AIAA JOURNAL
Vol. 39, No. 12, December 2001

Evaluation of Damage Tolerance Analysis Tools for Lap Joints

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The riveted lap joint design (common in fuselage structures) creates complex loading conditions that require various analysis methods for accomplishing a damage tolerance analysis (DTA). Under a U.S. Air Force research project, The Boeing Company evaluated the capabilities of two analysis tools for accomplishing a DTA of riveted lap joints. These existing structural analysis tools included a finite element code, FRANC2D/L, and a crack growth code, AFGROW. Analysis results of lap joint specimens showed good agreement between predicted and experimental test results for a typical lap joint geometry. The crack growth codes could also model the interference level created by the rivet squeeze force, which impacts crack growth.

I. Introduction

THE extended service of many of the U.S. Air Force aircraft is resulting in a severe impact on maintenance and readiness. The Air Force must be able to determine accurately the expected structural life and to evaluate the structural integrity of aircraft components. Improvements in damage tolerance analysis (DTA) methods can help to extend service life, reduce maintenance, and enhance aircraft readiness.

A common joint used in the fuselage construction is the riveted lap joint. One common design is the single lap joint, which overlaps two skin panels longitudinally along the fuselage and fastens the panels with three rows of countersunk rivets. The riveted lap joint is subjected to combined loading from fuselage pressurization and bending due to flight loads. The stress state in the joint is further complicated by the installation of countersunk holes, which introduce stress concentrations around the holes and in the countersink region. Rivet installation also introduces residual stresses around the hole depending on the amount of rivet squeeze force used in the installation. This complex stress state requires sophisticated and detailed analyses to determine accurately the damage tolerance behavior of these joints.

Several analysis methods are needed to characterize the complex stress state in the joint and accomplish a DTA. First, structural analysis and fracture mechanics methods are used to determine the stress distributions and stress intensity factors (SIFs) of cracks in the joint. Then, with properly characterized SIFs, crack propagation analyses can be performed to estimate the crack growth life of the joint. These methods are useful in analyzing the damage tolerance of an aircraft structural component, which can be used in an overall analysis approach to do a complete assessment of the component's structural integrity, as discussed in detail in Ref. 1. This complete assessment is important for identification of critical areas, determination of safety limits, and development of safety inspection requirements.

II. Structural Analysis Tools

Many structural analysis tools exist that have the capability to conduct fracture mechanics and crack propagation analyses. Two software codes, in particular, are well suited for analyzing riveted lap joints. They are a two-dimensional finite element analysis tool, FRANC2D/L, which simulates crack growth in layered structures[2] and a crack propagation analysis tool, AFGROW, which estimates the fatigue crack growth life of a structural component based on specified loading conditions and initial crack geometry.[3]

Figure 1 illustrates how these two analysis tools can be used in conjunction with each other to accomplish a DTA of a structural component. When used together, they provide the capability to determine accurately a joint's stress distribution and SIFs, to then estimate the crack growth life of the joint. Both software codes are public domain, and they are available at the following web sites: FRANC2D/L at URL:http//www.cfg.cornell.edu and AFGROW at URL:http//fibec.flight.wpafb.af.mil/fibec/afgrow.html.

A. Stress Analysis Tool: FRANC2D/L

FRANC2D/L is a personal-computer-based finite element analysis program for the simulation of crack growth in two-dimensional layered structures. The strength of FRANC2D/L lies in its ability to perform the following tasks in an automated fashion: 1) calculate stress intensity factors for multiple through-thickness cracks, 2) determine crack trajectories, and 3) implement crack growth at each crack through local remeshing around the crack tip. The program can represent layered structures, such as lap joints or bonded repairs, where each layer is modeled by a separate mesh and connected in overlap regions with rivet or adhesive elements. The code is limited to considering planar geometry only with plane stress or plane strain elements available. In addition, a linear bending option is available, which allows out-of-plane displacements and accounts for the offset distances that may exist between layers. When the bending option is used, bending stresses/strains and out-of-plane displacements are automatically calculated in addition to the standard in-plane stress, strain and displacement distributions. However, because the bending option is limited to linear behavior, this option could overestimate the bending effects due to load eccentricity in lap joints.

Additional features of the code include adhesive and spring elements to attach various layers in a joint and a nonlinear interface element. Adhesive elements provide for distributed shear load transfer between overlapping elements in adjacent layers, which allows explicit modeling of fasteners. Layered structure can also be attached with simplified spring elements (rivet element in FRANC2D/L) that connect overlapping nodes in each layer. The nonlinear interface element simulates the contact around the circumference of a fastener with the surrounding sheet material.

B. Crack Growth Analysis Tool: AFGROW

AFGROW is a personal-computer-based analysis code that calculates fatigue crack growth life for a defined crack geometry based on a given spectrum loading. It has the capability to account for the effect of various stress factors on crack growth by using the appropriate SIF (or stress level) that characterizes the physical and/or geometrical effect associated with the damage. Inputs include choice of 21 crack patterns, including user-defined through crack and part through crack configurations; initial flaw size; choice of several materials, including user-defined tabular data input; and a load schedule. Material da/dN vs ΔK tabular data may be viewed graphically to check material properties. AFGROW allows a peak load to be applied within the spectrum to simulate a severe loading application,

Received 1 July 1999; revision received 10 January 2001; accepted for publication 1 July 2001.

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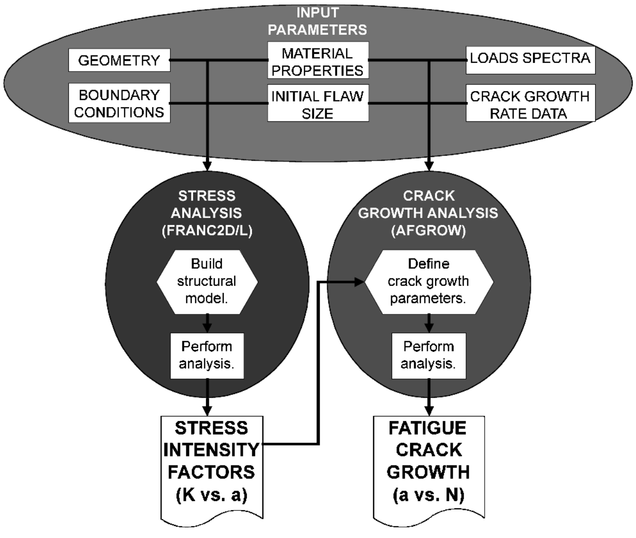


Fig. 1 Analysis tools for DTA of riveted lap joints.

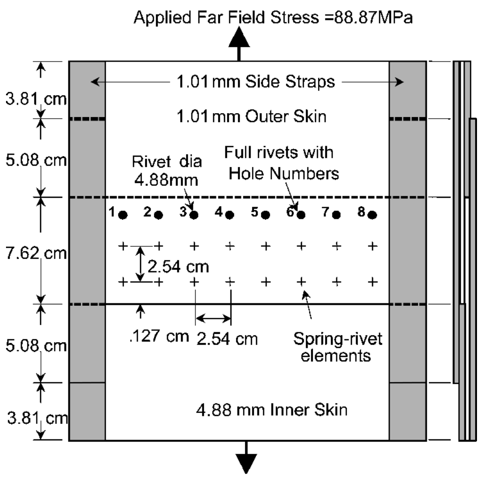


Fig. 2 Configuration of NRC lap joint specimens.

and the code contains the Wheeler, Willenborg, and Harter retardation models. Outputs include a graphical or text version of crack size vs cycle. Batch files can be written to automate analysis procedures, and different analysis runs may be plotted on a single graph or on individual charts allowing quick, direct comparisons.

III. Analysis Case Study

To evaluate the capabilities of these two analysis tools, a case study was conducted on lap joint coupon specimens. The National Research Council (NRC) of Canada fatigue tested eight lap joint specimens that had features common to a typical airframe fuselage lap joint. Eastaugh et al.[4] and Scott[5] discuss in detail the testing of these lap joint specimens. Figure 2 shows the geometry and configuration for the lap joint specimens. The specimens were constructed of two 4.88-mm sheets of 2024-T3 clad aluminum with three rows of 3.97-mm 2117-T4 countersunk rivets and 2.54-cm-wide straps adhesively bonded to each side of the test panel. The test specimens were 25.4 cm wide with 8 rivets in each row across the width.

Fatigue testing of these specimens included crack growth measurements (a vs N) of naturally occurring cracks, which were visually recorded when the crack had grown through the skin thickness from underneath the rivet head. While multiple cracks developed in the specimens during the testing, it was observed that at least 95% of the fatigue life was consumed in the development and extension of the lead, or first visually observed, crack alone. In analyzing the test data, the crack growth behavior of the lead crack can be normalized by shifting the measured cycle count so that the behavior is consistant between the specimens. The normalization showed that the lead crack pattern is similar between the specimens for crack growth from about 1.9 to 7.62 mm. The lead crack pattern ranged from a single crack on one side of a rivet to a double crack of equal length on each side of a rivet.

A. Stress Analysis of NRC Lap Joint Specimens

To investigate the tools' capabilities for predicting the crack growth behavior exhibited in these lap joint speciments, FRANC2D/L was used to model and analyze the specimens to determine the joint stresses and SIFs of cracks in the joint. Stress and fracture mechanics analyses were performed for models with the two crack patterns, and SIF values were generated as a function of crack length for use in the crack growth analysis.

The FRANC2D/L model configuration was based on the geometry, materials, and loading of the experimental specimens (Fig. 2). The inner and outer skins, modeled as discrete layers, were attached only at the rivet locations and along the side straps (which were adhesively bonded on the test specimens). The crack was assumed to be through the thickness of the plate and have a straight front perpendicular to the plate surface. No countersink geometry was modeled, and no plastic yielding was considered. The effect of the countersunk hole on SIF was approximated by a two-dimensional analysis of a straight shank hole, whose radius matched that of the countersink at midthickness. Dawicke and Newman[6] showed that this approximation compared well (within 0.2%) with three-dimensional SIF solution of a countersunk hole with a 4.44-mm crack. Under these assumptions, the problem could be adequately modeled using two-dimensional geometry.

Rivets were modeled using both explicit and spring fastener representations. For the critical upper row of rivets, explicit fastener models used a combination of standard finite elements to define the details of the fastener shank, adhesive elements to provide for distributed shear load transfer between overlapping fastener elements in adjacent layers, and nonlinear interface elements to define the contact between the rivet and the surrounding sheet material.[7,8] The lower two rivet rows are modeled with simplified spring elements that connect overlapping nodes in each layer. Material properties for the adhesive and spring-rivet elements are selected to ensure displacement compatibility between the layers and to provide proper load transfer in the joint.[9]

For the nonlinear interface elements, it is initially assumed that the contact between the rivet and surrounding sheet material is semi-infinitely stiff in compression and has negligible stiffness in tension. This assumption represents a neat-fit fastener where the sheet material will not compress into the rivet, but it will pull away from the rivet with minimal tension. Because a rivet is actually expanded in a fastener hole, the nonlinear interface element can also be used to model this rivet interference by defining a critical positive interfacial displacement that depends on the level of rivet interference. The interface condition governs the relative displacement between the rivet and the sheet material so that nonzero stresses are generated at zero displacement.[9]

It has been shown that rivet interference significantly impacts crack growth by reducing the initial crack growth rates.[9–11] Therefore, two levels of rivet interference, 0.00925 and 0.01905 mm, are assumed for the finite element analysis to determine their impact on the crack growth rate. The 0.01905-mm rivet interference level (0.8% of the rivet radius) was chosen based on measurements in previous experimental testing,[9] and the 0.00925-mm rivet interference level was chosen as an intermediate value.

For analysis, cracks were introduced into the outer sheet material in the critical upper rivet row according to the two crack patterns. In pattern 1, a single radial crack was located at the right-hand edge of rivet hole 4, and in pattern 2, two cracks of equal length, that is, a double crack, were located at both edges of rivet hole 4. Rivet hole 4 was chosen for the crack location because the majority of lead cracks in the test specimens started in the center of the panel. The cracks were incrementally grown using the automated crack propagation routine in FRANC2D/L, and crack tip SIFs were recorded at each propagation step.

The results of the FRANC2D/L finite element analysis are summarized in Fig. 3, which contains plots of the K solutions for the two crack patterns and three rivet interference levels. In each case,

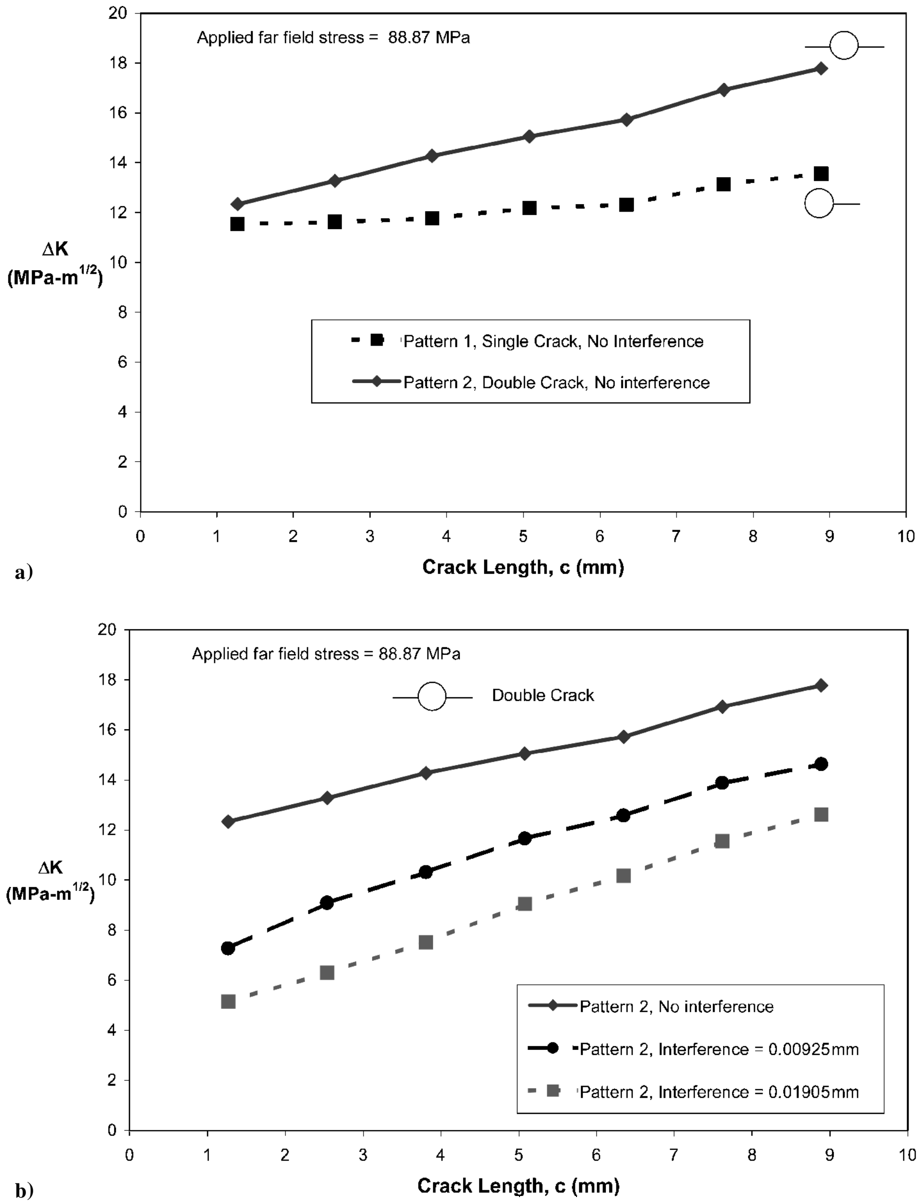


Fig. 3 FRANC2D/L SIF predictions for a) different crack patterns and b) different interference levels for pattern 2.

the K solution is plotted for the lead crack, which grows from 1.27 to 8.89 mm. The vertical axis in each plot contains ΔK, which is given by $\Delta K = K_{\max} - K_{\text{res}}$, where $K_{\max}$ is the crack tip SIF for the lap joint under maximum hoop load and K_{res} is the crack tip SIF under no hoop load. For the cases of no rivet interference, K_{res} is zero, but when rivet interference is present, K_{res} is nonzero.

Based on these results, several observations can be made regarding the effects of crack patterns and rivet interference levels on crack tip SIF. Figure 3a compares the SIF results for the two crack patterns. Figure 3a shows a significant increase in SIF for the case of diametrically opposed cracks compared to that of a single crack, as observed in previous studies. Figure 3b compares K solutions for three levels of rivet interference. The effect of rivet interference was to increase substantially the residual SIF value under no applied hoop load, K_{res}, and to increase slightly the SIF value at maximum applied hoop load, $K_{\max}$. The result was a large drop in ΔK over the entire range of crack growth. These results indicate how sensitive the ΔK solution is to the level of rivet interference, which confirms similar results in previous studies.[9]

B. Crack Growth Analysis of Multisite Damage Lap Joint Specimens

To compare analysis results to experimental results, a crack growth analysis was conducted with the K solutions obtained from the FRANC2D/L analysis. The K solutions were converted to beta factors for the crack growth analysis using the following equation, where σ_{ref} is the far-field stress, which was based on experimental load level:

$$\beta = \frac{K_{\max} - K_{\text{res}}}{\sigma_{\text{ref}}\sqrt{\pi c}} \tag{1}$$

Since $\Delta K = K_{\max} - K_{\text{res}}$, variation in the load ratio R was implicitly accounted for by the variation of K_{res} as a function of crack length. R varied from about 0.6 to 0.3 as the crack length increased. The resulting stress intensity factors and beta factors are found in Fig. 4 for each crack pattern and rivet interference level considered. Inputs for the crack growth analysis included a constant far-field stress amplitude of 12.89 ksi with an R ratio of 0.02. The material properties were for 2024-T3 clad aluminum with a $\mathrm{d}a/\mathrm{d}N$ lower limit of 2.54^{-10} mm/cycle. This lower limit was chosen as a first-order approximation of small crack effects.

Results of the fatigue crack growth analysis showing the effects of rivet interference are summarized in Fig. 5. The results show that without interference the analysis underpredicted the test data, whereas the interference analysis overpredicted the test data for both crack patterns at interference levels of 0.00925 and 0.01905 mm. The rivet interference level results in a large decrease in the SIF range, ΔK, over the entire length of the crack growth for both crack

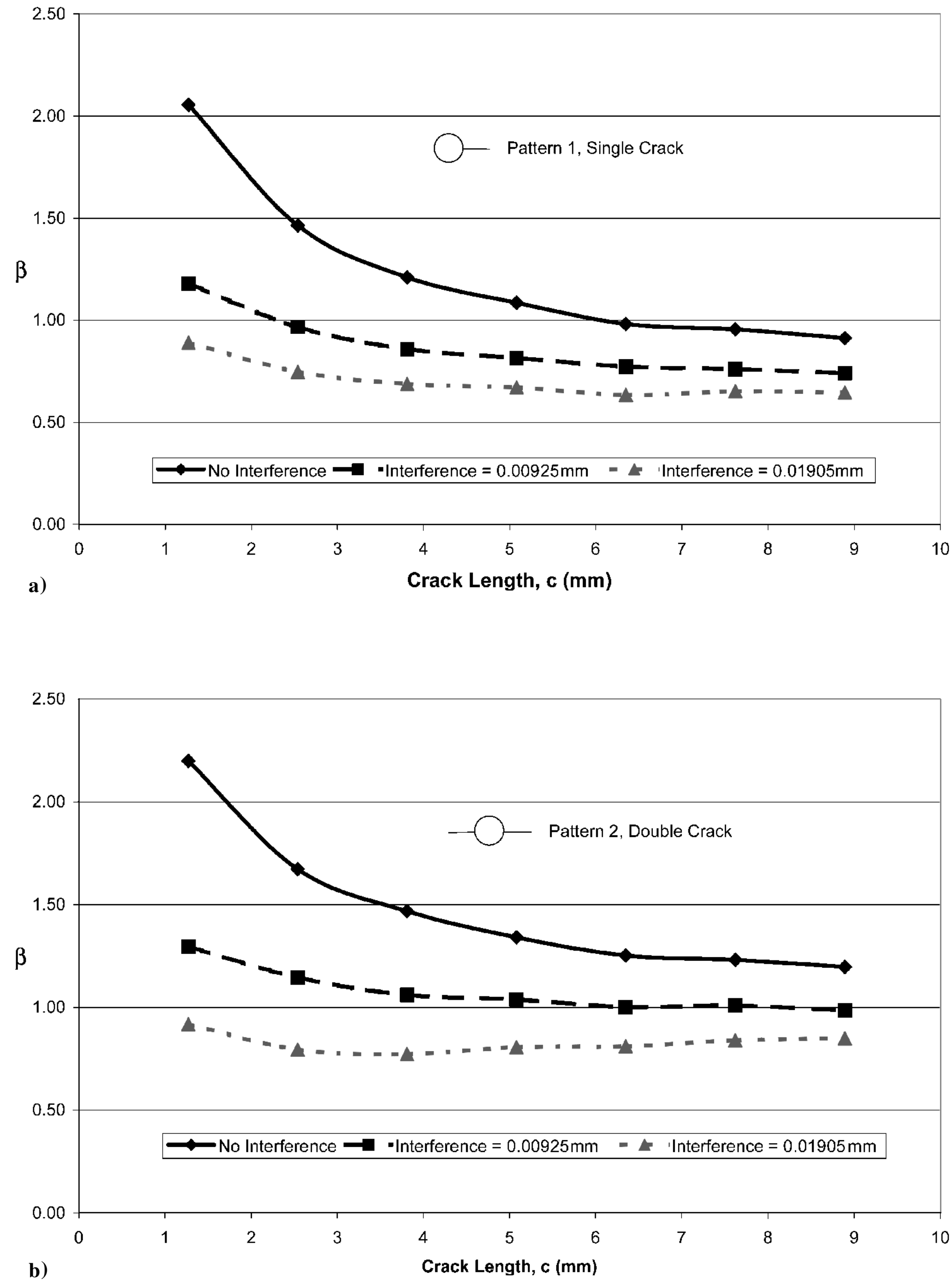
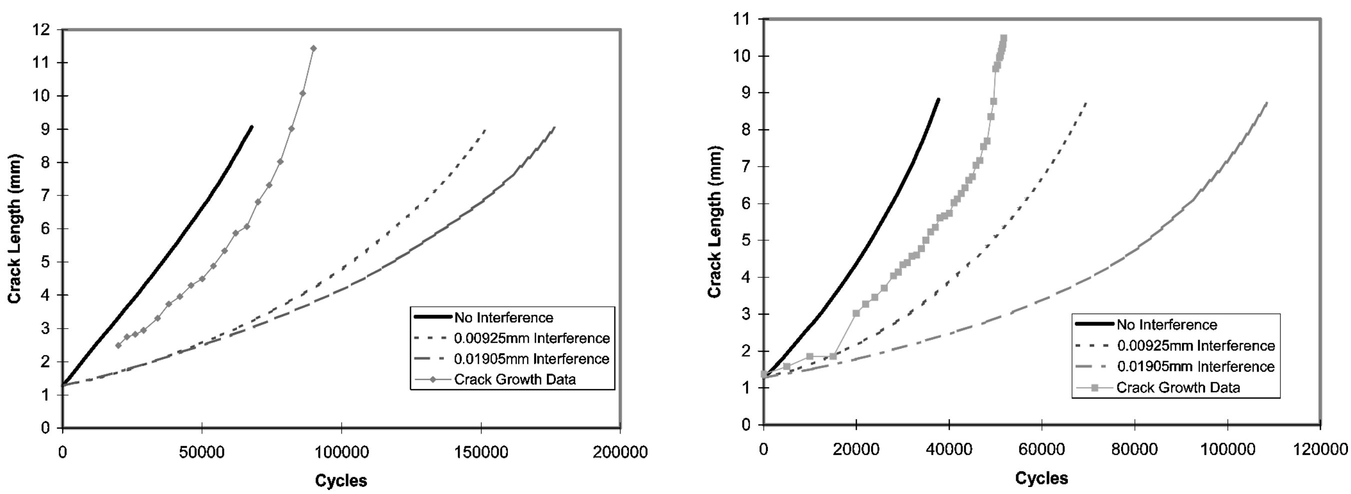


Fig. 4 Beta tables for different interference levels for a) pattern 1, single crack and b) pattern 2, double crack.



a) Pattern 1, single crack

b) Pattern 2, double crack

Fig. 5 Crack growth comparison with and without rivet interference.

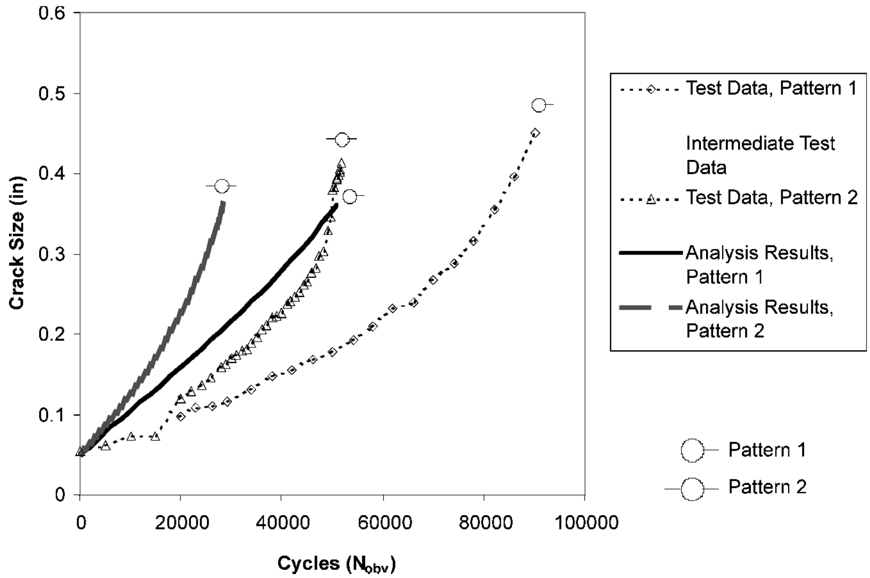


Fig. 6 NRC lap joint specimens crack growth analysis and test results for fatigue specimens.

patterns. Although the interference level used does not generate a perfect match with the test data, it does show a meaningful impact on life prediction because the test data fall between the analysis curves for no interference and 0.00925-mm interference. Whereas the prediction with 0.00925-mm interference came closer to the test data, it still did not match the test data. The predictions bounded the test data, but a lengthy iterative process would be required to find a rivet interference value that would enable a closer prediction of the crack growth life. Similar results, shown in Fig. 5b, were found for pattern 2 with double cracks of equal length emanating from a hole.

Another result from the fatigue crack growth analysis is that a rivet interference level of 0.4% of the rivet radius increased the crack growth life by over 225%, whereas an interference level of 0.8% only increased the crack growth life by an additional 36% for crack pattern 1. For crack pattern 2, the rivet interference level of 0.4% of the rivet radius increased the crack growth life by over 180%, whereas the interference level of 0.8% increased the crack growth life by an additional 100%. This indicates a possible relationship between rivet interference and the different crack patterns exhibited.

The next results, shown in Fig. 6, plot pattern 1 and 2 (solid lines) with no interference against all of the fatigued test data. Figure 6 shows the test data for specimens that correspond to patterns 1 and 2 along with the data from specimens with cracking patterns in between these two extremes. Although the predictions with no interference are conservative, they are within 20% of the exhibited crack growth life, and they mimic the crack growth behavior between the different crack patterns.

IV. Conclusions

This project evaluated the capabilities of existing damage tolerance analysis tools for estimating the crack growth behavior of riveted lap joints. FRANC2D/L and AFGROW have the capabilities to conduct fracture mechanics and crack propagation analyses of a riveted lap joint. When FRANC2D/L is used, one can conservatively model the joint to account for the complex stress state and accurately determine SIFs of cracks in the joints. In turn, using these SIFs, AFGROW can calculate the crack growth life for the joint based on a given spectrum loading. FRANC2D/L also provides the additional capability of modeling the rivet interference in a joint, which significantly impacts crack growth. It was also found that the rivet interference level results in large decreases in the SIF range over the entire length of crack growth. Although the crack growth analysis with no rivet interference was conservative (within 20% of the actual crack growth life based on test data), crack growth analyses with higher levels of rivet interference were grossly unconservative. Another conclusion is that a rivet interference level of 0.4% of the rivet radius increased the crack growth life by over 225%, whereas an interference level of 0.8% only increased the crack growth life by an additional 36% for crack pattern 1. For crack pattern 2, the rivet interference level of 0.4% of the rivet radius increased the crack growth life by over 180%, whereas the interference level of 0.8% increased the crack growth life by an additional 100%. These results indicates a possible relationship between rivet interference and the different crack patterns exhibited.

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