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FRACTURE MECHANICS RESEARCH AT NASA RELATED TO THE AGING COMMERCIAL TRANSPORT FLEET

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SUMMARY

NASA is conducting the Airframe Structural Integrity Program in support of the aging commercial transport fleet. This interdisciplinary program is being worked in cooperation with the U. S. airframe manufacturers, airline operators, and the FAA. Advanced analysis methods are under development and an extensive testing program is under way to study fatigue crack growth and fracture in complex built-up shell structures. Innovative nondestructive examination technologies are also being developed to provide large area inspection capability to detect corrosion, disbonds, and cracks. This paper reviews recent fracture mechanics results applicable to predicting the growth of cracks under monotonic and cyclic loading at rivets in fuselage lap-splice joints.

INTRODUCTION

On April 28, 1988, an Aloha Airlines Boeing 737 experienced an inflight 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 multi-site damage (MSD), helped focus the attention of the industry on the problems of operating an aging commercial transport fleet. Currently, about 46 percent of the jet airplanes in the fleet are over 15 years old, with 26 percent being over 20 years old. During the past two years 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 paper 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 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 fatigue crack growth and residual strength of complex built-up structure and innovative NDE technologies to detect cracks, corrosion, and disbonds in adhesively bonded joints. These key elements will be verified with an extensive test program on simple laboratory specimens and on built-up structure similar to the lap-splice joint region. The near term focus of the program is MSD in lap-splice joints and crack growth under mixed-mode conditions. 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.

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 and fracture characteristics 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 Figure 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 local crack-tip mechanics is used to predict fatigue crack growth and residual strength. 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 Figure 2. The individual program elements are discussed in more detail in the following sections. A brief overview of the direction of research for each element will be followed by a summary of the status of the work in progress. Relevant results will be discussed in areas where the research is sufficiently mature for presentation.

FATIGUE CRACK GROWTH AND 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 schematically in Figure 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 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 extreme crack growth behavior during proof testing [3] and the small-crack growth phenomenon exhibited by many aluminum alloys [4]. The crack growth rate data must be correlated with the effective stress-intensity factor range rather than the full range to give meaningful predictions of 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 [5]. This type of methodology is necessary to predict the growth of small cracks initiating at rivet holes 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 link-up of adjacent cracks occur.

Recent Results of Work-in-Progress

A computer code, FASTRAN, has been developed for predicting crack growth using an analytical closure model and the code is available in the public domain through COSMIC [6]. The present version FASTRAN-II, with improved spectrum load input options, was developed to run on mainframe and personal computers [7]. An example of the accuracy and computational efficiency of this code was demonstrated recently by comparing predicted lives with experimental lives from tests on center-crack tension coupons made of 7075-T6 aluminum alloy sheet subjected to the Mini-TWIST spectrum. These tests were conducted by Mr. E. P. Phillips at the NASA Langley Research Center. The Mini-TWIST spectrum is a standard transport wing spectra with about 64,000 loading amplitudes for 4,000 flights [8]. At a low mean stress, $S_m = 20$ MPa, the experimental life (average of two tests) was determined to be 202,000 flights from an initial 6 mm length crack to failure. The crack length is plotted against the opening stresses calculated from FASTRAN-II in Figure 4. The predicted life was 20 percent higher than the experimental life. At a high mean stress, $S_m = 60$ MPa, the experimental life (average of two tests) was determined to be 9,500 flights. In this case, the predicted life was 2 percent below the experimental life. The low and high mean stress cases required 16 and 1.3 CPU minutes, respectively, on a mainframe (CONVEX) computer using scalar and vector optimization. These predictions were based on calculating the opening stress during very small increments of crack extension throughout the life. However, by using a damage-weighted average opening stress, $\bar{S}_0$, the required computational time was reduced to 8 minutes and 1 minute for the low and high mean stress cases, respectively. A comparison between the model calculations and the average crack opening stress is shown in Figure 4. The predicted lives using $\bar{S}_0$ were 12 percent higher and 3 percent lower than the experimental values for the low and high mean stress cases, respectively. The first application of the Mini-TWIST spectrum was used to create the characteristic plastic wake for the spectrum. Then the damage-weighted average opening stress was calculated from the closure model during the second time through the complete spectrum. The average value was then used for the repeated spectra until failure was predicted. This approach makes the closure model computationally cost competitive with empirical crack growth models presently used in the aerospace industry. The use of the PC version of FASTRAN-II will result in even further computational cost reductions but the computer times will be much larger than those from the mainframe computer. However, the rapid developments that are being made in computer science will shortly make the PC a vector and parallel processing machine with speeds competitive with the mainframe computer of today.

THREE-DIMENSIONAL STRESS ANALYSES OF COUNTERSUNK HOLES

A riveted joint introduces discontinuities in the form of holes, changes in the load path due to lapping, and additional loads like rivet bearing and bending moments, as shown in Figure 5. Because of these complexities, local stresses are elevated in the joint. Accurate estimations of these local stresses are needed to predict fatigue life and joint strength.

Exhaustive studies on stress-concentration factors for holes and notches in two-dimensional bodies under a wide variety of loadings have been documented in handbooks. However, stress concentrations for holes in finite-thickness plates have only been reported for a few configurations and loadings (circular and elliptical holes under remote tension and bending loads). Surprisingly, stress analyses of countersunk holes have not been reported and only a few experimental results are in the literature.

A comprehensive analysis of three-dimensional stress concentrations and stress-intensity factors for surface or corner cracks in circular straight-shank and countersunk holes under typical loads encountered in structural joints is being undertaken in the NASA ASIP.

Recent Results of Work-in-Progress

A three-dimensional finite-element stress analyses code (FRAC3D), developed at the NASA Langley Research Center using 20-node isoparametric elements, was used to obtain stress concentrations for a wide range in hole sizes (hole-radius-to-plate-thickness ratios) and countersink depths (from knife-edge to straight-shank). The straight-shank and countersunk hole configurations and loadings are shown in Figure 6. Three types of loads, namely: remote tension, remote bending and wedge loading were considered for the straight-shank hole. Two types of loads, remote tension and remote bending, were considered for the countersunk holes. The wedge-load solution is used in combination with the remote tension solution to obtain a simulated pin-load solution. Using the finite-element results, series-type equations were developed to give the stress concentration at any location along the bore of the holes. These results are reported in a paper by Shivakumar and Newman.*

Some typical results for a countersunk hole with a straight-shank portion of 25 percent of the sheet thickness (b/t = 0.25) for a wide range in hole-radii-to-thickness (r/t) ratios are shown in Figure 7. The standard countersunk angle (θ_c) of 100 degrees was used in all cases. The stress concentration, K_t, is the ratio of local normal stress along the bore of the hole to the remote applied stress, S. As expected, the peak stress concentration occurred at the countersunk edge at a z/t value of -0.25 (the z coordinate is measured from the center of the sheet). Results from the finite-element analyses are shown as symbols. The curves represent the equations that were developed to fit these results.* The equations are useful in determining peak stress concentration factors when complex loading conditions, such as those encountered in service, are superimposed.

FRACTURE MECHANICS OF MULTI-SITE DAMAGE (MSD)

The MSD problem that has occurred recently in some high-time aircraft is generally associated with many neighboring cracks along a row of rivets, such as in the fuselage. However, MSD has not been confined to only the fuselage. Some early MSD problems developed in the wing structure. If a crack initiates at a single rivet hole, the displacement compatibility in the riveted joint will tend to unload the cracked hole and shed some load to its neighboring rivets. These adjacent holes will be overloaded and in turn develop cracks. All cracks tend to be of the same length except in regions near stiffeners or in regions of maximum pressure pillowing. This cracking and load redistribution process promotes the development of MSD. Thus, riveted lap-splice joints are prone to MSD if cracks ever develop. These joints should, therefore, be designed to prevent cracking or MSD from developing. However, to develop procedures to design against MSD, methods should be developed to predict initiation of cracks

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*Shivakumar, K. N. and Newman, J. C., Jr.: Stress Concentrations for Straight-Shank and Countersunk Holes in Plates Subjected to Tension, Bending and Pin Loads, Submitted for publication as a NASA TP, National Aeronautics and Space Administration, Washington, D. C.

and to analyze the complex problem of interacting cracks. Of course, a key element is an accurate stress analysis of the local stress conditions.

A rigorous fracture mechanics treatment of cracks initiating at rivet holes and MSD will require stress-intensity factor solutions for three fundamentally different levels of crack sizes. For very small cracks below the damage tolerance (inspectable size) regime, the finite-element method will be used to generate solutions to three-dimensional (3-D) crack configurations such as surface and corner cracks initiating at countersunk rivet holes, as shown in Figure 5. The anticipated results from these analyses will be a compendium of analytical expressions for the stress-intensity factors for several basic crack configurations. After the cracks extend through the wall thickness and beyond the rivet head, the cracks will be in the detectable range and amenable to the damage tolerance philosophy. A two-dimensional (2-D) indirect boundary element method is being used to generate stress-intensity factors for MSD crack configurations prior to extensive link-up, as shown in Figure 8. A PC-based computer code will be developed which will compute the stress-intensity factor for each crack tip for an unequal distribution of straight or curved cracks at adjacent rivet holes. After MSD crack link-up, the cracks are quite large and crack growth will be rapid. The stress-intensity factor for these cracks will be strongly influenced by the geometric nonlinear response of the stiffened fuselage shell structure. A geometric nonlinear finite-element shell code will be developed that will model the stiffening effects of longitudinal stiffeners and circumferential frames. The crack-tip stress-intensity factors will be calculated by employing special crack-tip modeling and an adaptive mesh strategy to properly model the trajectory of the growing crack. Research is underway at NASA to develop methods to rigorously and efficiently address all three levels of crack growth.

During the last decade, NASA has developed several computational methods for computing stress-intensity factor solutions to complex crack configurations. The Boundary-Force Method (BFM) [9] is well suited to analyze 2-D problems such as through cracks in thin sheet material. An example of the type of problem that can be efficiently treated by the BFM method is illustrated in Figure 9. This specimen, and a three-hole cracked specimen [10], was designed to be a simple specimen to simulate the results of a cracked stiffened panel. The stress-intensity factor solution is remarkable close to that for a stiffener located along the hole centerline [11].

For more complex problems, the finite-element method with the nodal-force method [12] and the virtual-crack-closure technique (VCCT) [13] have been successfully employed to obtain solutions to many 3-D crack configurations. One example, for a surface crack emanating from a semi-circular notch, is shown in Figure 10. Both methods give essentially the same results. A discrepancy occurs where the crack front intersects the notch (or free) boundary at a parametric angle φ of 90 degrees because of a boundary-layer effect. Empirical stress-intensity factor equations, such as that shown by the solid curve, have been developed for many of the 3-D crack configurations [14].

The equivalent domain integral method (EDI) [15,16] has also recently been implemented into several NASA finite-element codes. This technique is well suited for 2-D and 3-D crack problems involving mixed-mode loadings and material nonlinearity. For example, the J-integral computed from the EDI method is compared to analytical results from the VCCT [13] for an elastic problem in Figure 11. Both techniques gave nearly the same values of the J-integral and they compare well with the equation developed by Newman and Raju [14]. An additional advantage of the EDI method is that it does not require that the finite-element mesh be orthogonal to the crack front, as required in the nodal-force method, to calculate stress-intensity factors. Both the VCCT and EDI methods have been implemented into a public domain computer code, ZIP3D [17], available through COSMIC.

NASA has developed empirical stress-intensity factor equations for many basic 3-D crack configurations by fitting to the various finite-element results. Reference 14 gives equations for many of the crack configurations commonly encountered in structural applications.

Recent Results of Work-in-Progress

The near term focus of the NASA fracture mechanics research is on MSD prior to link-up to support the damage tolerance philosophy currently being implemented by the airline industry. An Alternating Indirect Boundary Element (AIBE) computer code [18], a force method version of the more familiar boundary-element method, is being developed for MSD crack configurations. The AIBE code will generate stress-intensity factors for individual cracks in an arbitrary distribution of unequal, interacting cracks extending from loaded rivet holes. Methods are being developed so that in-plane, out-of-plane, and rivet loads can also be included in the analysis. The current version of the code can only model straight cracks. However, a 2-D approach to analyze curved cracks is being developed using the distributed dislocation concept [19,20]. This method will also be available to analyze MSD crack configurations. Additionally, a special version of FASTRAN has been coupled to the AIBE code so that fatigue crack growth can also be computed.

Each new capability of the AIBE code is being verified by comparison to available analytical results from other computational techniques for simple crack configurations. A complete code verification will be achieved by comparing analytical predictions to experimental results. To date, AIBE code predictions have been compared to experimental results for the special case of multiple fatigue cracks growing from open holes in thin sheets subjected to constant-amplitude remote uniform tension loadings. Figure 12 shows a typical experimentally measured distribution of crack lengths along with the stress-intensity factors calculated for each crack. The stress-intensity factors are normalized by the stress-intensity factor for an average crack length assuming an infinite periodic array of equal cracks. Figure 13 shows comparisons between fatigue crack growth predictions for the unequal distribution of cracks, the predictions for an infinite periodic array of equal cracks, and experimental test results. It is obvious from these results that the simplistic approach of assuming equal crack lengths may not always generate accurate predictions of crack growth and cycles to crack link-up. Many additional experimental cases of crack configurations and loading conditions are being conducted in order to refine the AIBE code and to more fully verify its accuracy.

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. The consequences of multiple-element damage (MED), such as stiffener cracking, on the behavior of large cracks in the fuselage should also be accounted for in the analysis. 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, 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 Meshing

To predict accurately 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 Figure 14 taken from the work of Wawrzynek and Ingraffea [21]. The path of the growing crack is represented by the heavy dark line in Figure 14. 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 shown in Figure 15, 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 flat 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 benchmarks for the analysis methodology verification.

CONCLUDING REMARKS

NASA is conducting interdisciplinary research combining the disciplines of fracture mechanics, structural mechanics, material science, 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 analysis methodology and test 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 U. S. airframe manufacturers and airline operators. Fracture mechanics solutions to cracks extending from the rivets in fuselage splice joints are being developed which will be applicable to multi-site damage (MSD). A plasticity-induced closure model is being developed which will be applicable to predicting the fatigue crack growth of MSD crack configurations. This fracture mechanics methodology is being integrated into a finite-element based stiffened-shell structural analysis methodology so that significant geometric nonlinear effects and MED on crack growth may be accurately predicted. The integrated methodology will be verified by analyzing fatigue and damage tolerance test results on curved panels with stiffeners and frames.

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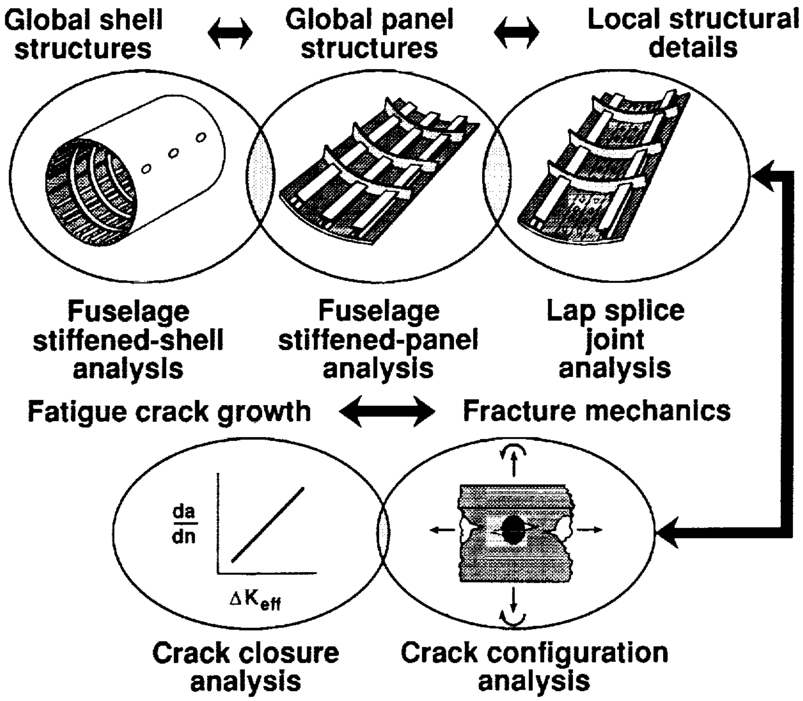


Figure 1. Integrated shell analysis-fracture analysis methodology.

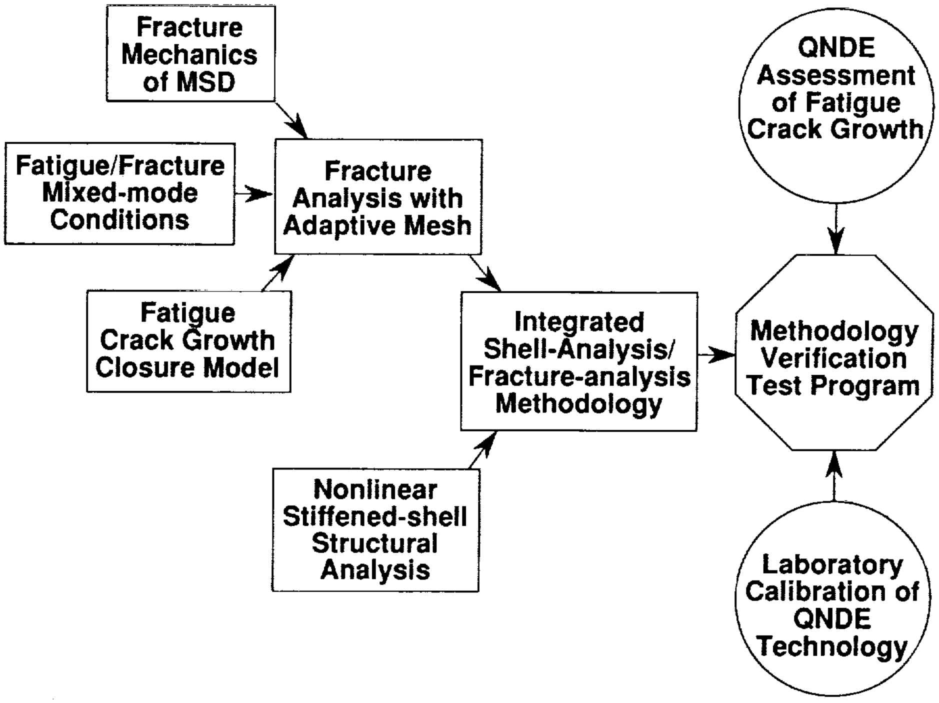


Figure 2. Logic diagram for analysis methodology program.

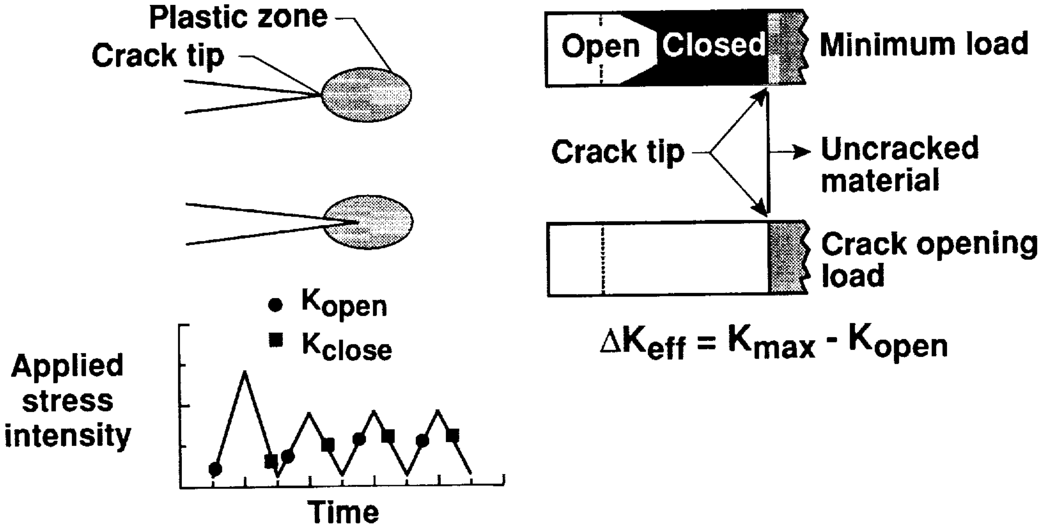


Figure 3. Fatigue crack growth controlled by closure mechanism.

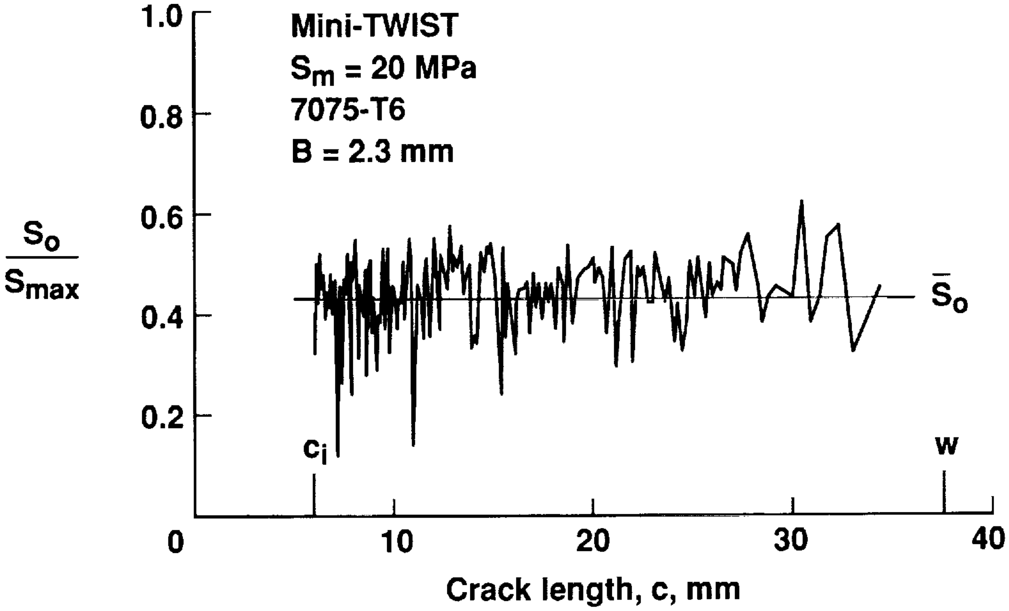


Figure 4. Crack-opening stress variation during flight-by-flight loading.

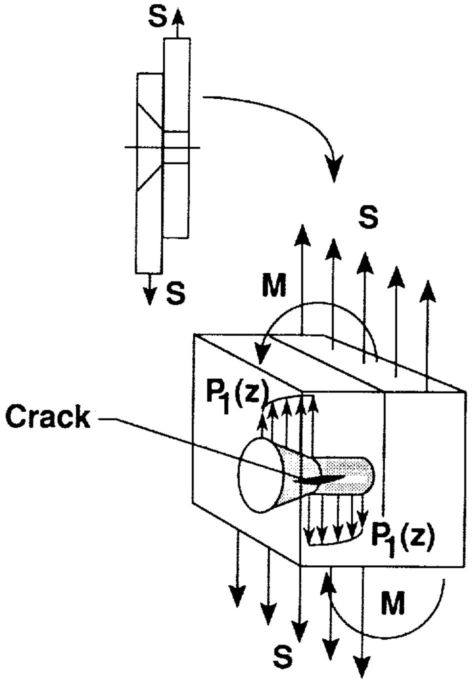
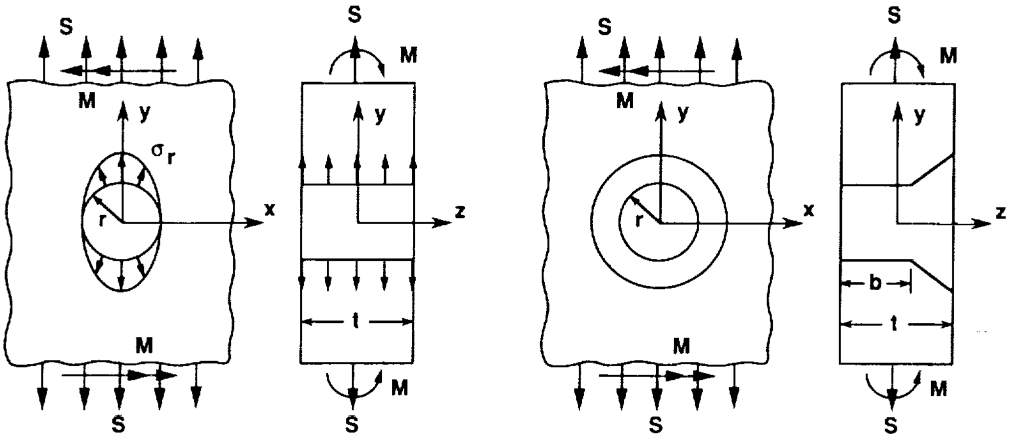


Figure 5. Cracking and loading conditions encountered at countersunk rivets.



(a) Straight-shank hole.

(b) Countersunk hole.

Figure 6.- Straight-shank and countersunk hole configurations and loadings.

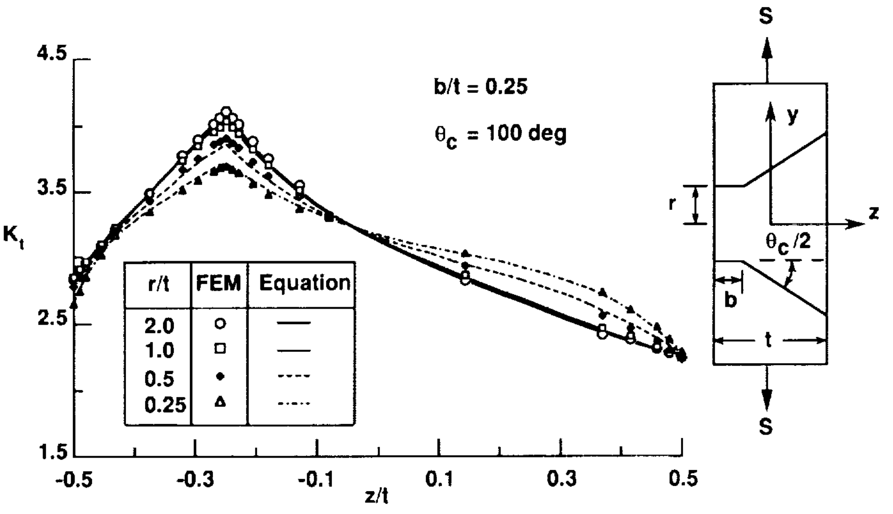


Figure 7. Comparison of stress concentration factors from finite-element analyses and equations for countersunk rivet hole under remote tension.

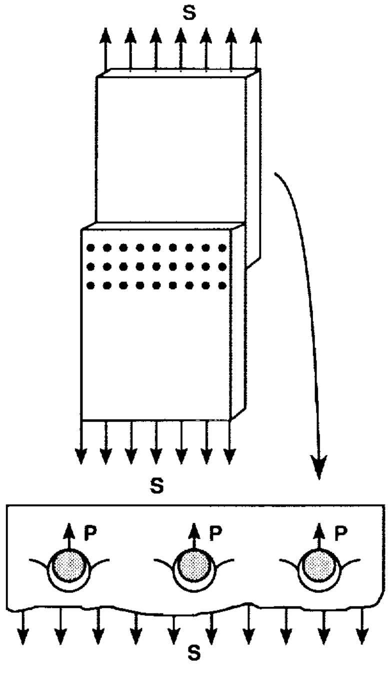


Figure 8. Fracture mechanics analyses of multiple-site cracks.

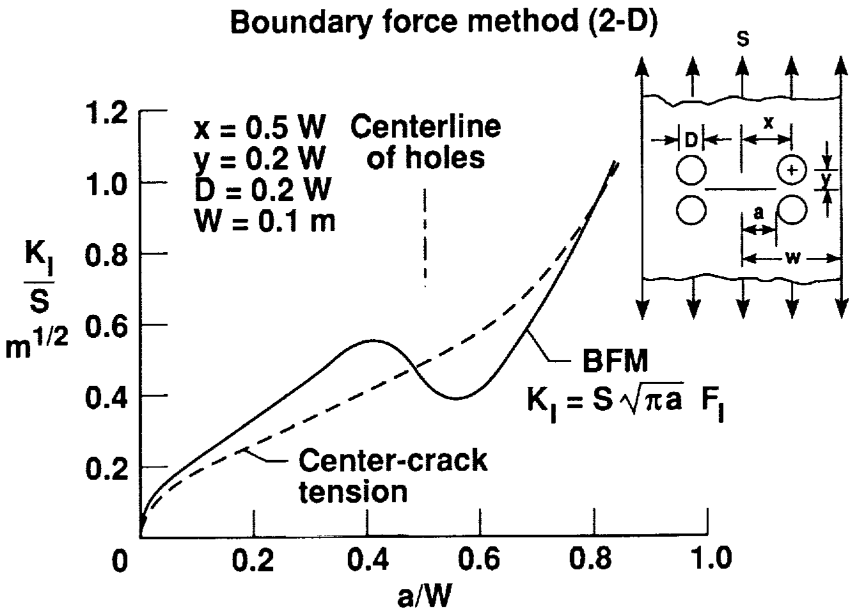


Figure 9. Stress-intensity factors for a four-hole cracked specimen.

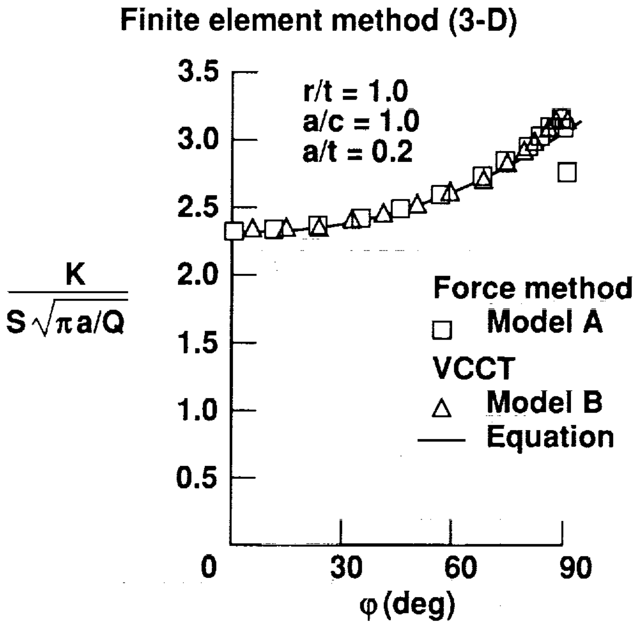


Figure 10. Stress-intensity factors for a surface crack emanating from a semi-circular notch.

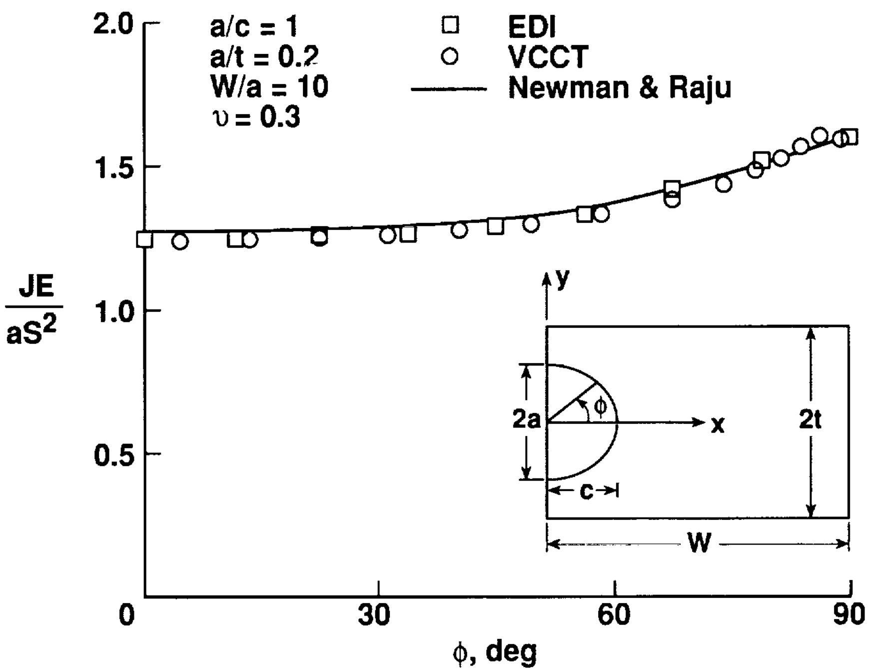


Figure 11. Comparison of normalized J distribution for a semicircular surface crack from EDI, VCCT, and force methods.

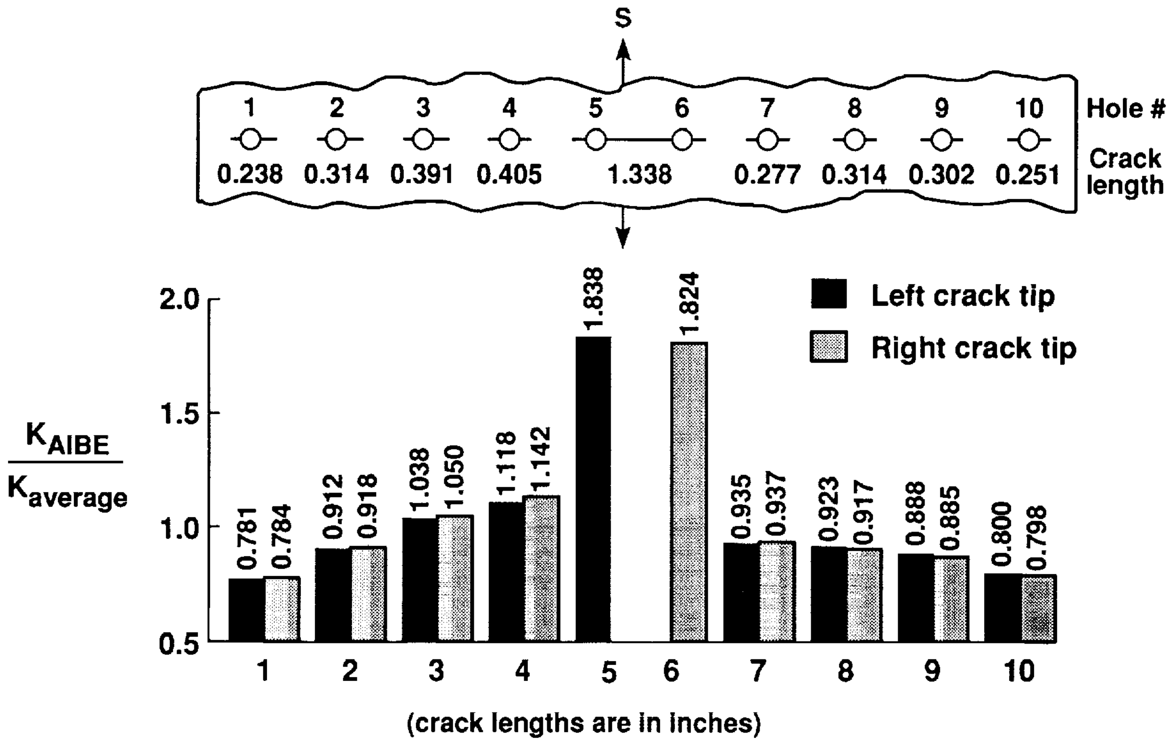


Figure 12. AIBE determined stress intensity factor distribution for an open hole MSD experiment.

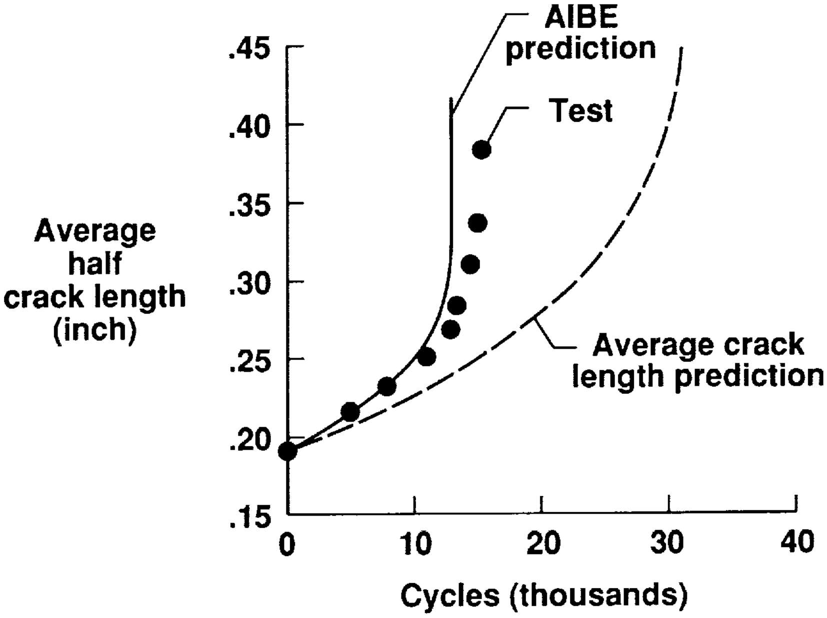
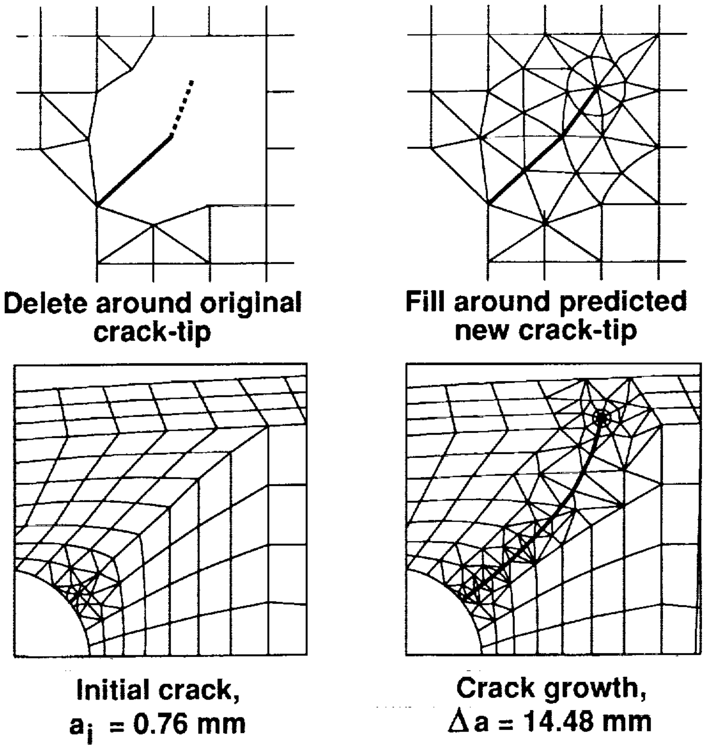


Figure 13. Predicted fatigue crack growth behavior for an open hole MSD experiment.



Initial crack,
$a_i = 0.76$ mm

Crack growth,
$\Delta a = 14.48$ mm

Figure 14. Crack propagation by adaptive remeshing using the finite element method.

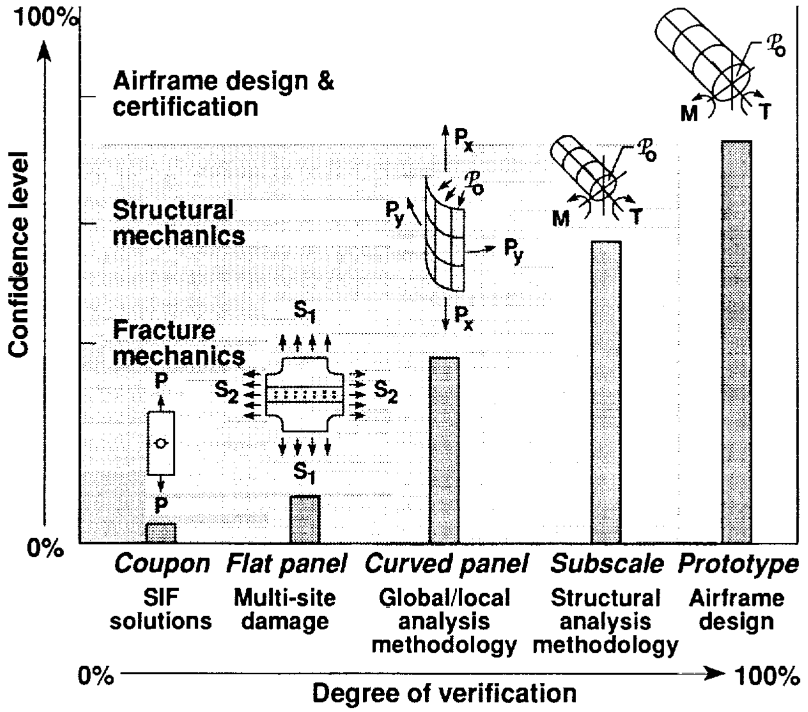


Figure 15. Prediction methodology verification program.