COMPUTATIONAL AND EXPERIMENTAL FRACTURE ANALYSIS OF A PIN-LOADED LUG

Thomas J. Curtin(1), Robert A. Adey(2), Thomas R. Brussat(3)

(1) Computational Mechanics Inc., Billerica, MA 01821
(2) Computational Mechanics BEASY, Ashurst Lodge, Southampton, SO40 7AA, UK
(3) Lockheed Martin Aeronautics Company, 86 South Cobb Drive, Marietta, GA, 30063

ABSTRACT

The structural fatigue failure of a common connecting joint used to attach aircraft control surface components was investigated. Fatigue testing and computer modeling were used to determine the Mode I stress intensity factor (K) solution for an aluminum lug with a single corner crack. The lug was loaded through contact with a steel pin restrained on one face only in order to simulate a clevis.

Experimental results were available for two lug end specimens. A single crack-like mechanical notch was machined at the intersection of the lug face and hole bore at the critical circumferential location. By subsequent fatigue cycling, a nearly-quarter-circular corner crack was introduced at the desired location. Crack growth measurements, on the lug surface and along the hole bore, were made at various load cycle increments. These data were transformed, using the known relationship between crack growth rate (*da/dN*) and stress intensity factor range (ΔK) from material crack growth tests, to estimate K values for the corner crack.

Computational models were created to predict K values for the same lug configuration used in the fatigue test. Both the BEASY Fatigue and Crack Growth and NASGRO software packages were used to analyze the corner crack in the lug. The methodology of each modeling approach is discussed and comparison is made with the experimentally determined K values. The sensitivity of K to changes in clearance fit was investigated, as well as the corresponding changes in distribution of contact stress at the pin-lug interface.

NOMENCLATURE

K	mode I stress intensity factor
$K^{(A)}$, $K^{(C)}$	values of K near hole wall and lug face, respectively
ΔK	stress intensity factor range
da/dN	crack growth rate
ΔP	cyclic tensile load
E	elastic modulus
ν	Poisson ratio
ρ	radius from crack front
r	hole radius
Δr	radial clearance (hole radius minus pin radius)
Δu	displacement normal to crack surface
μ	shear modulus
κ	$(3-4\nu)$ (*plane strain);* $(3-\nu)/(1+\nu)$ (*plane stress)*
σ_b	bearing stress
Ψ	non-dimensional pin clearance parameter, Equation (2)
p	pin pressure

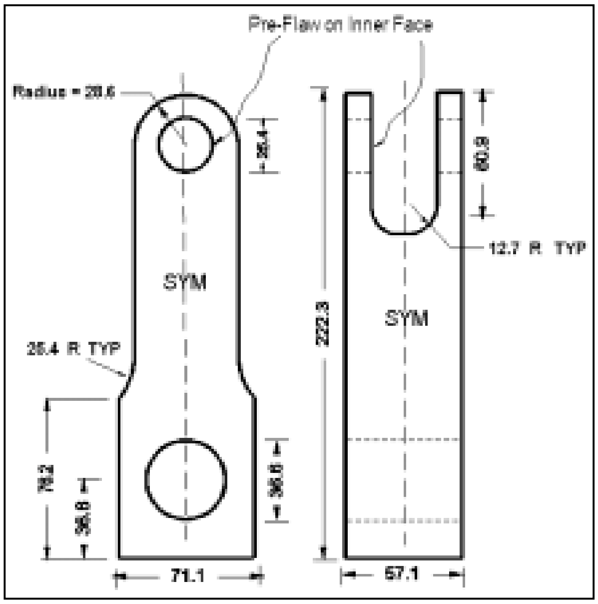

Figure 1. Clevis Specimen Tested and Analyzed

1 INTRODUCTION

Pin-loaded lugs are commonly used in aircraft applications. In the fatigue crack growth and fracture analysis of lugs, accurate calculation of the stress intensity factor (K) is essential. Two-dimensional finite element analysis for through-thickness cracks in lugs (e.g., [1]) has demonstrated that K depends strongly on the true distribution of pin contact pressure, and that the presence of the crack strongly influences that pressure distribution. Furthermore, for through-thickness cracks, analysis [2] has shown that increased radial clearance causes significant increases in K.

Although damage tolerance calculations for lugs are most often concerned with the growth of quarter-elliptic corner cracks, 3-dimensional analysis studies of K are not common. The 3-D finite-element-based results [3] used in the NASGRO computer program are an exception. However, there has not been a detailed study of the effects of pin clearance on contact pressure distributions and stress intensity factors for corner cracks.

Extensive fatigue crack growth data are available in [1] for corner cracks in a variety of lug configurations. Utilizing data from two of those specimens for empirical comparison, the goal here is to analytically investigate pin clearance effects on pin pressure distribution and K for a corner crack.

2 EXPERIMENTAL PROCEDURE

Test data from Reference [1] were used to estimate the stress intensity factor of the crack in the lug. The observed instantaneous crack growth rate at the selected crack size in each pre-cracked lug was matched to a point on a crack growth rate curve developed on conventional compact tension specimens machined from the same lot of material. The value of K from the rate curve was the experimental estimate of K for the lug.

2.1 Test Specimens

The test specimen selected from [1], shown in Figure 1, represents a typical clevis fitting used in aircraft applications. (The lug end section used for the present fracture analysis is also identified in this figure). The clevises were machined to the Figure 1 configuration from 57.15-mm-thick 7075-T651 aluminum plate. Each of the two lugs comprising the clevis was 12.7 mm thick, 57.15 mm wide, and contained a 25.45-mm diameter bored hole. An initial flaw was introduced in one lug at the intersection of the hole with the inner-facing surface (see Figure 1) by electro-discharge machining (EDM). The EDM flaw was triangular in shape, measuring .508 mm along the hole wall and lug surface and .718 mm on the diagonal.

2.2 Test Procedure, Apparatus, and Measurements

A periodic loading sequence was developed and used which marked the fracture surface so that the flaw shape history could be observed after the test. For a reference load P, this loading sequence consisted of 1900 cycles with peak and valley magnitudes of P and 0.1P, respectively, following 100 cycles with peak 1.3P and valley 0.1P. This same sequence was applied to the compact tension specimens used for the basic material growth rate testing. All tests were conducted under ambient conditions.

The clevis was supported at the base and the loads were applied using a lug fixture connected to the clevis through a 25.4 mm diameter steel pin. (In the analysis the pin is assumed to be in frictionless contact in the hole.) The nominal radial pin clearance in the clevis was .0254 mm. The pin was lubricated to provide nearly frictionless contact with the lug. The loading sequence described above was applied, using P = 35 kN, to prompt the crack to emanate from the starter EDM flaw and then grow as a near-circular corner crack. Incremental measurements of crack length on the lug face were recorded during cycling. Subsequent to failure, the fracture surface markings (like those in Figure 2) were examined to measure flaw depth history. Two identical clevises were tested.

2.3 Test Results and Data Analysis

The markings on the fracture surface were visually apparent. The spacings between adjacent markings indicated precisely how far the crack progressed each 2000 cycles. Measurements of crack growth in the depth and surface length directions were taken directly from fracture surface photographs. These were matched to the growth rates observed in the compact specimens, for which the stress intensity factor formulation is precisely known. The average K for the two replicate clevis specimens was recorded both at the surface ($K^{(C)}$) and at the bore of the hole ($K^{(A)}$) when the crack was approximately a 2.54-mm radius corner crack. Of course the crack, while nearly circular, was not exactly so. Therefore, an analytical correction was made to the measured data. The measured crack shape, nearly identical on both specimens, was depth (a) =2.74 mm, length (c) = 2.39 mm. The respective ΔK values (for load range = 0.9P) were $K^{(A)} = 11.95$, $K^{(C)} = 10.72$ Mpa(m)$^{.5}$. Using the theoretical ΔK results from NASFLAW for the two flaw shapes, one can correct these ΔK values by the ratio of the NASFLAW K values for the quarter-circular flaw of radius 0.10 inch to the theoretical K for the observed flaw shape. The correction amounts to a 6% reduction in $K^{(C)}$ and a 2% increase in $K^{(A)}$. The corrected experimental values appear in Table 1.

Figure 2. Typical Fracture Surface Markings from [1]

3 ANALYTICAL PROCEDURES

This section describes the use of the BEASY Fatigue and Fracture Mechanics software [4] and the NASFLA module of the NASGRO Computer Code [5] for determining K solutions. The BEASY software is a fully functional modeling and analysis code. Consequently it provides advanced fracture mechanics analysis capability in terms of complex loading and modeling of non-standard crack geometry. The NASFLA module is based on fracture mechanics principles that can be used to calculate K, critical crack sizes, and to perform fatigue crack growth analysis. In terms of K calculation the NASFLA module is an easy to use tool that provides very fast solutions, however it is limited to a database of standard cracked specimen geometry and simple three-dimensional loading cases.

3.1 Boundary Element Analysis

A boundary integral equation method was used to perform the linear elastic fracture mechanics analysis of the pin-lug assembly. The boundary integral method is based on the numerical solution of integral equations that directly relate boundary tractions to boundary displacements without the need to model the interior volume. Since the K analysis only requires information on crack opening displacements it is not necessary to determine the interior stresses near the crack tip.

A total of 1180 three-dimensional boundary elements with quadrilateral-element topology were used in the computer model (Figure 3). All elements were defined using quadratic-order interpolation functions. The boundary element method, unlike the finite element method, allows the use of continuous or discontinuous type elements or some combination of both. Continuous elements were used to define the lug and pin; however, discontinuous elements were used on the crack surface.

A discontinuous element has node points (or solution points) that are not necessarily coincident with the mesh points that control geometry and thus may have nodes that are not shared between elements. A notable benefit of a discontinuous element is the ability to model discontinuous stress results since problem variables are not forced to be continuous across elements. Discontinuous elements are extremely useful in the field of fracture mechanics where stress behavior at the crack tip is highly discontinuous, essentially undergoing a step transition from a very low stress (on the crack surface itself) to an extremely high stress (in the material next to the crack tip).

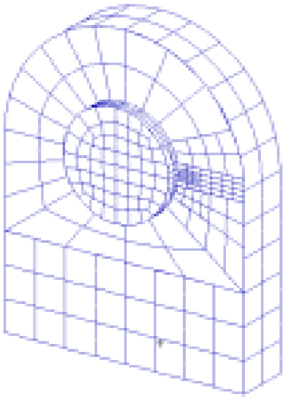

Figure 3. Boundary Element Model of Pin and Lug

The corner crack faces were modeled as free surfaces using the zone interface method. An internal spring boundary condition with near-zero spring stiffness was prescribed on the crack surface. A total of 32 elements were used to define the crack front. The radial edge length of the crack front elements was approximately 2% of the crack radius, well within the 5% limit typically recommended for accurate computation of K [6].

3.1.1 Contact Analysis

A contact stress analysis was used to analyze the load transfer between the pin and lug. A contact analysis was useful in providing results to characterize the non-uniform bearing stress on the lug resulting from the clevis type loading. The stress redistribution resulting from the opening crack is also captured using a contact analysis, as opposed to simply applying a uniform traction representing the pin loading.

The boundary element contact algorithm is based on a direct constraint approach that is not only suitable for large-scale three-dimensional analysis but is also numerically efficient. The contact algorithm is implemented in three stages as follows:

1) An initial stress analysis is performed to determine the condition on the prescribed contact areas using a predefined fraction of the total applied load.
2) After the first load increment the analysis computes displacements, tractions, and stresses at each node on the contact surface. A contact analyzer routine then determines if the surfaces are separated, sticking, or sliding.
3) The newly-identified contact condition is then introduced into the analysis using a constraint approach that expresses the equilibrium and compatibility conditions on the contact surface. These equations are added to the system matrix in such a way that only a partial reduction of the matrix is required after each load increment.
4) The analysis is then repeated using the new configuration and next load increment until the solution converges. The load increments are predefined and adjusted automatically depending on the rate of convergence of the solution.

3.1.2 Stress Intensity Factor

The three-dimensional K solution was inferred from the displacement field in the cracked structure. An extrapolation technique was used that involves correlation of the nodal displacements on the crack surface with the theoretical values from the crack front elastic fields. The Mode I stress intensity factor (K) was estimated using the following equation [6]:

$$K = \frac{2\mu}{\kappa + 1}\lim_{\rho \to o}\left[\sqrt{\frac{2\pi}{\rho}}\Delta u\right] \qquad (1)$$

This equation is based on the displacement component perpendicular to the crack surface which is referred to as the opening mode, or Mode I crack deformation. Since this equation is not valid at the crack tip, displacement results at nodal locations near the crack tip are used for extrapolation to the crack tip.

NASGRO K Solution

The NASGRO K solution for a corner crack from a hole in a single lug is Crack Case CC03 in the NASFLA software module. The solution is based on a series of polynomial equations developed from 3-D FEM analyses [3]. The K solution is obtained by simply defining appropriate geometric dimensions and the applied load in the software input menus. Both the K for the specific crack case and any applicable correction factors are then computed.

4 RESULTS AND DISCUSSION

Table 1 compares the calculated stress intensity factor results from the experimental approach, the BEASY boundary element analysis, and the standard formulas from NASFLA. The BEASY and NASGRO results agree closely. The experimental result is about 90 percent of the two analytical results. This verifies a prior observation by Newman and Raju [7]. Based on their conclusion, the NASGRO computer code multiplies the computed ΔK for a corner crack by a factor β_R when calculating fatigue crack growth based on da/dN data for through-thickness cracks. For zero-to-tension fatigue cycles, $\beta_R = 0.9$.

Table 1. Comparison of K Results (MPa (m)$^{.5}$)

	Experimental	**BEASY**	**NASGRO**
Ka	**12.21**	**14.25**	**13.55**
Kc	**10.04**	**11.35**	**10.81**

Figure 5 shows BEASY results for various amounts of pin clearance. The pin distributions change when the clearance varies. This in turn results in substantial changes in K. A non-dimensional parameter Ψ can be defined which uniquely captures the combined effect of radial clearance (Δr) and bearing stress magnitude (σ_b) on both pressure distribution and K. For Young's modulus E and pin radius r, this parameter is defined as

$$\Psi = E\,\Delta r / (r\,\sigma_b) \qquad (2)$$

BEASY analysis was conducted for σ_b = S, Δr = .0508 mm; and repeated for σ_b = S/4, Δr = .0127 mm. The pressure distributions and K values, when presented in normalized form as in Figures 5 and 6, were identical, verifying their unique dependence on Ψ, which is 2.94 in both cases. Figure 6 shows the calculated variation of K along the crack front. Note the sudden drop in K at 0 and 90 degrees. Elasticity theory predicts a boundary layer effect at the surfaces, where the true K drops abruptly to zero. The standard approach [7] is to use the value of K at a point 10 degrees from each surface for fracture mechanics predictions.

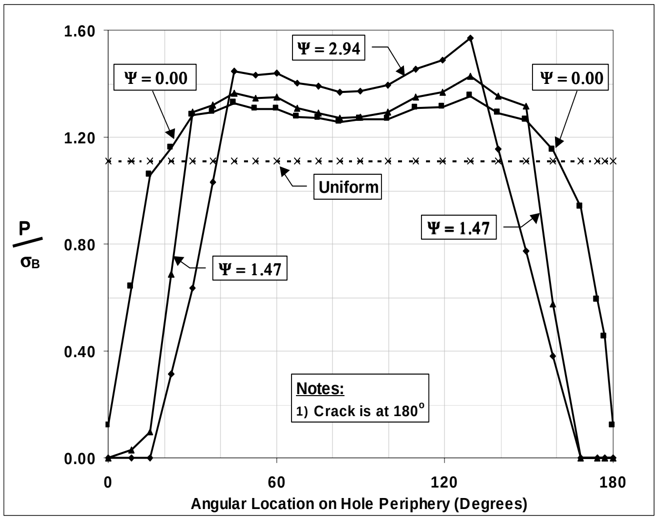

Figure 5. Pin Pressure Distributions 1 mm From Front Face

These values of K near the hole bore and near the lug surface are plotted in Figure 7 against the clearance parameter Ψ. For the given applied load, the stress intensity factors for the corner crack increase as much as thirty percent when the pin clearance is increased from a "neat" fit (zero clearance) to a radial clearance of .0508 mm, or 0.4 percent of the radius.

CONCLUSIONS

1. BEASY solution for K agrees well with solution used in NASGRO.
2. Experimental result supports hypothesis [7] that effective ΔK for fatigue growth of a corner crack is about 90% of calculated ΔK.

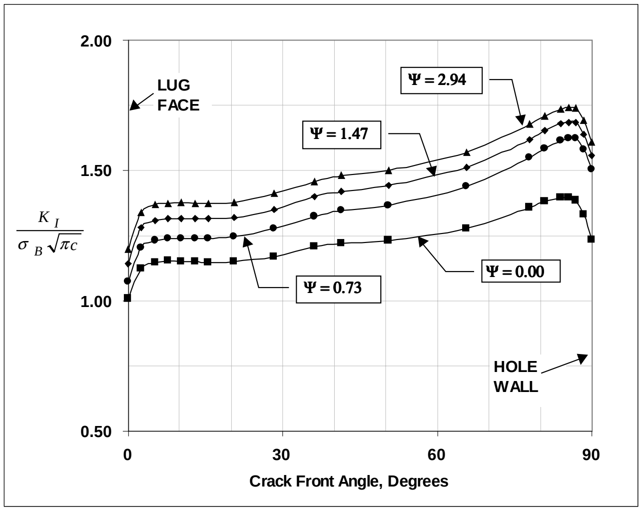

Figure 6. Variation in K Along the Crack Front

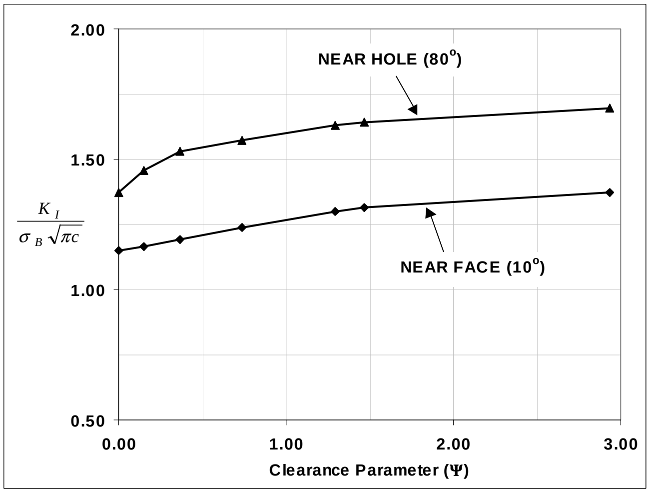

Figure 7. Variation in K with Pin Clearance

3. Strong effects of pin clearance on pin-lug contact pressure and stress intensity factors are calculated for corner cracks. This agrees with prior results for through-thickness cracks.
4. K increases with clearance parameter Ψ, which is proportional to pin clearance and inversely proportional to bearing stress.
5. BEASY analysis is an effective tool for 3-D fracture mechanics analysis of cracked lugs of various physical dimensions, crack sizes, pin clearances, and loading directions.

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