The Fundamentals of the ACR Method and the Master Curve Concept

By:
Keith Donald
Fracture Technology Associates

Acknowledgements

Mark James, Gary Bray, Bob Bucci
Alcoa Technical Center

Ed Phillips
NASA-Langley Research Center

Paul Paris
Washington University

Diana Lados
Worcester Polytechnic Institute

Introduction

- The adjusted compliance ratio (ACR) is an experimental method of determining a reduction in ΔK due to crack closure and is designated ΔK_{ACR}. It is particularly useful for remote closure associated with long crack samples such as the C(T).
- ACR is one example of a partial closure model that assumes crack-tip strain below the opening load, even at P_{min}
- It is derived from the compliance ratio (CR) concept that uses near crack-tip strain measurements to estimate ΔK_{eff}.
- ACR allows remote displacement or strain measurements to be used for estimating ΔK_{ACR}.

Significant Events

- 1968 Crack closure discovered (Elber).
- 1985 Offset method of measuring crack closure introduced (FTA).
- 1990 Crack tip strain validates Compliance Ratio (CR) concept (FTA).
- 1995 E647 Annex added for opening load measurement.
- 1996 Adjusted Compliance Ratio (ACR) concept introduced (FTA).
- 1997 Second ASTM RR opening data re-analyzed using ACR method.
- 1997 ACR combined with K_{max} sensitivity using "Master Curve" (FTA).
- 1998 $2/\pi$ partial closure model introduced (Paris) .
- 2005 Real-time "Crack-compliance" method of $K_{residual}$ introduced (FTA).
- 2009 E647 draft annex of ACR method, ACR Workshop
- 2013 E647 includes annex for ACR method
- 2015 Partitioning Crack Closure Mechanisms Using CR (FTA)

Compliance Ratio

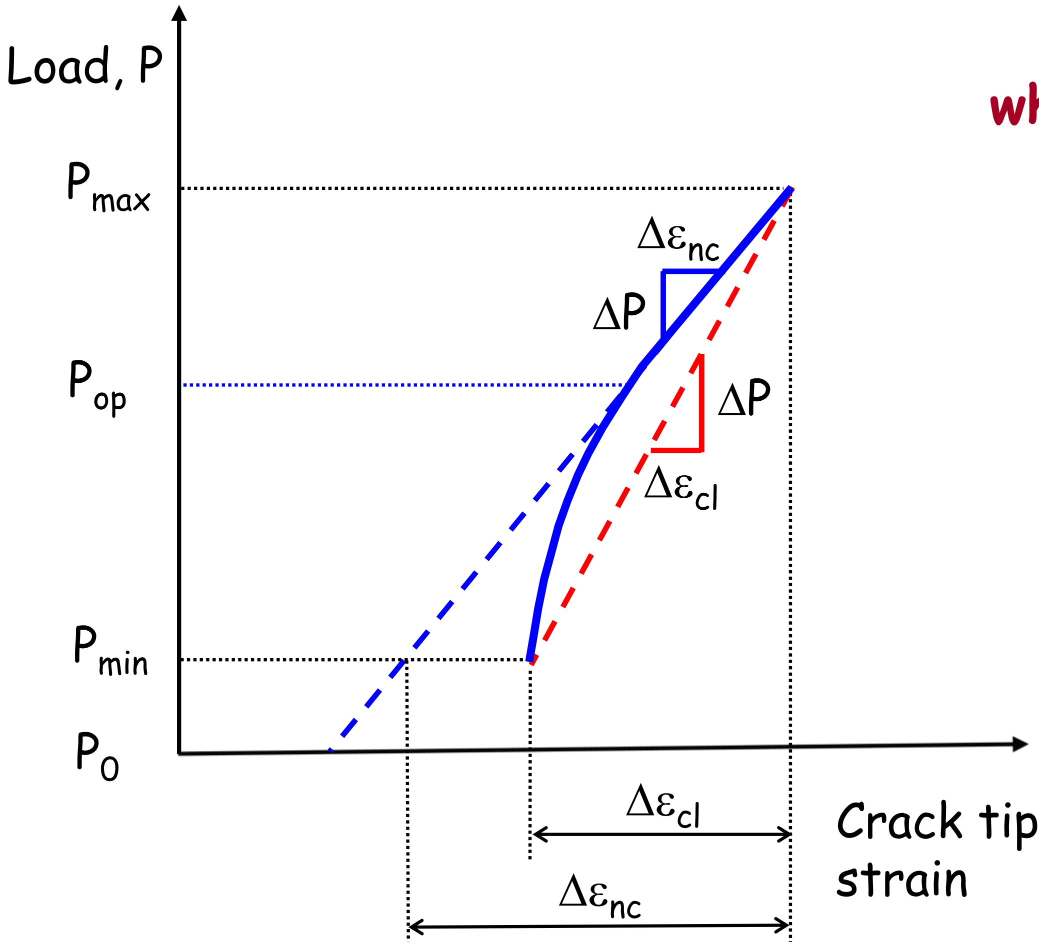
Compliance Ratio (CR) requires near crack-tip strain measurements to estimate ΔK_{eff}.

Basic Assumptions and Limitations:

1 An elastic analysis is assumed.
2 Strain gage must be large relative to the size of the crack tip plastic zone (plane strain).
3 Strain gage must be small relative to sample size and crack size.
4 Strain gage must be nearer the crack tip than the bulk of the crack closure shielding mechanism.

This is difficult to achieve: The compliance ratio is extremely sensitive to the measurement location.

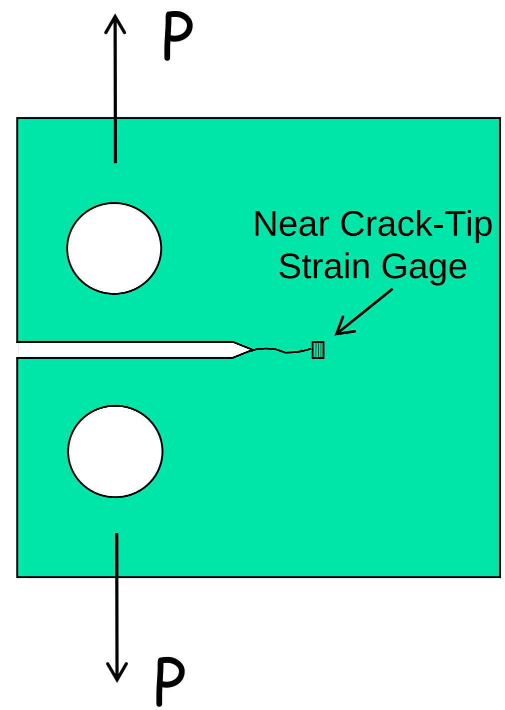
Compliance Ratio



$$\Delta K_{CR} = CR \cdot \Delta K_{app}$$

where

$$CR = \frac{\Delta \varepsilon_{cl}}{\Delta \varepsilon_{nc}}$$



Adjusted Compliance Ratio

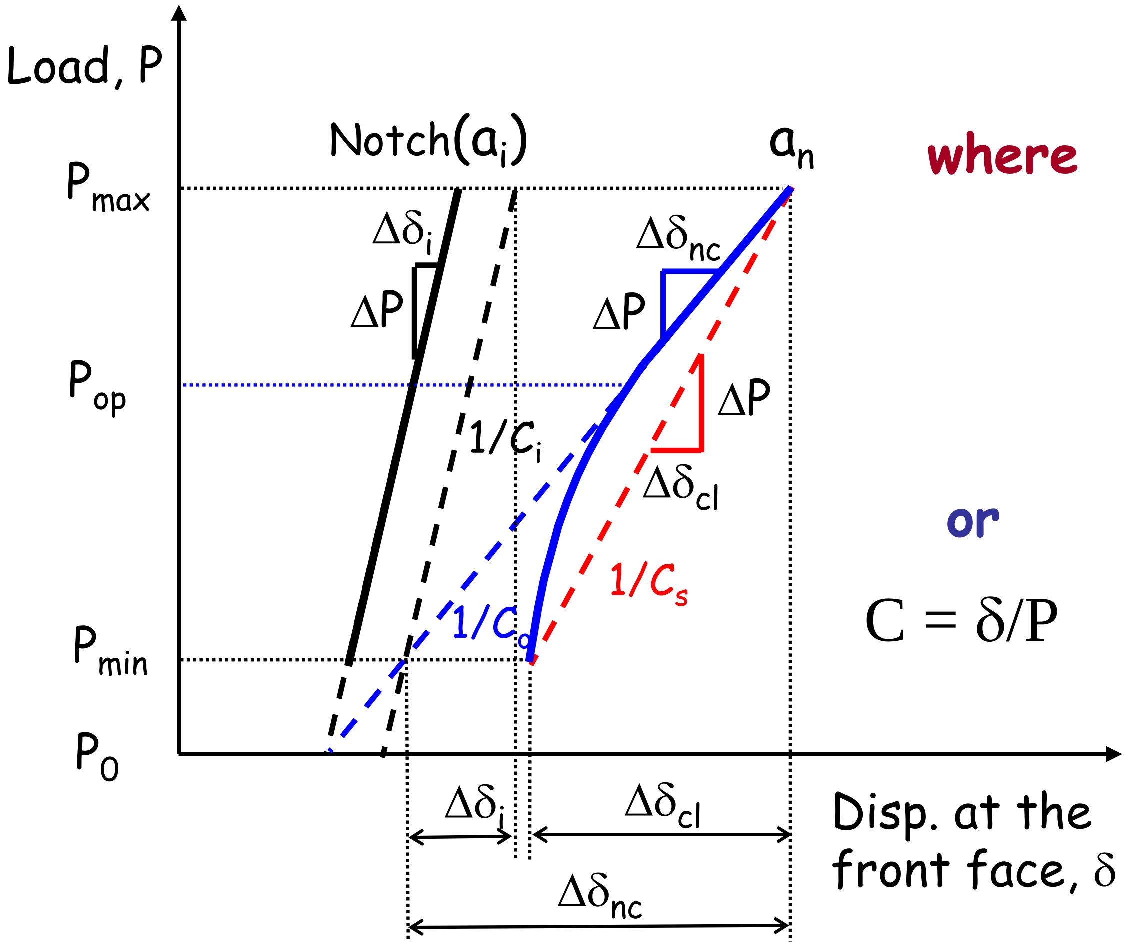
By subtracting the compliance prior to initiation of a crack, ACR allows remote displacement or strain measurements to be used for determining ΔK_{ACR}.

Basic Assumptions:

1. An elastic analysis is assumed.
2. Remote locations include crack mouth opening displacement and back-face strain gages.
3. The remote location must be sufficiently removed from the crack so that the bulk closure mechanism is characterized.
4. Local locations such as strain gages in or near the path of the crack may not be reliable since even the sign of the compliance could change as the crack advances (compact tension sample).

ACR is easy to implement using remote measurements and appears to be insensitive to the measurement location.

Adjusted Compliance Ratio (ACR)



$$\Delta K_{ACR} = ACR \cdot \Delta K_{app}$$

where

$$ACR = \frac{\Delta\delta_{cl} - \Delta\delta_i}{\Delta\delta_{nc} - \Delta\delta_i}$$

(constant load only)

or

$$C = \delta/P$$

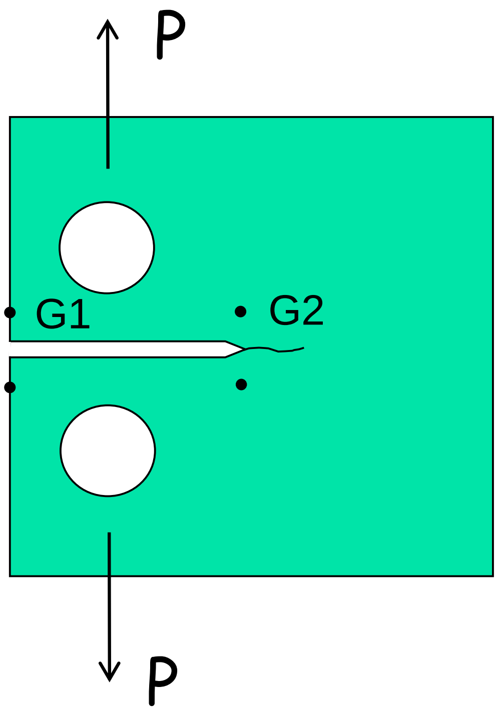
$$ACR = \frac{C_s - C_i}{C_o - C_i}$$

(suitable for K-control)

Useful Characteristics of the ACR Method

- Different remote measurement locations give the same value of ACR.
- ACR is easily implemented since it uses the same load-displacement data as the opening load concept.
- The ACR method is most suitable for removing the effects of remote closure. Ideal for load-shedding decreasing-K and long crack to physically small crack correlation.
- ACR combined with K_{max} sensitivity offers a novel approach to material characterization by utilizing a "Master Curve".

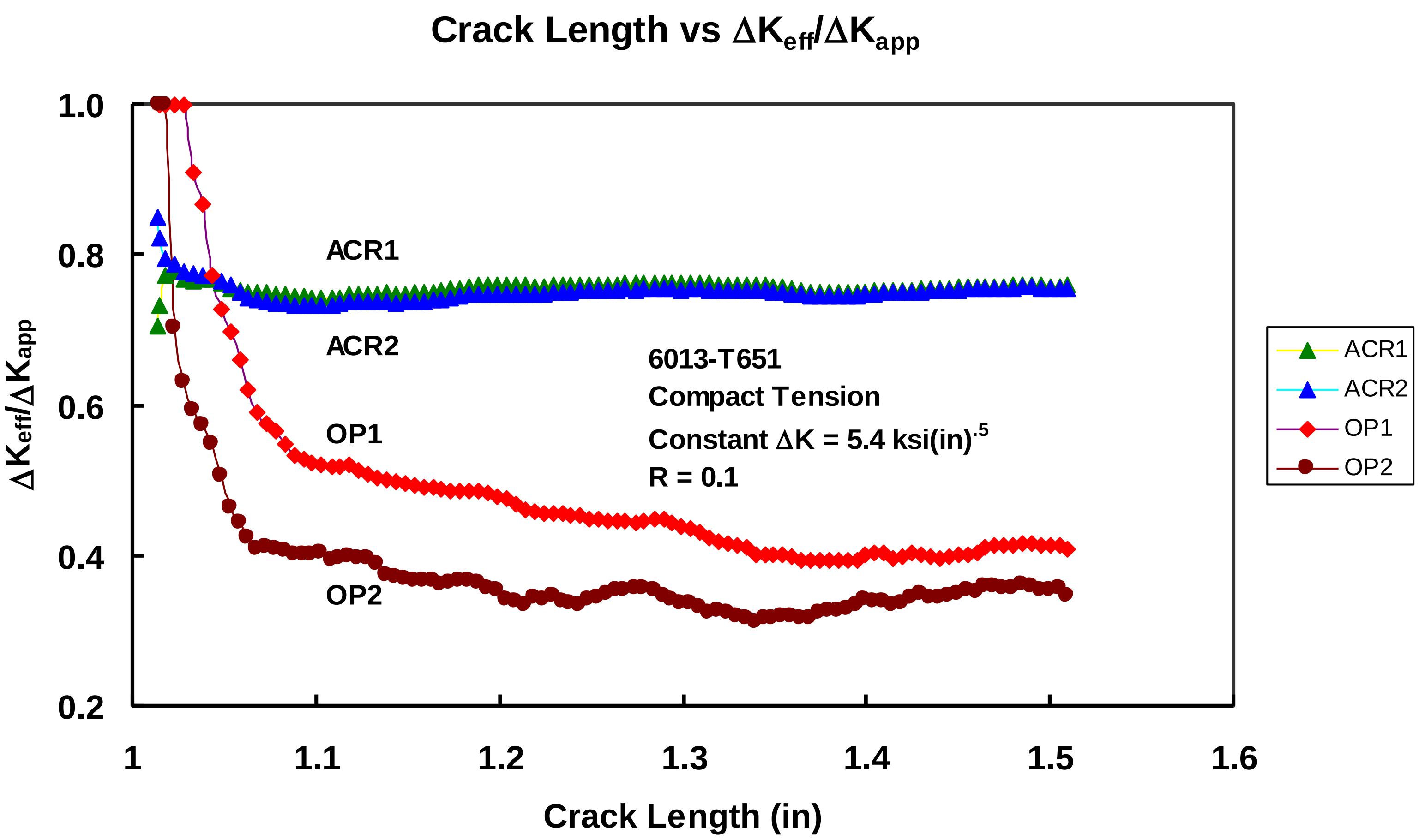
The ACR value is independent of the remote measurement location



Two measurement locations, G1 and G2, have very difference compliances, compliance ratios, and ASTM opening loads.

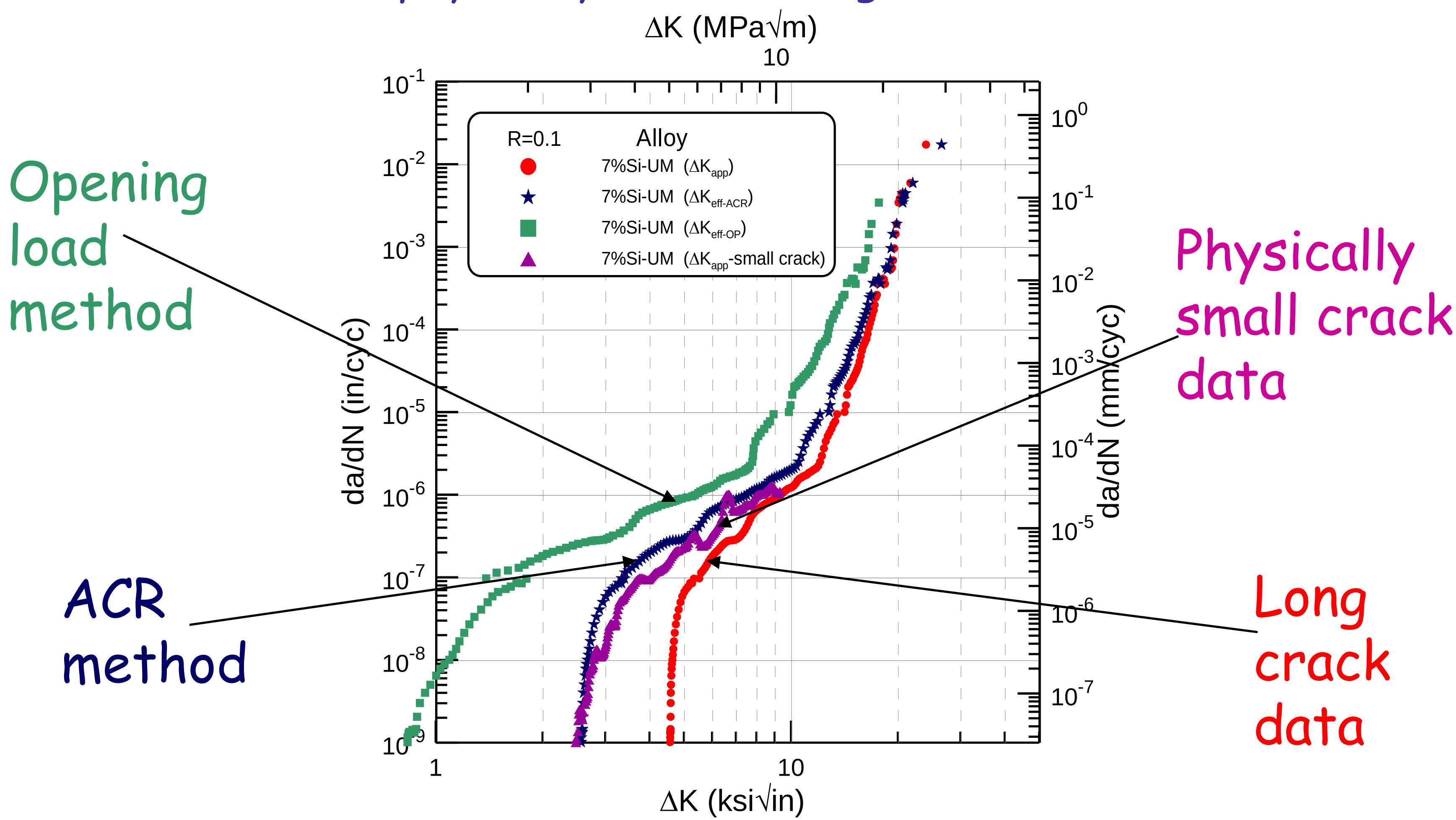
The ACR for these two locations is the same.

Same ACR for G1 and G2 Locations



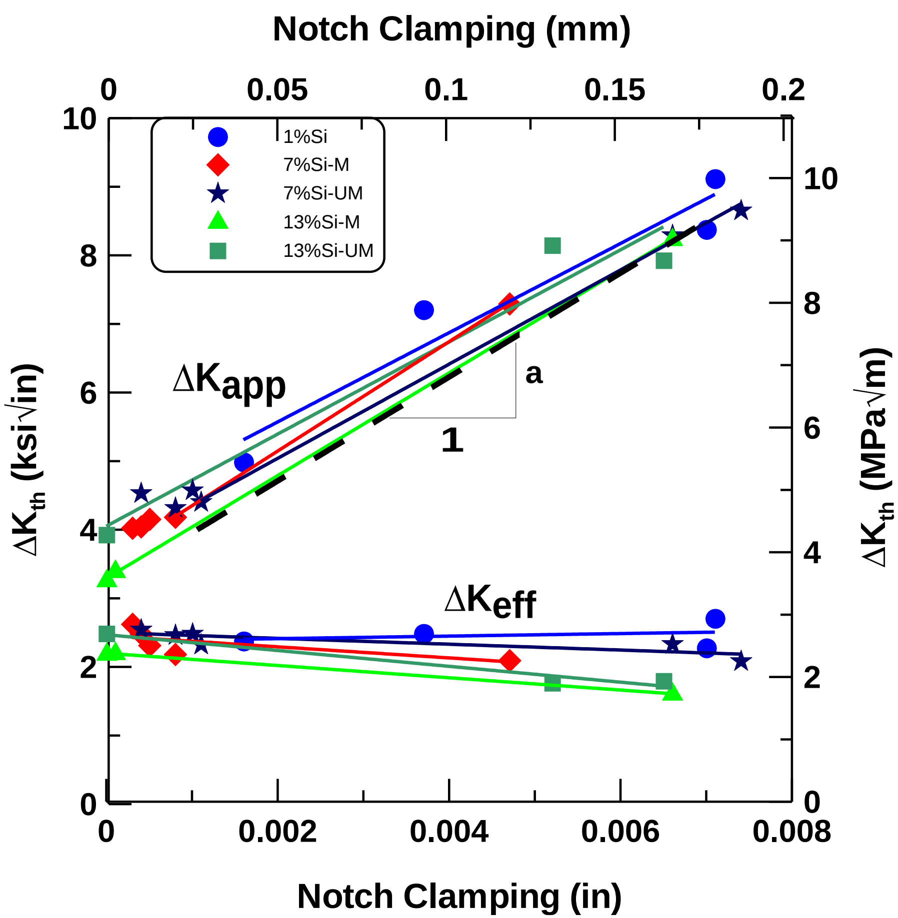
ACR compensates for physically small crack behavior

7%Si … Long crack before and after closure correction vs. physically small crack growth data …



ACR Corrects for Compressive Residual Stress

Restoring force model for clamping effect.



Diana A. Lados

"Fatigue Crack Growth Mechanisms in Al-Si-Mg Alloys"

Ph.D. Dissertation – Chapter 3

Worcester Polytechnic Institute

January 2004

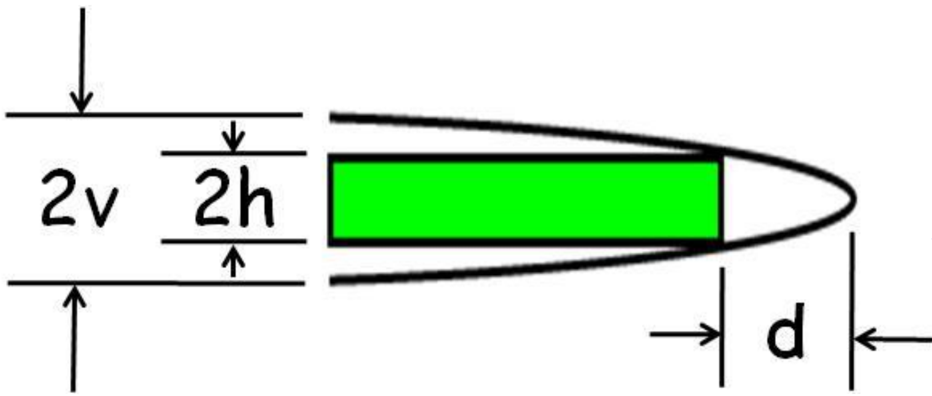
Limitations of the ACR Method

ACR is least effective under scenarios where events local to the crack tip drive dominant shielding.

For example:

- Region II increasing K whereby closure maybe be dominated by crack tip plasticity.
- Any other scenario whereby the shielding mechanism is predominately local to the crack tip.

The 2/π Partial Closure Model (Paris)



Note: Analysis is independent of the size of the gap at the crack tip.

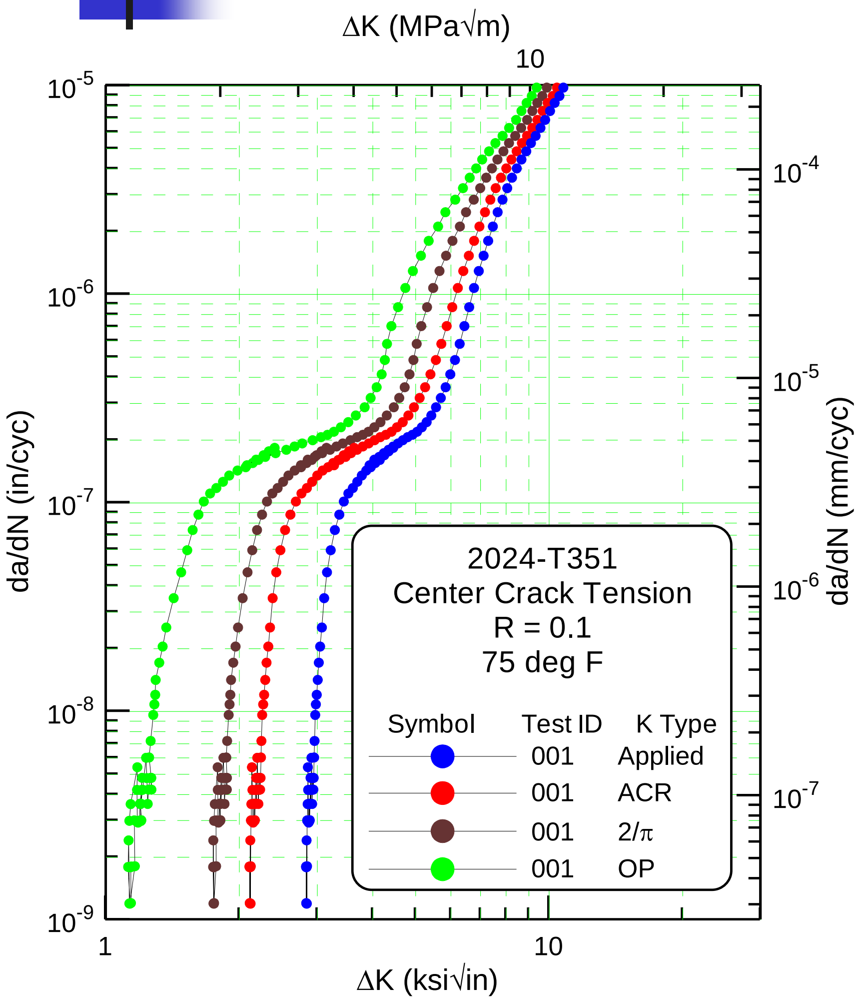
$$K = \frac{E \cdot v}{2}\sqrt{\frac{\pi}{2d}}$$ (remote stress)

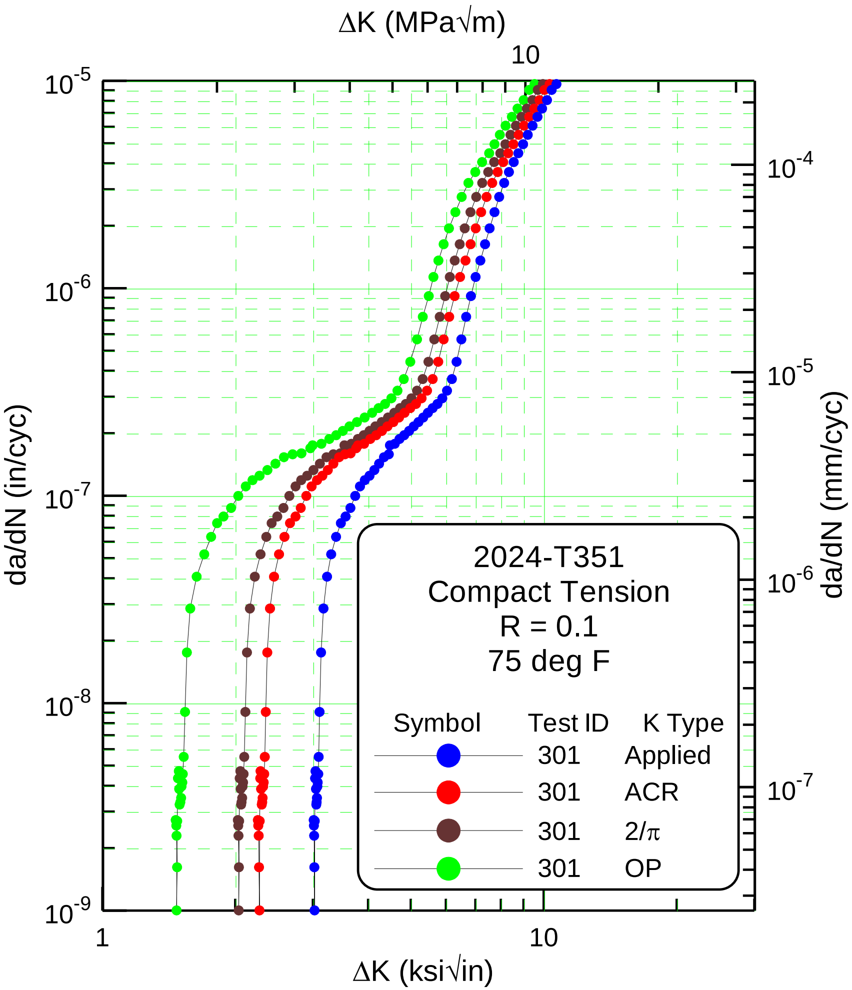
$$K_{wedge} = \frac{E \cdot h}{\sqrt{2\pi d}}$$ (no remote stress, K due to wedge)

@ h=v $$\frac{K_{wedge}}{K} = \frac{2}{\pi}$$

$\therefore K_{op} \bullet (1 - 2/\pi)$ is added to ΔK_{op} for estimation of ΔK_{eff}

Closure Model Comparisons: ΔK_{app}, ΔK_{ACR}, $\Delta K_{2/\pi}$, ΔK_{op}





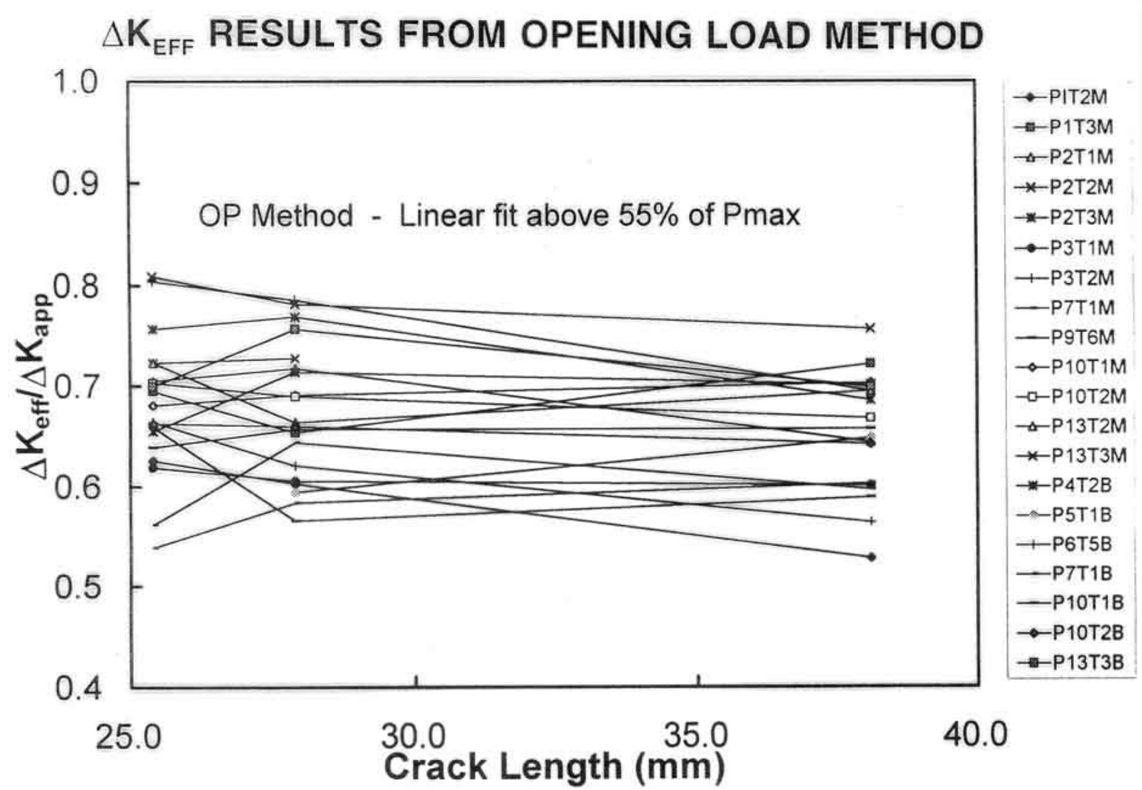
Useful Applications

1 Second ASTM RR opening data were re-analyzed using ACR method. ACR method links variation in growth rates to ΔK_{ACR} whereas the ASTM opening load method does not correlate using ΔK_{eff}.

2 K_{max} sensitivity concept combined with ACR suggests that stress ratio effect is not just related to closure but is also a function of K_{max}.

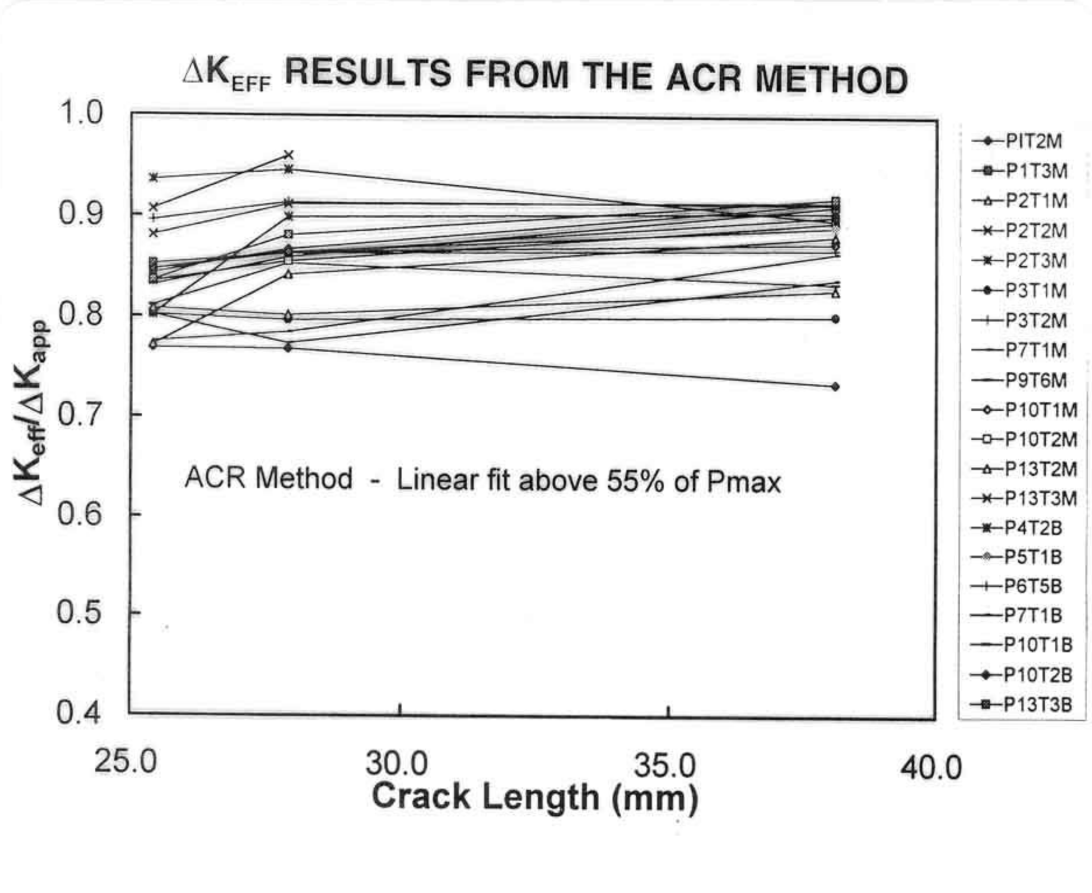
3 Crack size effects were correlated using ACR on 2024-T351 from the ASTM Round Robin Program

Example 1: OP Analysis of ASTM RR Data



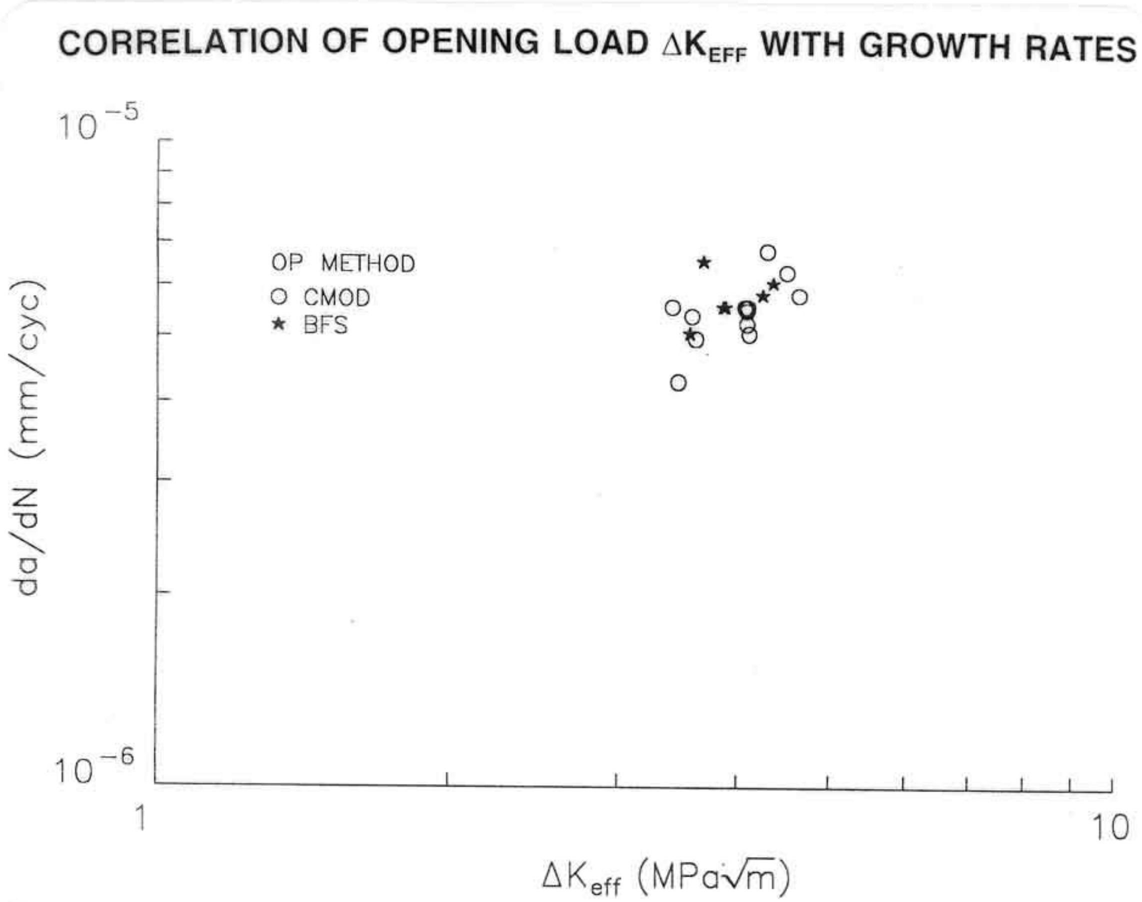
Large variation in estimation of ΔK_{eff} using ASTM opening load method.

Example 1: ACR Analysis of ASTM RR Data



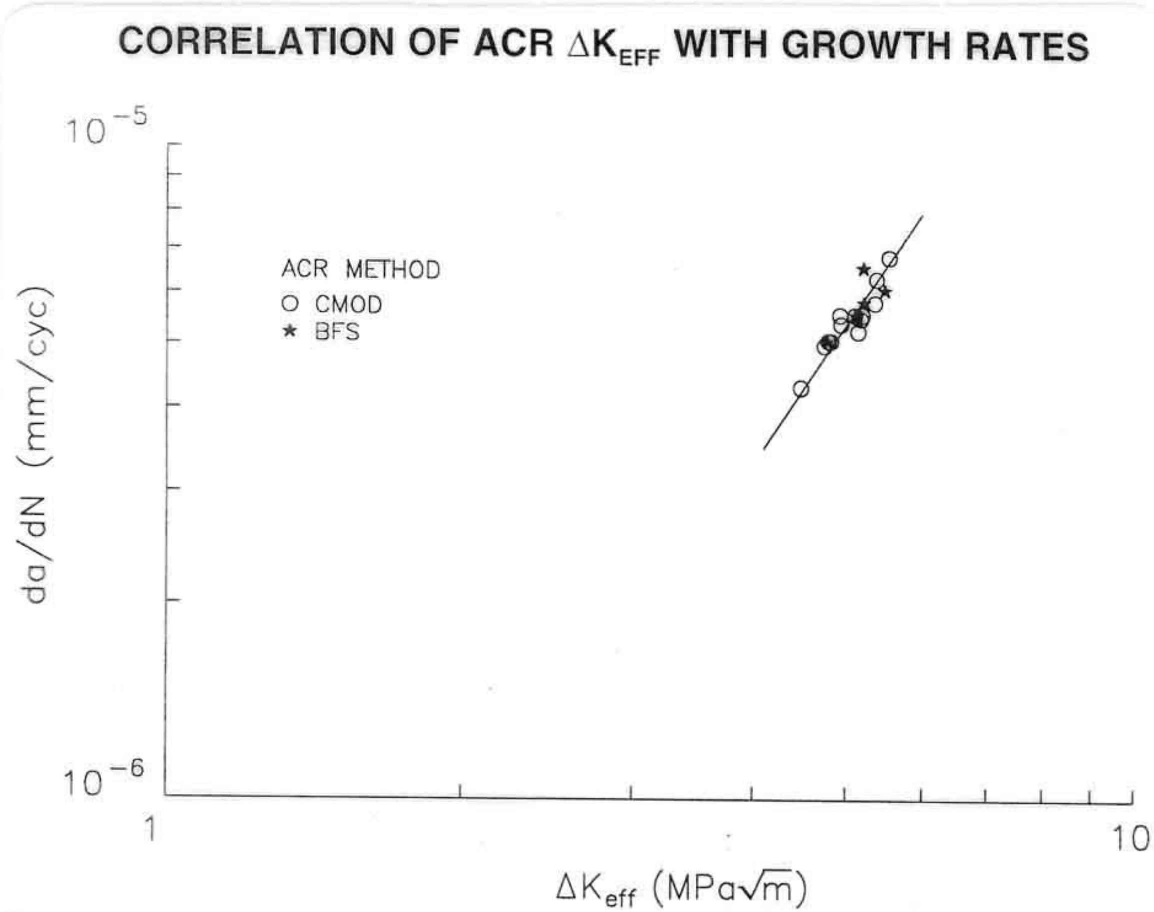
Large variation in estimation of ΔK_{eff} using ACR method.

Example 1:
OP Analysis of ASTM RR Data



Minimal correlation of crack growth rates with ΔK_{eff} using opening load method.

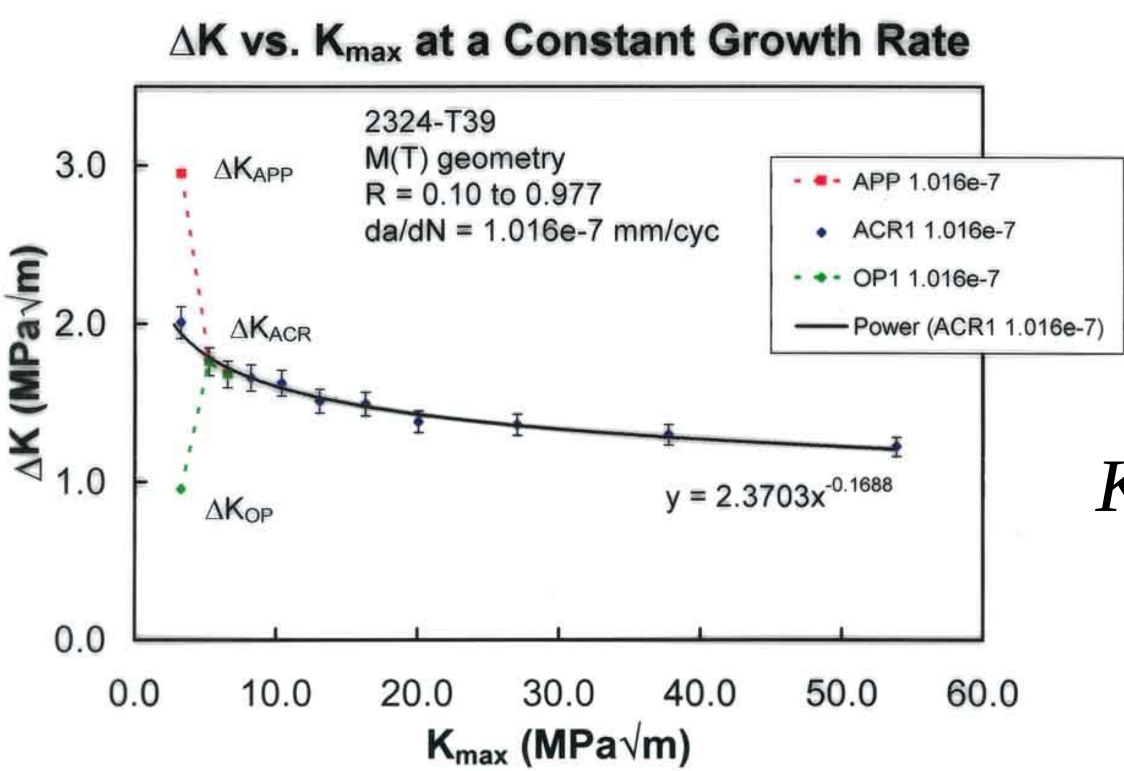
Example 1: ACR Analysis of ASTM RR Data



Strong correlation of crack growth rates with ΔK_{ACR}.

Crack mouth opening displacement (o) and back face strain gages (★) demonstrate remote measurement location independence.

Example 2: K_{max} Sensitivity Concept



ACR method gives best correlation with high stress ratio (constant K_{max}) data when K_{max} sensitivity is accounted for.

$$K_{norm} = \Delta K^{1-n} \bullet K_{\max}{}^{n}$$

n = 0.144

Example 2: "Master Curve" Approach

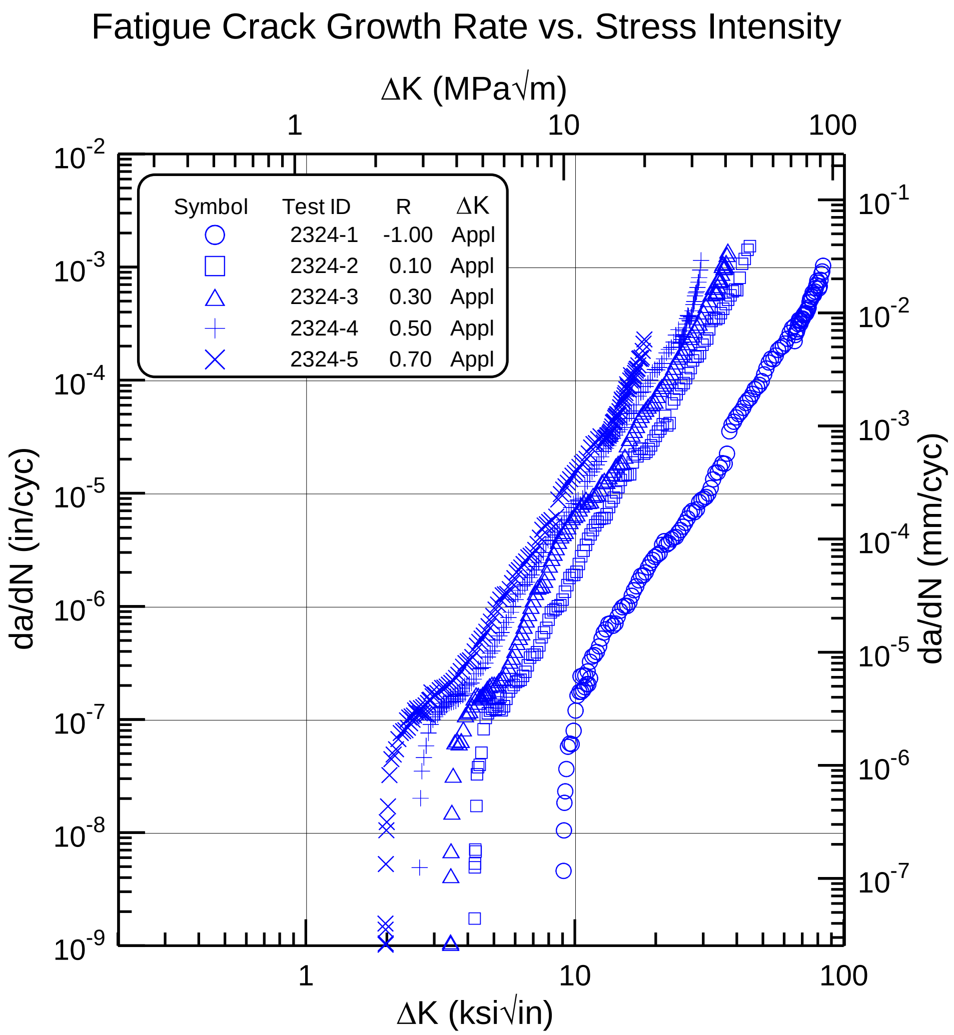
Small crack:

$$K_{norm} = \Delta K^{1-n} \bullet K_{max}{}^{n}$$

Long crack:

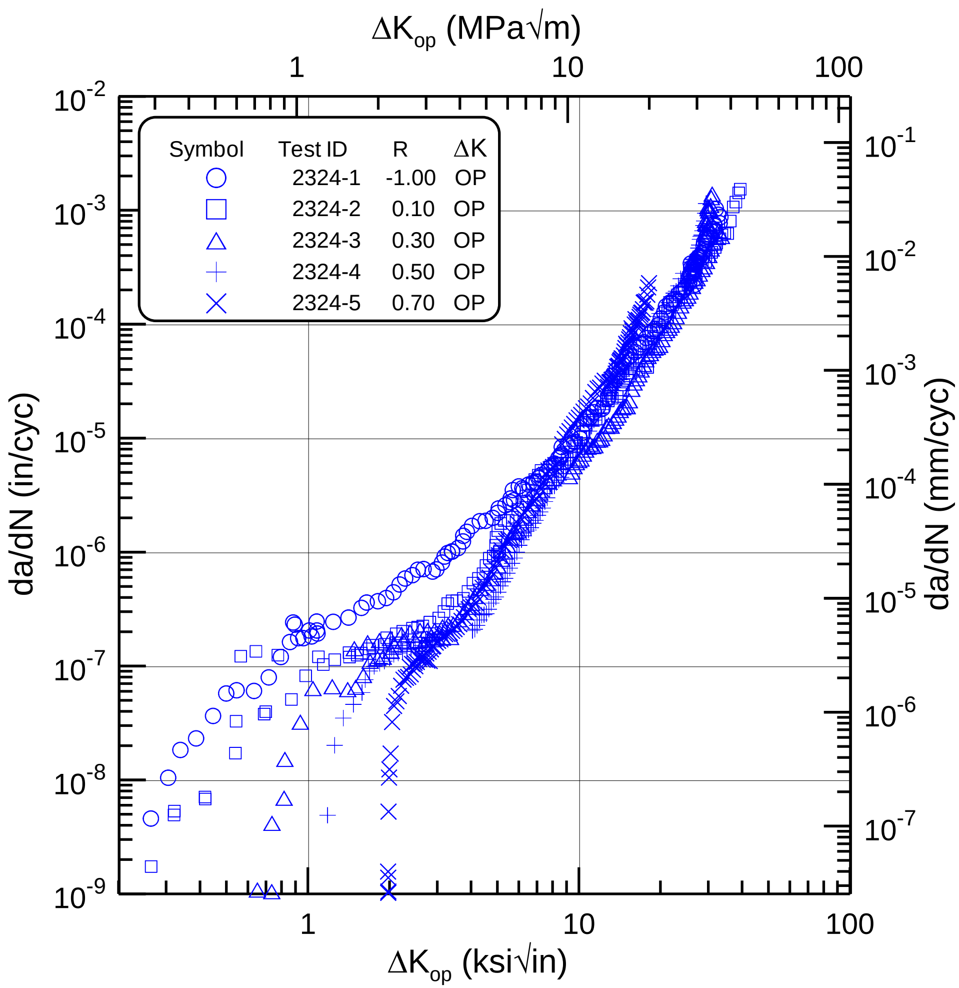
$$K_{norm} = \Delta K_{ACR}{}^{1-n} \bullet K_{max}{}^{n}$$

Example 2: $\Delta K_{applied}$



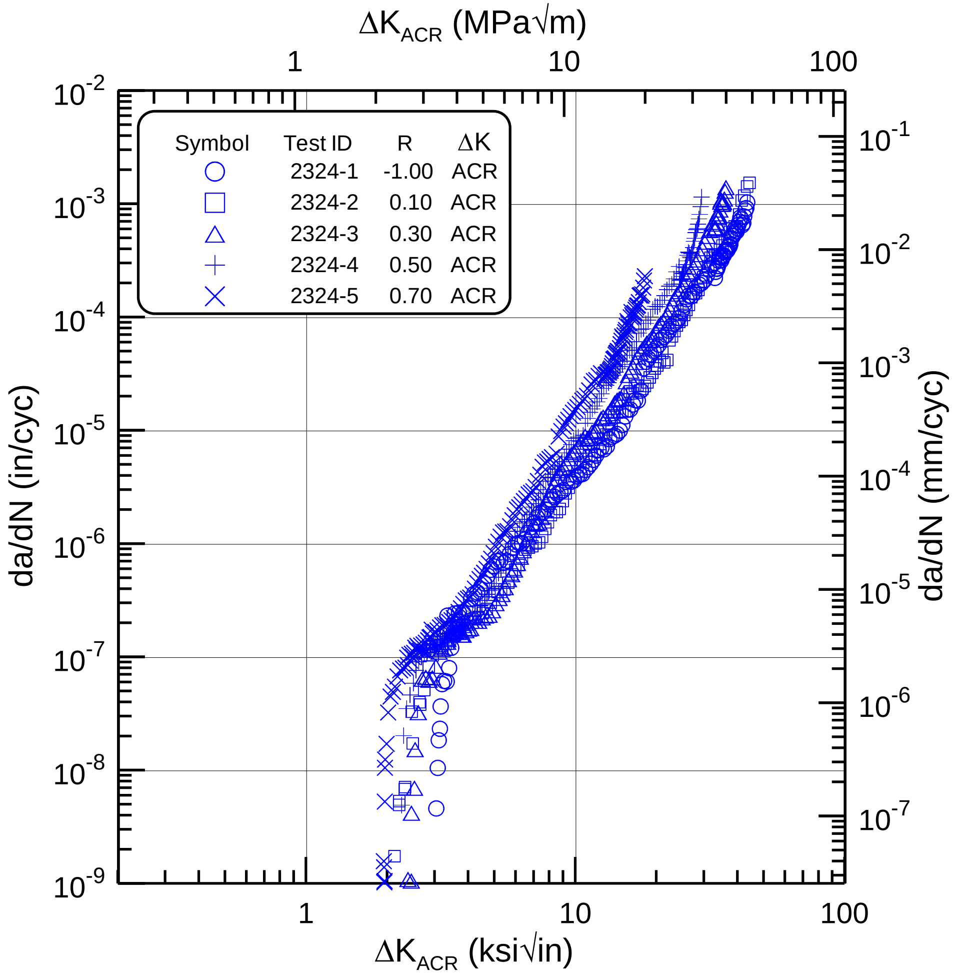
Example 2: ΔK_{op}

Fatigue Crack Growth Rate vs. Stress Intensity

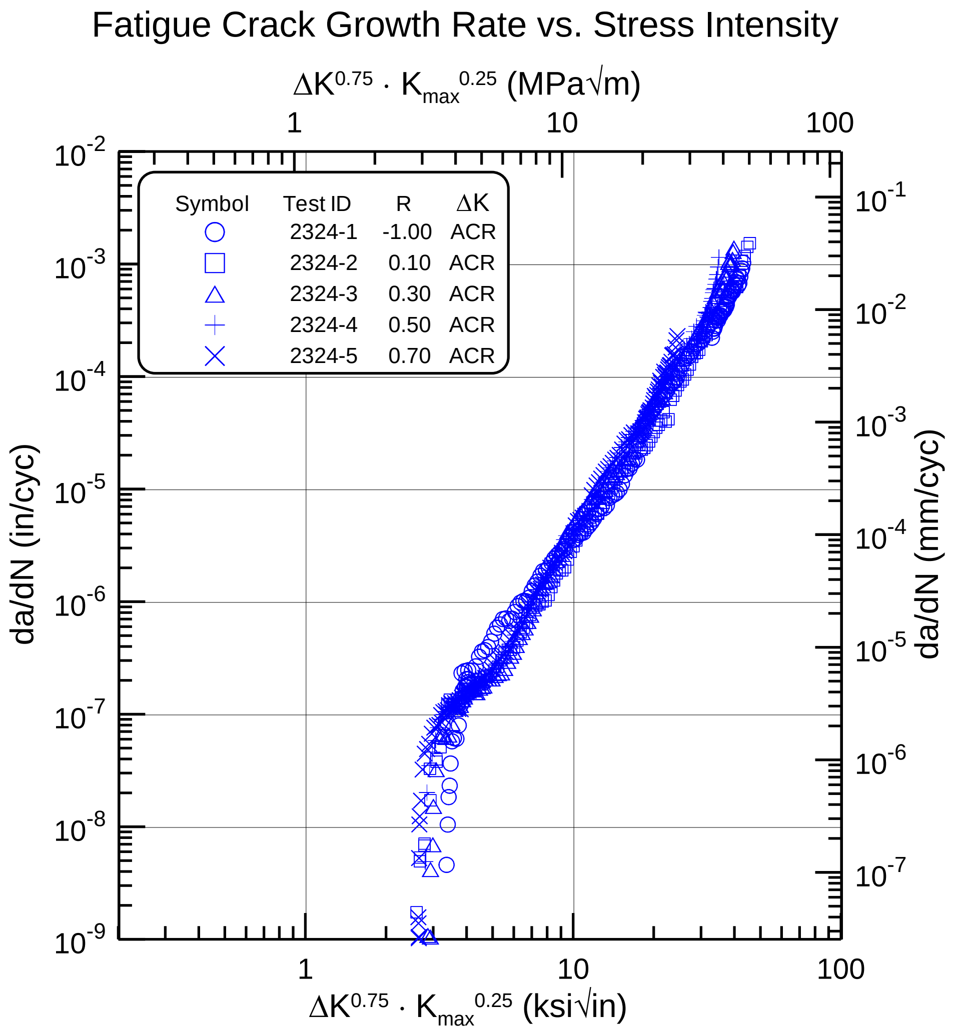


Example 2: ΔK_{ACR}

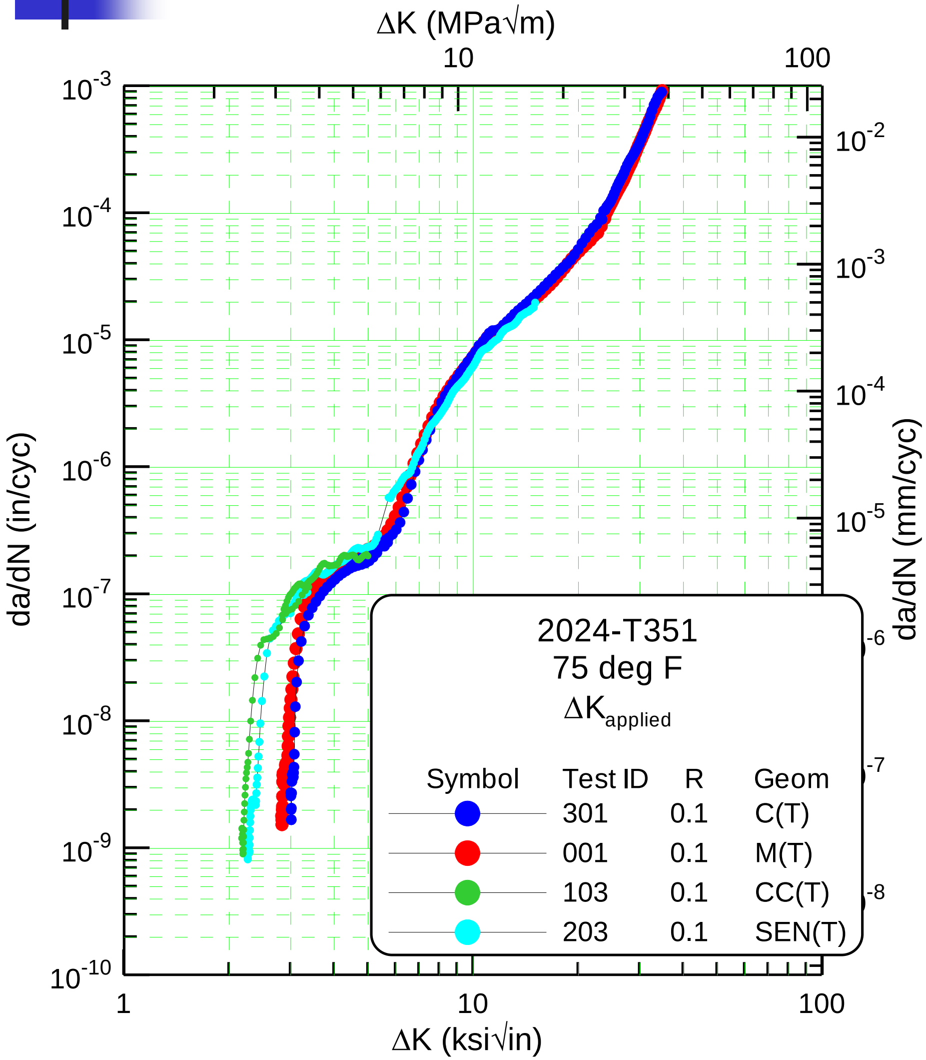
Fatigue Crack Growth Rate vs. Stress Intensity



Example 2: K_{norm} ("Master Curve")



Example 3: "Low" stress ratio FCGR data

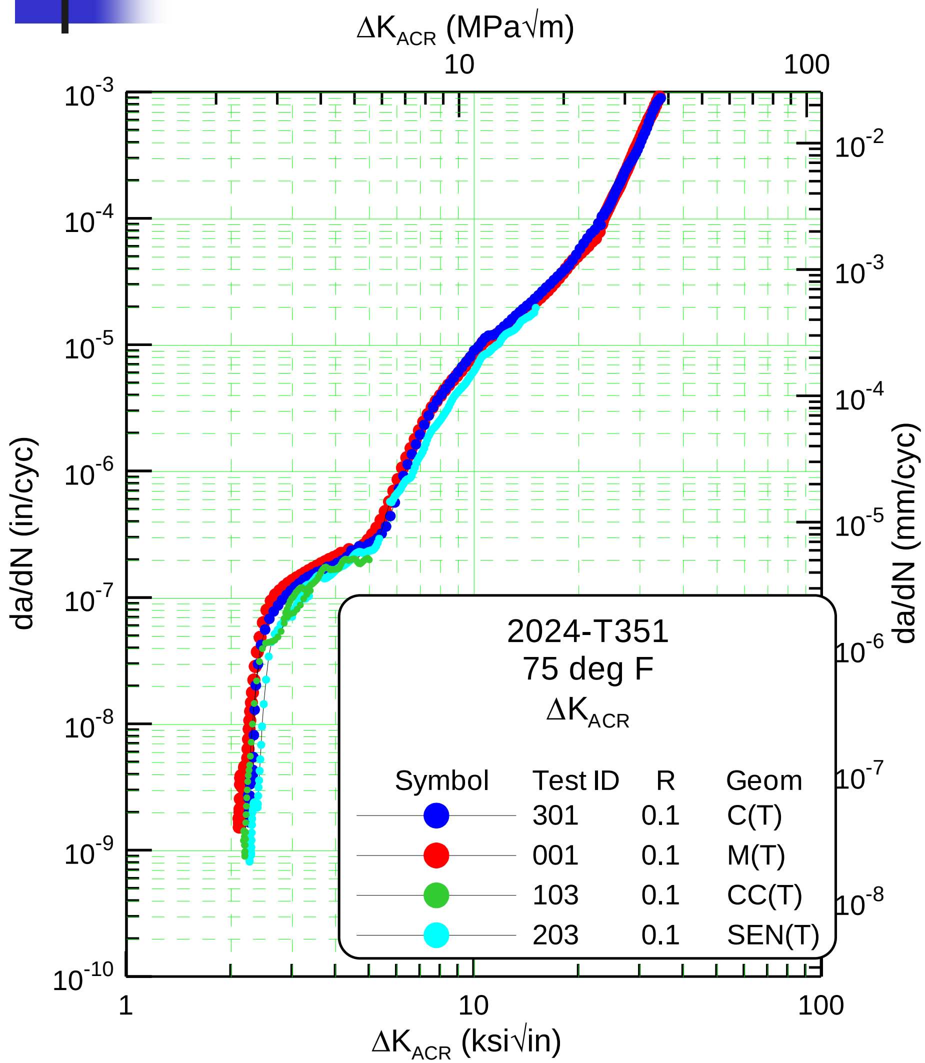


R = 0.1

"Long" crack samples give higher threshold than "physically small/short" crack samples.

This is most likely the result of "remote" closure associated with the "long" crack samples.

Example 3:
"Long" crack data corrected using ACR



R = 0.1

ACR method captures physically small crack behavior by compensating for remote closure.

Summary and Conclusions

- ACR provides additional information about the crack closure process that cannot be obtained from opening load alone.
- ACR is easily implemented since it uses the same load-displacement data as the opening load concept.
- ACR combined with K_{max} sensitivity offers a novel approach to material characterization by utilizing a "Master Curve".