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Comparative Study of Fatigue Crack Closure

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Introduction

ONE of the more widely studied concepts for describing fatigue crack growth is the "crack closure" concept advanced by Elber.[1] According to this concept, the crack remains closed over a portion of the tensile part of the load cycle and the crack can propagate only during that portion of the load cycle in which the crack is open. The difference between the maximum applied load and the load at which the crack opens then is considered to be an effective load, which is responsible for advancing the crack. In terms of the stress intensity at the tip of the crack, this becomes

$$\Delta K_{eff} = K_{max} - K_{op} \tag{1}$$

where

ΔK_{eff} = effective stress intensity range
K_{max} = maximum stress intensity
K_{op} = opening stress intensity

Elber measured the displacement at the edge of the crack during loading with a very sensitive displacement gage and determined the crack opening load by analyzing the nonlinearities of the resulting load vs crack edge displacement curve. The resulting crack opening load is determined from a tangency point on the load vs crack edge displacement curve.

In this investigation, two different techniques were used to measure the crack edge displacements and resulting crack opening loads for constant-amplitude loading with four different stress ratios. In addition, one of the methods was used to measure the crack opening load following an overload/underload type of loading sequence. These results were compared with an inverse method.

Crack Opening Measurement

Many of the experimental investigations of fatigue crack closure have utilized crack edge displacement measurements to obtain the load-displacement curves from which the opening load can be determined. Other methods include the electrical potential method[2-4] and ultrasonic measurements.[5] Edge crack displacement measurements have been made using foil strain gages straddling the crack and bonded only at the ends at the gage.[6] Very sensitive strain gage extensometers using geometries with high strain concentrations have been used for crack edge displacement measurements.[1,7,8]

Pitoniak et al.[9] used an interferometry method to obtain the complete three-dimensional crack surface displacement field in transparent polymethylmethacrylate. Successive photomicrographs were used by Adams[10] to measure crack edge displacements. In this study, crack edge displacement measurements, to determine crack closure behavior, were made using both a strain gage extensometer and a specially developed laser interferometric technique. The laser interferometric technique developed in this study was similar to that used by Sharpe and Grandt.[11] With this system, two horizontal indentations are made on either side of the crack tip using a wedge-shaped diamond indentor. When the two grooves are illuminated by monochromatic light, two interference, or fringe, patterns are formed in space, one above and one below the crack. As the grooves are displaced relative to each other, the fringe patterns move in space. The fringe pattern is focused with a cylindrical lens and transmitted to a phototransistor detector. As the specimen is loaded, the displacements of the grooves cause the fringes to move past a detection slit in front of each of the phototransistors. Calibration is determined from the wavelength of the light emitted from the laser.

If the fatigue crack propagation is described by the effective stress intensity range ΔK_{eff}, as given by Eq. (1), then an inverse technique[12] can be used to determine K_{op} when it varies with geometry or as a result of a load variation. This assumes that ΔK_{eff} establishes the crack growth rate. If the growth rate under steady, constant-amplitude loading conditions is known and can be described as a function of ΔK_{eff}, then, for varying conditions, measuring the growth rate determines the value of ΔK_{eff} which must be advancing the crack under that set of loading conditions. By knowing K_{max} from the given loading conditions, Eq. (1) then can be solved for K_{op}. Alzos et al.[13] used this method to determine the change in K_{op} following overload/underload type of loading sequences.

Experimental Results

Crack closure measurements were made using 2024-T3 aluminum alloy center crack specimens, 559×152×2.5 mm. All tests were performed at room temperature in laboratory air. The crack growth was measured with a 100× microscope mounted on a measuring traverse. The test frequency was 20 Hz, and the overload and the cycles for crack opening measurements were applied at 0.02 Hz. (A triangle wave was used for the latter.) For the constant-amplitude tests, the load amplitude was held constant. For the overload/underload tests, the stress intensity was held quasiconstant by load-shedding each 5% of crack growth prior to and following the overload/underload sequence.

For each K_{op} measurement with constant-amplitude loading, the Elber gage was mounted near the crack tip and the data recorded for several cycles. The Elber gage then was removed, and the crack opening displacement was measured with the laser system. The narrow column of light was aligned with the indentations made by the Elber gage which resulted in taking the measurement at nearly the same location relative to the crack tip with each of the two methods. Crack growth data also were obtained.

A series of 16 constant-amplitude tests was run to allow comparison of the crack opening load obtained from the Elber gage with that obtained from the laser interferometric system. Four levels of the stress ratio R were used, 0.01, 0.11, 0.22, and 0.33. For each R, four different stress levels were used. Analysis of the a vs N data confirmed that the results were representative.

Elber defined the parameter

$$U = (K_{max} - K_{op})/(K_{max} - K_{min}) \tag{2}$$

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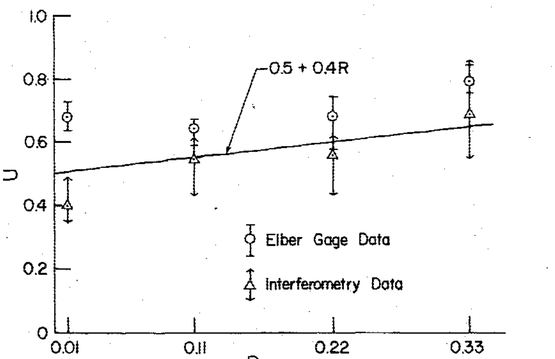

Fig. 1 *U* vs stress ratio, *R*, for constant-amplitude test results.

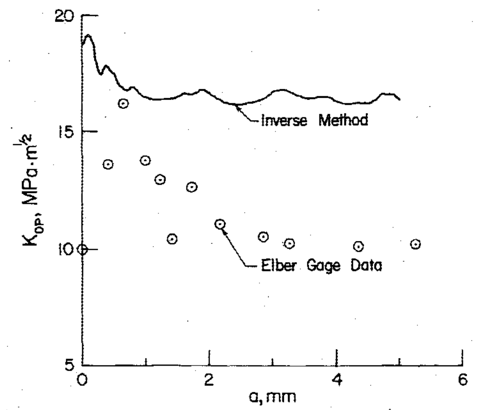

Fig. 2 Typical results of K_{op} vs crack length, *a*, following overload/underload (test 8).

Using the measured values for K_{op}, the results for U using each measurement method are compared in Fig. 1.

A major portion of the scatter observed in these results can be attributed to the location relative to the crack tip where the displacement was measured. Four of the tests were rerun because of lower than expected growth rates. For these repeated tests, the Elber gage was positioned at three locations: behind the crack tip approximately 0.5 mm, near the crack tip, and slightly ahead of the crack tip. These results showed that K_{op} determined from measurement behind the crack was consistently higher by about 10% than that obtained from measurements slightly ahead of the crack tip. The results from measurements near but behind the crack tip were between these two values. This demonstrates that the position of the crack edge displacement measurement relative to the crack tip can affect the measured value of K_{op} significantly. A 10% variation in K_{op} will account for nearly all of the scatter in U seen in Fig. 1.

Alzos et al.[13] showed that the crack delay behavior due to single overload/underload load sequences could be correlated with the maximum value of K_{op} following the overload/underload sequence. Alzos determined K_{op} using the inverse method. It also was the purpose of this investigation to compare K_{op} for an overload/underload sequence from direct measurements with that determined from the inverse method.

Six overload/underload tests were selected from Alzos' test matrix as being representative of expected K_{op} values as determined by the inverse technique. All tests were performed with the same K_{op}; thus the effect of the overload level was not investigated. The overload level produced plane stress conditions.[13] Elber gage data were collected at several points throughout the overload affected region and K_{op} determined from the displacement traces. For each test, the a vs N data were collected and da/dN determined through the overload affected region. Using the constant-amplitude data from Alzos' study, K_{op} following the overload also was determined using the inverse method.

The measured values of K_{op} through the overload region are compared with the results for the inverse method in Fig. 2 for one of the tests. These are typical results. These measurements confirmed the increase in K_{op} following the overload as predicted using the inverse method, although the measured values of K_{op} are significantly lower and there is considerable scatter. Further details of the results for the other tests are described in Ref. 14.

Conclusions

Based on the results of this investigation, the following conclusions are made:

1) The measurement of crack opening K_{op} using crack edge displacement is a difficult procedure and subject to considerable scatter. The definition of the opening load as a tangency point on the load displacement curve does not describe a discrete point or value corresponding to the load when the crack opens. A measurement method that precisely describes the opening load is required if crack opening is to be used quantitatively.

2) The overload/underload test results confirm the expected crack opening behavior as suggested by the crack closure theory. Although crack closure is confirmed, the actual values of K_{op} with the associated scatter are probably of little value for quantitatively assessing or predicting crack growth behavior.

3) The location relative to the crack tip at which the crack edge displacement measurements are made influences the resulting opening load.

4) The laser interferometric system provides an accurate, convenient method for measuring crack edge displacements; however, if it is to be used to make a large number of measurements, an improvement in the data-reduction method would be desirable.

Acknowledgments

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Influence of Spin Rate on Side Force of an Axisymmetric Body

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Introduction

THE study of the side force on bodies of revolution at high angles of attack and zero sideslip has received considerable attention in recent years.[1-3] On foreboides it has been found that the side force can be as much as 1.5 times the normal force.[1] In some investigations, the model was tested at several fixed angles of roll, and it was found that in some positions a side force was produced which was opposite in sign and nearly equal in magnitude to that found in other positions. In addition, a model with a removable portion of the tip was tested with the tip at several fixed angles of roll, and changes in the side-force direction were obtained which were similar to the changes when the complete model was rotated. Other investigations have spun models about their axes of symmetry and observed the variation in side force.[3] The results given herein are from an investigation in which a cone was spun at several rates about its axis of symmetry, and the resulting side force was recorded on an oscillograph. The results are compared to determine the influence of spin rate on side force.

Experiment and Discussion

The model used in this investigation was a 10-deg half-angle pointed cone, 57.9 cm in length. The cone was made of magnesium, for lightness and to minimize inertial effects, and was machined internally to house a six-component strain gage balance and an electric motor to rotate the cone about its longitudinal axis. Tests were conducted in the 6-×6-ft transonic/supersonic wind tunnel and the 12-ft pressure wind tunnel at Ames Research Center at a Mach number of 0.6 and a Reynolds number R_d of 1×10^6 (based on diameter). Static tests were conducted at various fixed roll angles and angles of attack. Spin tests then were conducted at angles of attack of 42.5-45 deg and of 58-60 deg. Because they demonstrate better the changes in side force direction with roll, only the data taken at angles of attack of 58-60 deg are presented.

The model was spun in both directions, and oscillograph traces of the signal from the balance were recorded. A calibration of the dynamic response of the balance used was not made; however, these Task balances are known to have a natural frequency above 1 kHz, which is far above those

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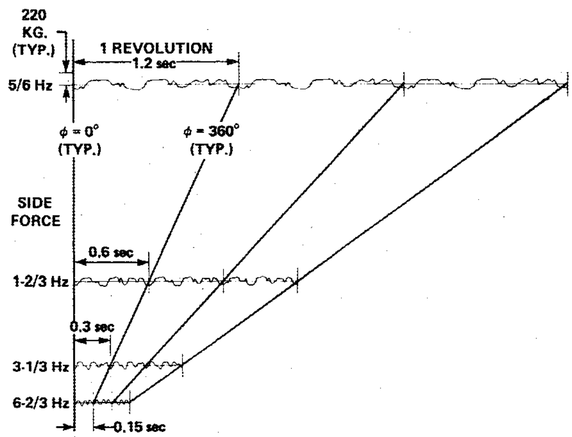

Fig. 1 Typical oscillograph traces of aft side-force gage of six-component balance.

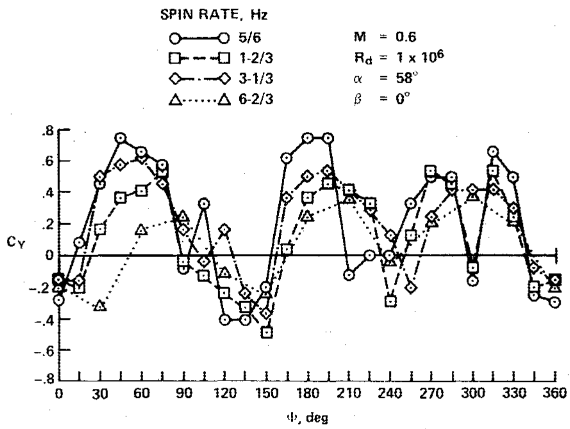

Fig. 2 Side-force coefficient vs roll position.

frequencies experienced during the test. The dynamic balance of the model was checked at zero air velocity and at the angles of attack and spin rates at which data were taken. No model imbalance could be detected in the oscillograph traces. The model roll position Φ was measured from a vertical axis, in a counterclockwise direction looking forward, to an arbitrarily established radial line on the model. Curves were hand-faired through the noise so as to produce smooth traces and yet maintain the basic form of the curves as much as possible. Most of the data presented are for counterclockwise rotation.

The resulting traces from the aft side-force gage are shown in Fig. 1. Three revolutions at each spin rate are shown. The side force changes direction in an irregular manner within a cycle; however, this irregular pattern was repeatable from cycle to cycle. The change in direction of side force is thought to be the result of a changing vortex pattern over the model caused by asymmetries in the model geometry, especially near the tip. As the spin rate is increased, it is seen that the general shape of the trace is maintained, whereas the smaller excursions tend to disappear. The signal traces from the forward side-force gage showed similar characteristics, but the magnitude was much less.

Presented in Fig. 2 is the variation of the side-force coefficient with roll position Φ at several spin rates. The total side force was obtained by adding the measured side forces from the forward and aft side-force gages. The side force is seen to experience roughly three cycles during one revolution of the model. This cyclic variation of side force could be attributed to the physical shape of asymmetries in the model tip and to the manner in which the resulting flow is influenced by spin rate. However, the basic shape of the side-force curve is not a strong function of spin rate. There is some evidence that the cyclic variation of side force at the higher spin rates lags that