Summary of Recent Round Robin Life Prediction Efforts for Crack Shape and Residual Stress Effects

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Abstract. Two round-robin life prediction efforts were conducted to assess the ability to perform blind life predictions for test data obtained for corner cracks at centered and offset holes in 7075-T651 and 2024-T351 Aluminum alloys. The first round robin effort was conducted as part of a recent AFGROW Crack Growth Life Prediction Software Workshop focused on the ability to accurately predict crack shape evolution, and the second was conducted by the Engineered Residual Stress Initiative (ERSI) Workshop on the effect of split sleeve cold-working. The goal of the ERSI round-robin was to quantify specific sources of systematic uncertainties based on fixed input data provided to each participant. The blind predictions of crack growth life for the AFGROW Workshop were in very good agreement with the test data, and the predictions for the ERSI effort were generally within the statistical variation of the test data. However, the predictions of crack shape evolution did not show good agreement with the test results for either effort. The crack growth predictions for each crack direction were made using a single crack growth rate model based on the test specimen grain orientation and crack growth in the radial direction from the hole (L-T orientation). On further investigation, it was determined that different crack growth rate models (L-T and L-S) were required to predict crack shape changes as the initial corner cracks grew through the thickness of the test specimens. This paper will summarize the results of each blind round robin effort and compare the crack shape predictions made using single and dual crack growth rate models.

Keywords: Crack growth life prediction · Round robin life prediction · Crack shape prediction · Crack growth rate · Residual stress

1 Introduction

Many aspects of a crack growth assessment are critical when establishing the life limits and inspection intervals for critical structural components. The ability to not only assess the crack growth life, but to also accurately characterize crack shape evolution can have significant impacts on recurring inspection intervals and non-destructive inspections. Previous evaluations by the United States Air Force (USAF) A-10 analysis team have

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demonstrated difficulties accurately predicting crack shape evolution from a corner crack at a fastener hole [1, 2]. These evaluations have indicated differences in crack growth rate may be partly responsible for the differences observed between predictions and experimental results. To address this question, the A-10 team has initiated an effort to develop material properties in the L-T, L-S, and L-TS orientations to represent corner crack growth at a fastener hole.

To compliment the experimental testing program, the AFGROW and ERSI working groups specifically focused on predicted versus experimental crack aspect ratio comparisons in the round robin efforts. These round robin efforts utilized similar test specimen geometries and loading, however, focused on two difference aluminum alloys, 7075-T651 and 2024-T351.

2 Test Specimen Geometry

The test specimen geometry used for both efforts was a single corner crack at an open hole as shown in Fig. 1.

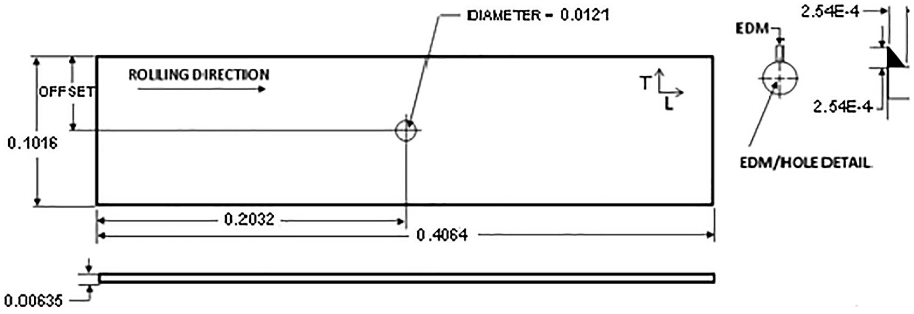

Fig. 1. Specimen geometry (Dimensions in meters)

3 AFGROW Workshop Summary

The AFGROW round-robin test effort was performed to determine the variability of users, given the same loading spectrum, material data, and Initial Flaw Size (IFS) information to predict the evolution of crack aspect ratio (a/c) and crack growth life using the AFGROW framework as the life prediction tool. The material used for this effort was 7075-T651 aluminum. A constant amplitude (R = 0.1) loading spectrum included marker cycles to produce marker bands on the fracture surface. The test specimens and material data were provided by the U.S. Air Force (A-10) and Southwest Research, Inc. Specimen testing was performed by SAFE, Inc., and post-test fractography analysis was done by APES, Inc.

A total of nine participants made blind crack growth predictions using the same baseline information. Each participant was assigned a code name to maintain anonymity (Fig. 2).

	MacAllan - A	MacAllan - B	MacAllan - C	Dalwhinne	FinLaggan	Black Label	Dewars	Jura	Cathead
K-Solution - Center K-Solution - Offset	Two Point Advanced	Two Point Advanced	Two Point Advanced	Advance Classic	FEA	Advanced w/β Correction	FEA Advanced	Unknown	Unknown
Load Interaction	None	Hsu	Hsu, β_R	β_R	None	None	None	Unknown	Unknown
a/c constant	No	No	No	No	No	No	No	No	No

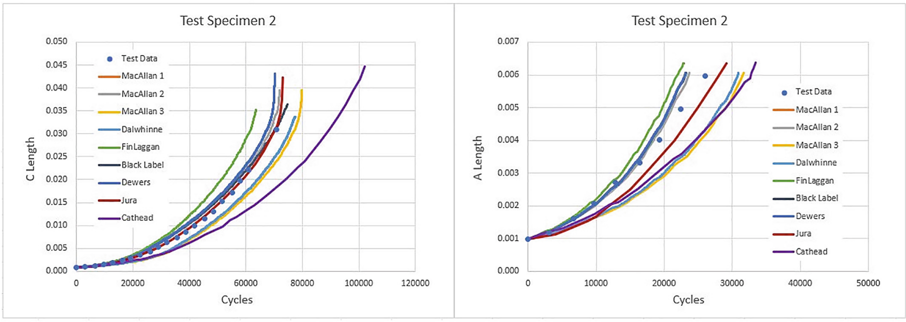

Fig. 2. Crack growth predictions for a typical test specimen

The blind life predictions for all participants were in good agreement with the test results. However, predictions of crack shape did not follow the trends seen in the fractographic analysis of the test data (Fig. 3).

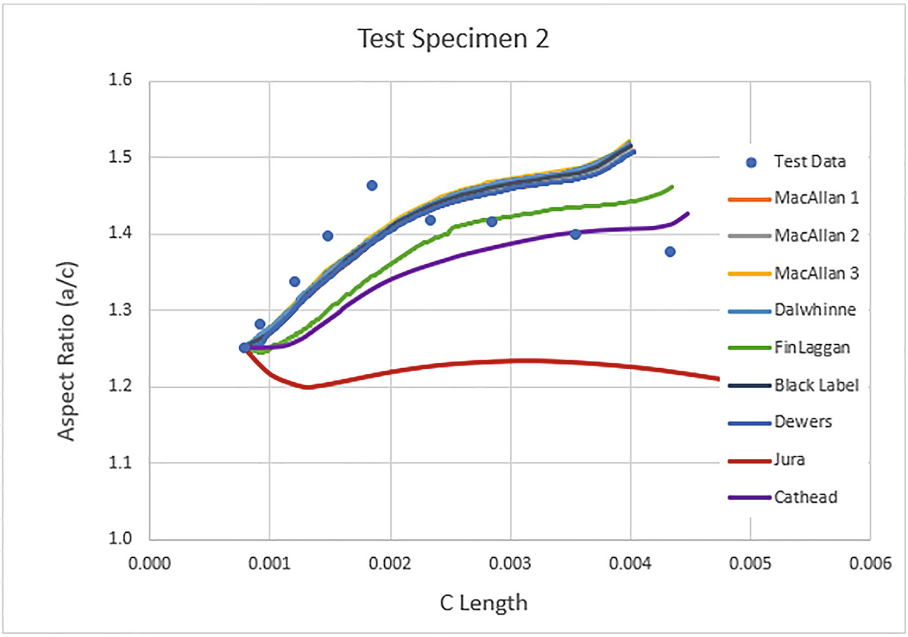

Fig. 3. Crack shape predictions

The fractographic results generally indicated an increase in corner crack aspect ratio followed by a decrease as a function of the crack length in the c-direction. The fractographic data for a number of crack lengths were used to generate da/dN vs. DK plots for each crack growth direction and compare the result to the single crack growth rate curve that was provided to each participant (Fig. 4).

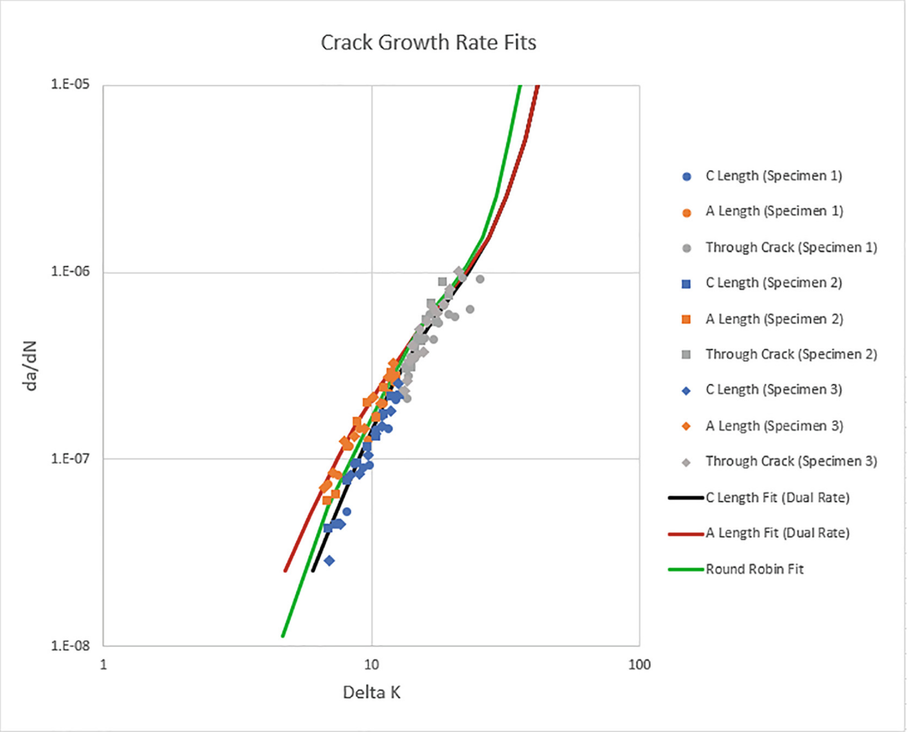

Fig. 4. Crack growth rate curves

The crack growth rate data extracted from the fractographic data for the a-direction was clearly different than the data for the c-direction. The data appear to converge to the through crack data, but the slopes of the two curves are different. When the growth rate data for each direction were applied for the appropriate crack growth direction (dual rates), the crack shape predictions were in very good agreement with the test results (Fig. 5).

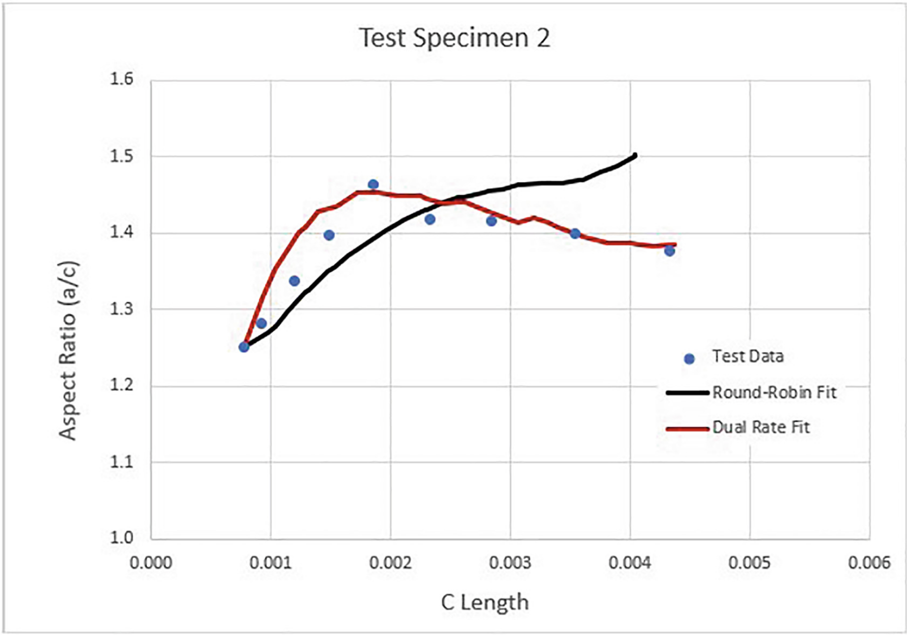

Fig. 5. Crack shape prediction example for single vs. dual growth rate data

To be clear, the dual rate prediction would be expected to give a good result since the data were obtained from the test data. However, it would not have been possible to predict the crack shape results without using different growth rate data in each direction. For the given stress intensity values in each direction, the two growth rate curves must have different slopes to produce the crack shape trends seen in the test data.

4 ERSI Workshop Summary

Concurrently with the AFGROW round robin, the ERSI Fatigue Crack Growth (FCG) Analysis Methods subcommittee was also completing a round robin within their working group. The primary purpose of this round robin was focus on blind analytical predictions of cracks at cold-worked (Cx) fastener holes, specifically focused on quantifying the epistemic uncertainties in the prediction of crack growth life, given a fixed set of input data. Specific input data were fixed to minimize the effect of random uncertainties; however, the analysts were free to use any means to incorporate the residual stresses into their Damage Tolerance Assessments (DTA). The effort was an opportunity to exercise various analytical methods, comparing to experimental results, and uncovering strengths and weaknesses of the various approaches.

Four conditions, including baseline non-Cx and Cx, were selected for the round robin effort. These conditions were selected based on the relevance to actual aircraft conditions as well as clear documentation of all the inputs provided to the analysts. Additional details of the experimental results were previously published [3, 4]. Specific inputs were provided to participants, including coupon geometries, material properties, initial flaw (size, shape, location, and orientation), constant amplitude (CA) loading spectrum, boundary conditions, and residual stress (developed via the contour method) [5, 6]. FCG rate data were supplied in tabular form. The average of the starting crack size from the experimental results were provided to the analysts as inputs. A summary of the provided inputs is included in Table 1. Analysts were free to use any means to incorporate the residual stress into the DTA, any software suite, etc., however, it was important that the analysts adhered closely to the guidance provided so that the variability in the predictions was limited to the aspects left to the analyst's discretion.

Table 1. Benchmark specimen conditions.

Case #	Material	Specimen Type	Thickness in (mm)	Width in (mm)	Hole Diameter in (mm)	Hole Edge Margin	Loading	Max Stress ksi (MPa)
1	2024-T351	Non-CX Baseline	0.25 (6.35)	4.00 (101.6)	0.50 (12.7)	4.0	CA (R=0.1)	10 (68.9)
2		CX						25 (172.4)
3		Non-CX Baseline				1.2		10 (68.9)
4		CX						25 (172.4)

A total of eight analysts participated in the round robin, each taking a different approach to analyze the conditions provided. Analysts utilized various software packages including AFGROW, NASGRO®, and coupled Finite Element Analysis (FEA) to FCG software such as Broad Application for Modeling Failure (BAMF), and the Crack Propagation Analysis Tool (CPAT). Many analysts took the round robin effort as an opportunity to evaluate multiple analytical approaches, highlighting the strengths and weaknesses of each. A summary of the key modeling factors for each submission for the baseline non-Cx cases is detailed in Table 2. FCG predictions and aspect ratio trends for the non-Cx cases are shown in Fig. 6 to Fig. 7, with classic AFGROW predictions colored green, NASGRO® predictions colored blue, and coupled FEA-FCG software colored red. The submitted predictions were compared to experimental results looking at surface and bore crack length versus cycles (c vs N, a vs N), crack growth rates versus cycles (dc/dN vs N, da/dN vs N), crack aspect ratio evolution (a/c vs a/t), stress intensity comparisons ($K_{applied}$ and $K_{residual}$), through thickness transition, critical crack lengths, and the slope at the transition point.

Table 2. Summary of modeling considerations for baseline cases #1 and #3.

Submission #	Key Modeling Factors Baseline Cases 1 & 3				
	Software		Crack Definition		
	Lifing Software	FE Software	Crack Front Shape	# of Crack Front Points	Stress Intensity Calculation
1	CPAT	StressCheck	Multi-Point	30	Contour Integral Method
2	CPAT	StressCheck	Multi-Point	20	Contour Integral Method
3	AFGROW	N/A	Elliptical	2	Standard, Classic Newman/Raju
4a	NASGRO	N/A	Elliptical / Straight Thru	2	NASGRO CC08/TC13 univariant WF
4b	NASGRO	N/A	Elliptical / Straight Thru	2	NASGRO CC16/TC03 Fawaz/Anderson
4c	NASGRO	N/A	Elliptical / Straight Thru	2	NASGRO CC10/TC13 bivariant WF
4d	NASGRO	N/A	Elliptical / Straight Thru	2	NASGRO CC08/TC13 univariant WF
4e	NASGRO	N/A	Elliptical / Straight Thru	2	NASGRO CC16/TC03 Fawaz/Anderson
4f	NASGRO	N/A	Elliptical / Straight Thru	2	NASGRO CC10/TC13 bivariant WF
5	BAMF	StressCheck	Multi-Point	11	Contour Integral Method
6	AFGROW	N/A	Elliptical / Straight Thru	2	Standard, Classic Newman/Raju
7	CPAT	StressCheck	Multi-Point	15	Contour Integral Method
8	AFGROW	N/A	Elliptical / Straight Thru	2	Standard, Classic Newman/Raju

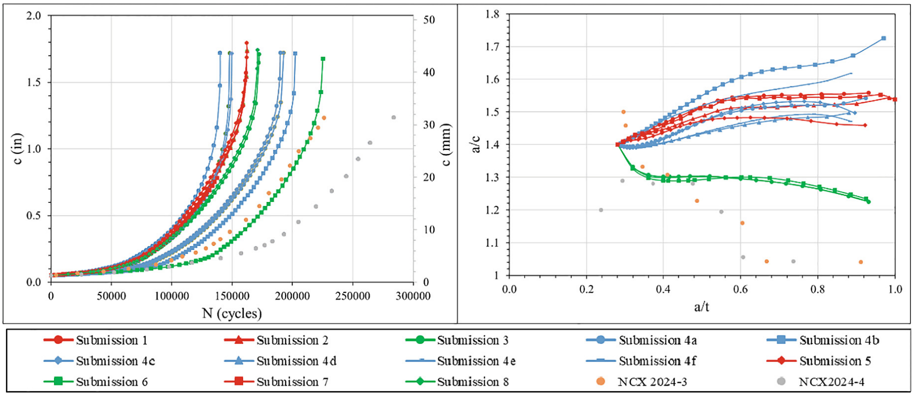

Fig. 6. Prediction of fatigue crack propagation life (left) and crack aspect ratio (right) for Case #1. Symbols without lines correspond to experimental data.

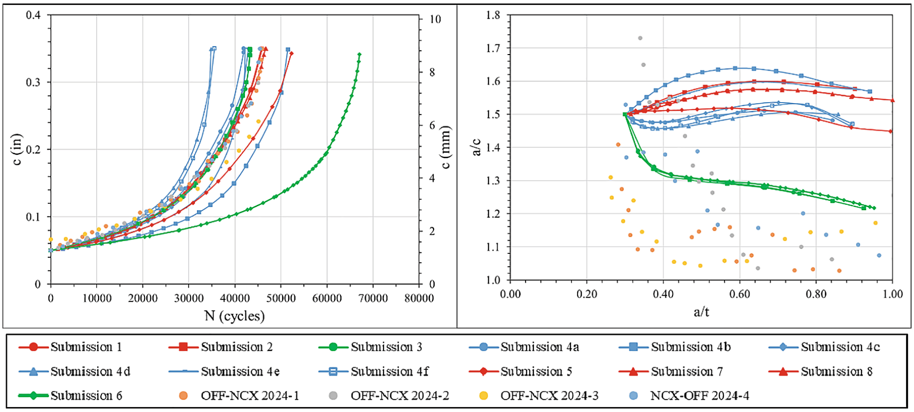

Fig. 7. Prediction of fatigue crack propagation life (left) and crack aspect ratio (right) for Case #3. Symbols without lines correspond to experimental data.

Similar to the findings from the AFGROW round robin, the overall life predictions were consistent with experimental results, however, the predicted versus experimental aspect ratio trends differed significantly. Note that the analysts were provided the average starting crack sizes for the population of experimental data, with no predictions matching the experimental data starting crack sizes exactly; however, the overall trends indicated an issue with the predictions.

In an effort to mimic the approach from the AFGROW round robin, dual rate FCG data was inversely fit and the analyses were re-accomplished investigate the impacts to crack growth life predictions and aspect ratio trends. The original FCG rate data provided to participants was based on available aluminum 2024-T351 middle and compact tension test data for through cracks tested at a stress ratio of R = 0.1. Inversely calculated rate data utilized growth rates of the corner cracks in the ‘a’ and ‘c’ directions. Figure 8 details the differences between the as-provided and the inversely fit rate data. The analysis predictions were re-accomplished utilizing the exact starting crack sizes and aspect ratio from the experiments for both the single and dual rate data for cases #1 and #3 (see Fig. 9).

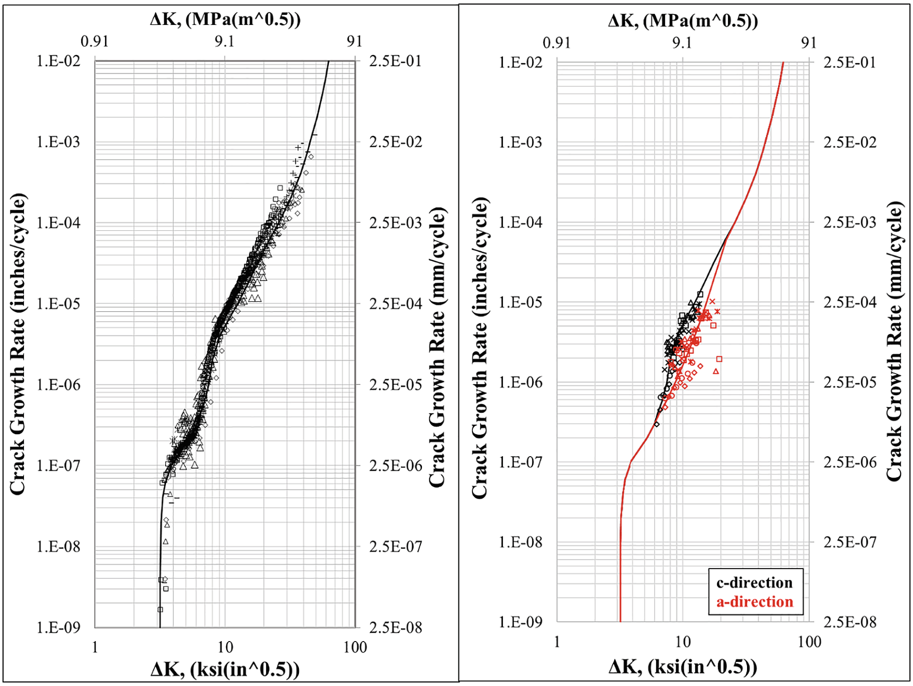

Fig. 8. Fatigue crack growth rate data provided to round robin participants (left) and inversely fit from corner crack data, 2024-T351 (R = 0.1). Symbols without lines correspond to experimental data.

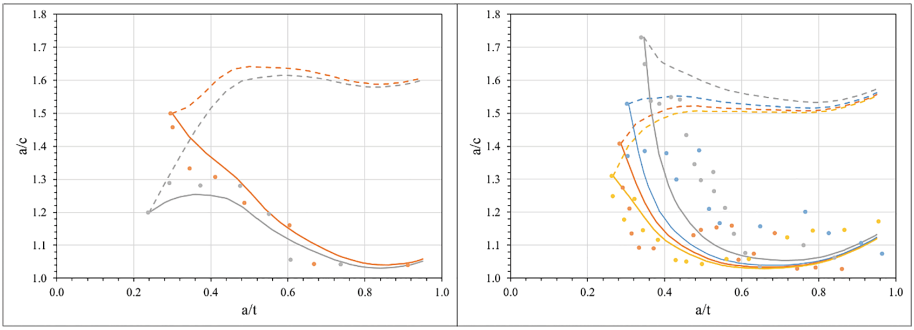

Fig. 9. Predicted crack aspect ratio behavior for single rate (dashed lines) and dual rate (solid lines) FCG rate data, case #1 (left) and case #3 (right). Symbols without lines correspond to experimental data.

5 Conclusion

The blind life predictions made for both round robin efforts were in good agreement with the test results. However, it was clear that the trends seen in the crack shape behavior of the test specimens were not accurately predicted using a single crack growth rate curve.

Predictions made using inverse fit crack growth rate data for each crack direction (dual rate data) showed good agreement with the test results. Although the use of crack growth rate data obtained from the same test specimens would be expected to produce good results, it is important to note that the use of dual rate data was required to predict the crack shape trends seen in the test data.

Since crack shape can have a significant effect on the stress intensity factor for each crack dimension, it is also important to note that the crack shape changes in these examples were relatively small (1 to 1.5). This helps to explain why the life predictions using a single crack growth rate curve were relatively good while the predictions of crack shape did not agree with the test results. When large changes in crack shape are expected, the ability to model crack growth rate behavior in each direction will have greater influence on the accuracy of life predictions. Additional work is currently planned to expand this effort to include predictions for multiple points along a crack front. This will require crack growth rate information for multiple directions to be interpolated for each point on the crack front.

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