Growth. Small crack growth data was generated in pin-loaded specimens and analyzed using FASTRAN. Testing was conducted by AFRL under various load transfer conditions. In general, good correlation was obtained between test and analysis for open-hole specimens under constant-amplitude loads. However, analysis predicted 20 to 30 percent faster crack growth rate for the pin-loaded specimens.

4. MSD in Flat Panels. The CTOA, T*-integral, and PZL criteria were used to analyze flat panels with MSD. Tests were conducted by AFRL using large flat panels with four joint configurations representative of aircraft joint construction. The PZL criterion provides a quick and simple way for residual strength estimations. T*-integral, together with FEAM, was able to predict the stable tearing of MSD cracks in a flat spliced panel. Using STAGS code, the CTOA criterion was able to predict the residual strengths of MSD in splice joints. Using these criteria, predictions of the residual strength were within 8 percent.

5. MSD in Curved Panels. The CTOA criterion was used to analyze curved panels with MSD. Tests were conducted by the FAA William J. Hughes Technical Center using the Full-Scale Aircraft Structural Test Evaluation and Research facility. CTOA predictions agree well with the curved panel test results, within 5 percent.

6. MSD in Aft Pressure Bulkhead. The CTOA criterion was used to analyze an aft pressure bulkhead with MSD. Tests were conducted by the AFRL. CTOA predictions agree well with the curved panel test results, within 5 percent.

In summary, this project demonstrated a successful transfer of technology developed from basic research to real-work applications. Using this technology, a methodology to assess the development of MSD and its effect on the residual strength of aircraft structure was developed. The three major components of the methodology are crack initiation, crack growth and linkup, and residual strength. The crack initiation methodology used experimentally generated EIFS data and an analytical closure model to determine initial flaw sizes and distribution for multiple-site cracking. The CTOA, T*-integral, and PZT criteria were used to predict crack growth and linkup. Elastic-plastic finite element analyses were used with the CTOA to determine the residual strength of an aircraft structure containing a long lead crack in the presence of MSD. The methodologies were verified through a comprehensive test program.

# APPENDIX A—CRITERIA

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