SAE INTERNATIONAL

WCX APRIL 9-11 2019 DETROIT

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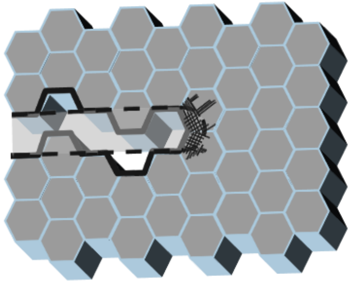
# SAE FD&E Total Life Project Overview

Dan Lingenfelser, nCode Federal LLC

# Total Life Project and Total Life (WholeLife) Method

- Contributors
- Background – Why total life is significant
- Status and future work
- Total life method - Fundamental concept
- Summary



**Engineering is the art of modeling materials we do not wholly understand, into shapes we cannot precisely analyze, so as to withstand forces we cannot properly assess, in such a way that the public has no reason to suspect the extent of our ignorance.**
Dr. A.R. Dykes, Chairman, British Institute of Structural Engineers

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# FDE Total Life Project … Contributing Organizations

## Industry

- B & W Trailer Hitches
- Caterpillar
- Deere and Company
- MTS
- Hendrickson Trailer Suspensions
- Element Materials Technology
- Trilion Quality Systems
- Lambda Technologies
- Hill Engineering
- nCode (Prenscia)

## Academia

- Mississippi State University
- Kansas State University
- University of Windsor
- University of Waterloo
- Carleton University

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# Background

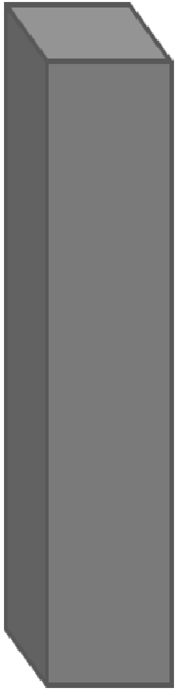
- **Historically FDE has championed strain life methods**
- **More recently FDE recognized need to better evaluate useful life**
  - Total Life project initiated by Tom Cordes in 2012
- **Total Life Projective Objectives:**
  - Develop set of test results to evaluate life prediction methods
  - Evaluate unified theory of fatigue developed by prof. G. Glinka
    - Evolving technology that is now ready for production application
  - Develop improved measure of useful life than cycles to initiation
  - Provide ability to quantify improvements in the life of weldments due to geometry and residual stress

# Project Tasks

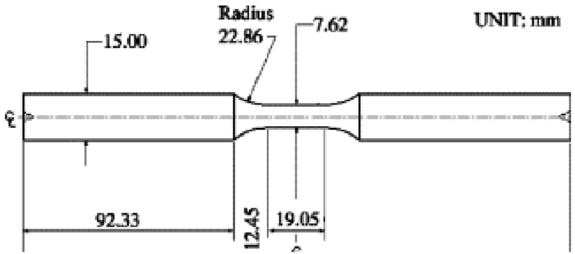
- **Planning, Organization & Leadership**
  - Specimen Design, Procurement, Documentation
- **Strain-life, Crack Growth Testing, And Strain Measurements**
- **T-joint Component Finite Element Analysis**
- **Machined & Welded T-joint Component Fabrication**
- **T-joint Component Fatigue Testing**
- **Residual Stress Distribution Simulation And Measurement**
- **Striation (Marker Band) Measurements And Fractography**
- **Fatigue Life Predictions And Correlation To Test Data**
- **Documentation**
  - Science not documented is science not done

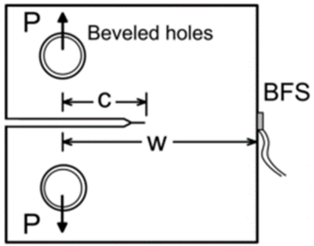
# Material

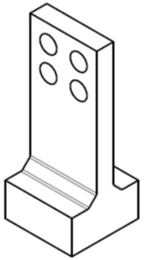
## Procured 80 feet of 4” x 4” RCS A36 HR bar



Microstructure, Chemistry & Hardness Sample



- Challenging material for crack growth
- Both fully machined and welded test samples

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# Participants

**Tom Cordes** (Project Champion)

**Stephen Horstemeyer**
**Jonathan Pickworth**
**Semyon Mikheevskiy**
**Stephanie Swanson**
**Grzegorz Glinka**
**James Patterson**
**Sergey Bogdanov**
**Narendra Singh**
**Phil Dindinger**
**N. Jayaraman**

**William Ulrich**
**Adrian DeWald**
**Brandon Evans**
**Chad Kerestes**
**Charlie Sieck**
**Doug Hornbach**
**Matt Campbell**
**Peter Huffman**
**Brian Dabell**
**Eric Johnson**

**Hayley Brown**
**Jeff Mentley**
**Mary Wickham**
**Rakesh Goyal**
**Taylor Jones**
**Vipul Shinde**
**Casey Gales**
**Eric Norton**
**John Goldak**
**Justin Mach**

**David Griffith**
**Lingyun Pan**
**Mike Lister**
**Paul Prevey**
**Perry Mason**
**Ryan Blodig**
**Timothy Vik**
**Randy Peck**
**Steve Haeg**
**Al Conle**

# Project Status

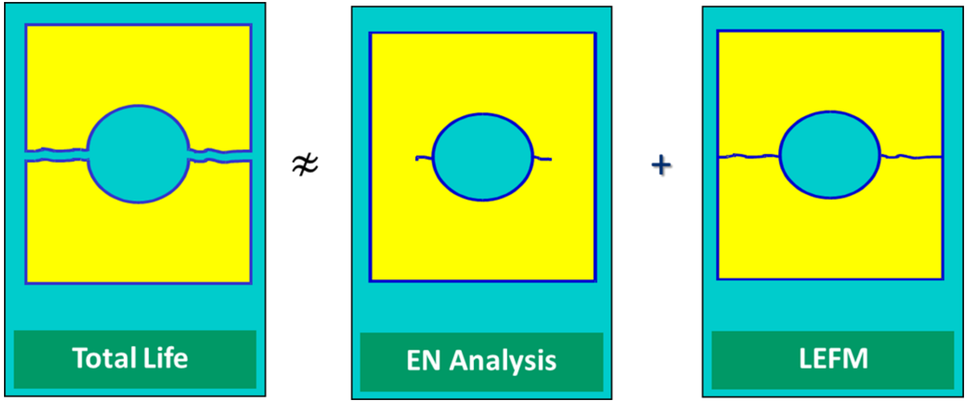
- **Developed high quality material properties**
- **Fabricated and tested “components”**
  - Six different loading histories
  - Thirty tests completed to date
    - 13 machined & 17 welded samples
  - Additional test articles ready to test
- **Residual stress measured and compared to simulations**
  - Work continues to resolve differences
- **Life predictions complete**
- **Following papers provide details and documents results to date**

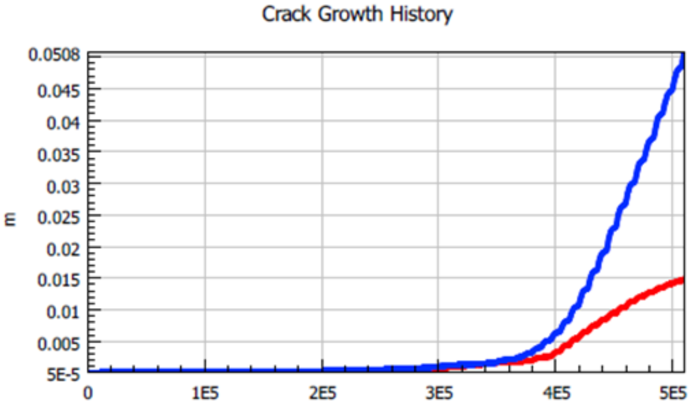
# Following papers document Total Life Project

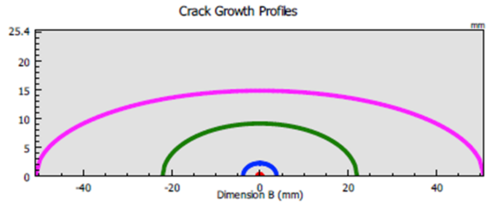
- FD&E Total Life T-sample Residual Stress Analytical Predictions And Measured Results
- Fatigue Life Prediction For F.D.E. Welded Plate Specimen
- Testing Of Welded And Machined A36 Steel T-joint Configuration Specimens
- Comparison Of Total Fatigue Life Predictions Of Welded And Machined A36 Steel T-joints
- Accounting For Geometry And Residual Stresses In Weld Fatigue: A Strain Energy Density Approach To Total Life Of Welded T-specimens
- A Finite Element Based Methodology For Combined Crack Initiation And Crack Growth Prediction In Welded Structures
- For latest results and information on the FD&E; visit www.fatigue.org

# Total Life Method ≉ Crack Initiation + Crack Growth

"The idea of splitting the fatigue life into the initiation and propagation stages is very useful in practice, although the distinction between the …. stages is still under discussion."   G.Glinka - 1986

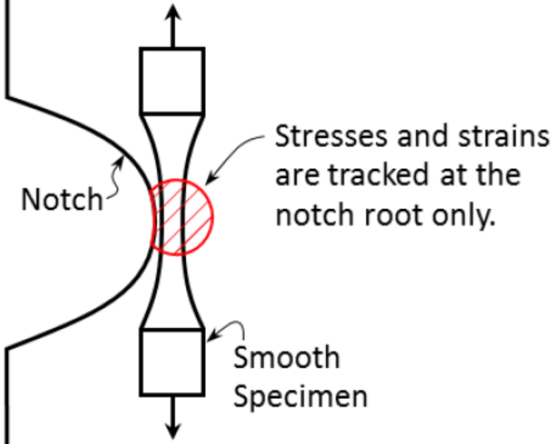


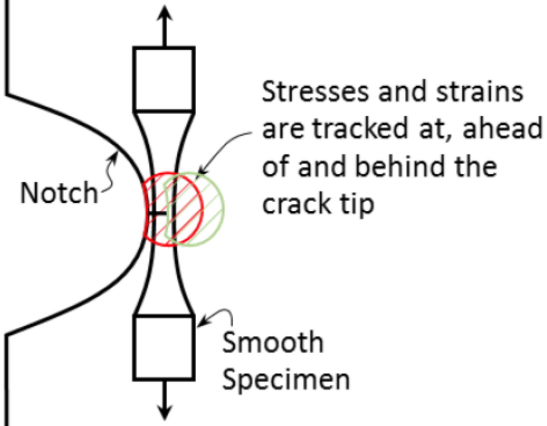

**Total Life Method is much different than simply Ni + Np**

## Methodology: Strain-Life Approach




Stress-strain cycles are then taken into a cycle by cycle local strain linear Miner's damage rule analysis to calculate the fatigue life to "crack initiation".

## Methodology: Total Life Approach



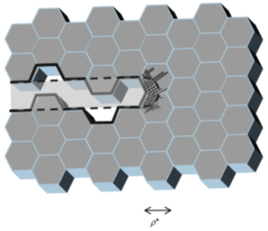

Stress distribution cycles are then taken into a cycle by cycle fracture mechanics da/dN vs Total Driving Force analysis to calculate the fatigue life to "crack initiation" + "crack propagation".

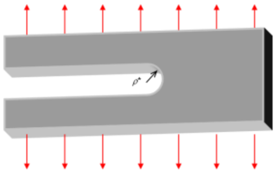
# Total Life Method ... Fundamental concepts

*AKA - Unified Theory of fatigue (UniGrow)*

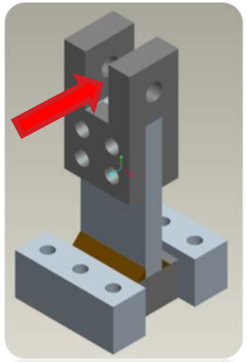
*Developed by Prof. G. Glinka,*

*University of Waterloo, Canada*





- **Radius at tip not a singularity – radius = $\rho$* (Rho star)**
- **Radius enables use of Neuber to determine local stress and strain plasticity**
- **Track cyclic local stress-strain ahead and behind crack “tip”**
- **Universal weight functions used to determine stress intensity into the plate and along surface**
- **Enables superposition of applied and residual stresses**
- **Repeated initiation at crack tip radius**
- **Delta kappa is driving force**

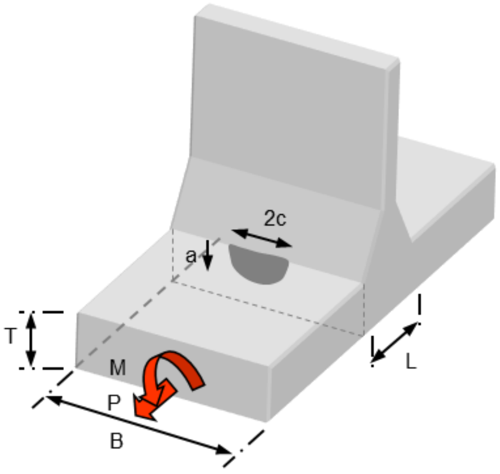


# Universal Weight Function (UWF) Solutions

$$K = \sigma C_f Y \sqrt{\pi a} + K_r$$

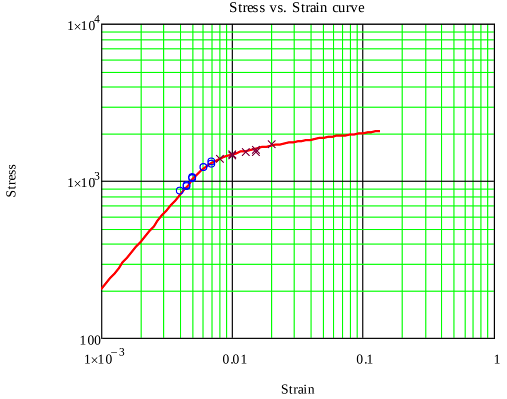
*Y = f(geometry, stress profile)*

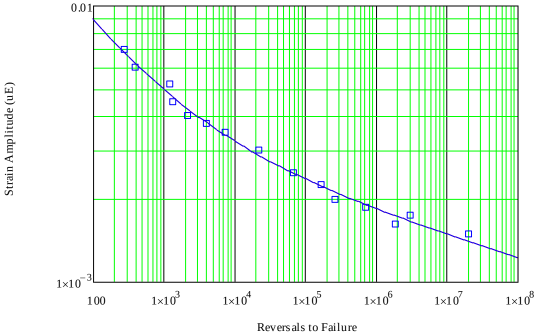
- **Transforms nominal stress into Stress Intensity (SI) at the crack tip**
- **UWF applies stress profile explicitly of the geometry (i.e. use a single geometry for any number of stress distributions)**
- **UWF can deal with complex stress distributions such as residual stress fields and crack-tip wake stresses**



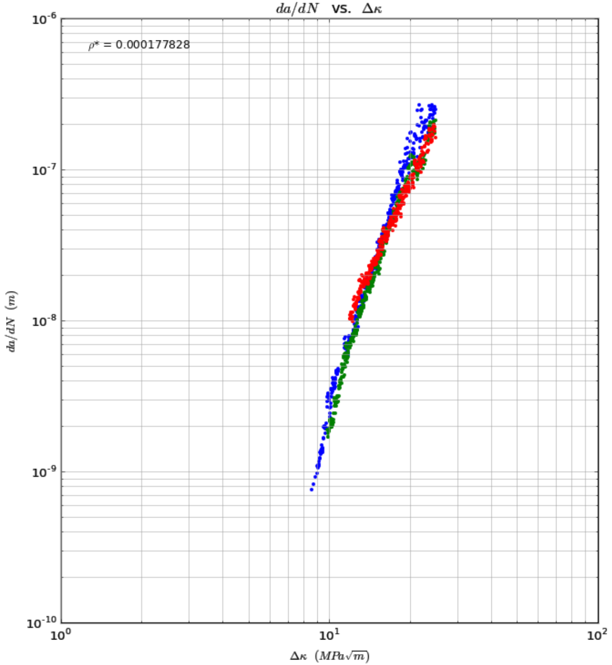
# Total Life Inputs

## *Strain-Life (EN) properties*



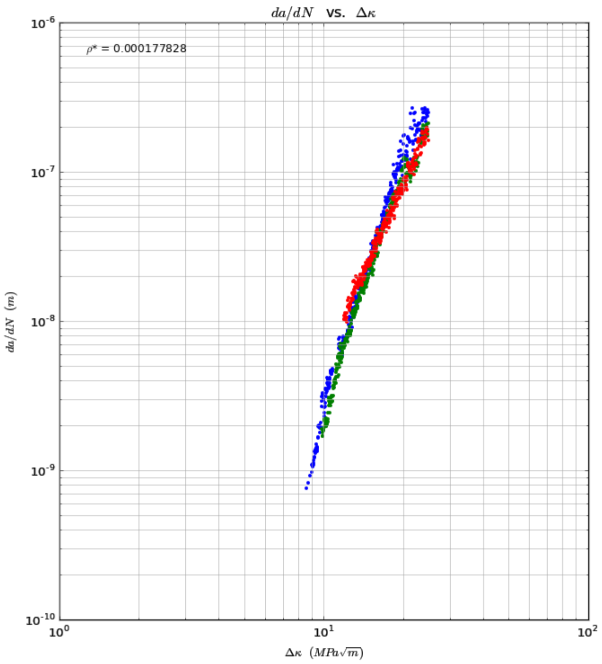




## *LEFM crack growth properties da/dN vs delta Kappa*



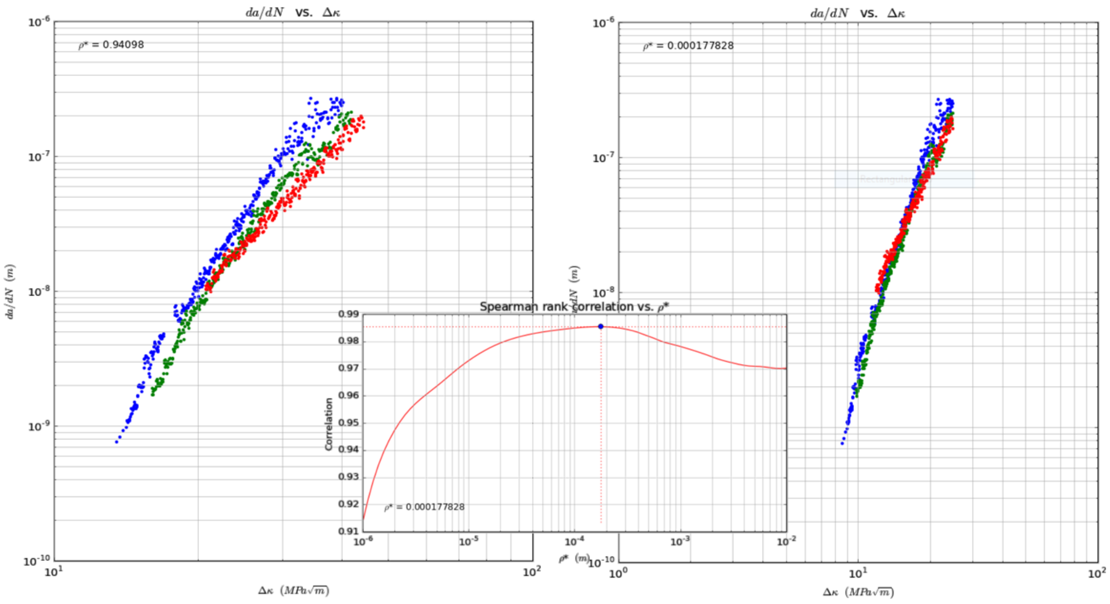
# Crack Growth Model $da/dN$ vs $\Delta\kappa$

- Crack growth rate ${}^{da}/_{dN}$ is a function of the 'crack-tip driving force'; $\Delta\kappa$ $\frac{da}{dN} = C\Delta\kappa^{m}$
- $\Delta\kappa$ is a function of the 'stress intensity' and R ratio (after Walker); $\Delta\kappa = K_{max}^{p}(K_{max} - K_{min})^{1-p}$
- $K$ is a function of stress $\sigma$, geometry $Y$, crack length $a$, and the residual stress field at the tip of the crack $K_r$; $K = \sigma C_f Y\sqrt{\pi a} + K_r$
- $C_f$ is the 'small crack correction'; $C_f = \left(1 + \frac{1}{2}\sqrt{\frac{\rho^*}{a}}\right)$



# Estimating $\frac{da}{dn}$ $vs\ \Delta Kappa\ and\ \rho^*$

Collapse crack growth curves at multiple R ratios to collapsed segmented curve while optimizing regression coefficients

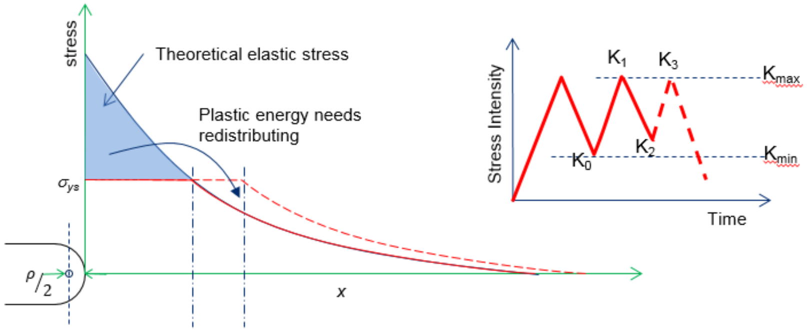



Un-collapsed curve ➔ Collapsed curve

# Cyclic Crack-tip Plasticity Model $K_r$ … Estimating local stress

Crack-tip opening

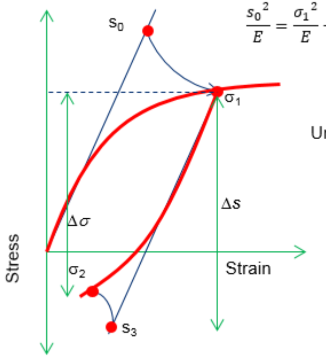
$$\overrightarrow{K_0K_1}$$




Crack-tip closing

$$\overrightarrow{K_1K_2}$$

Crack-tip plasticity is based on multiaxial Neuber-Ramberg-Osgood cyclic plasticity model with plastic redistribution:




Loading

$$\frac{s_0{}^2}{E} = \frac{\sigma_1{}^2}{E} + \sigma_1\left(\frac{\sigma_1}{K'}\right)^{\frac{1}{n'}}$$

Unloading

$$\frac{\Delta s^2}{E} = \frac{\Delta\sigma^2}{E} + 2\Delta\sigma\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}$$

# Cyclic Crack-tip Plasticity Model $K_r$

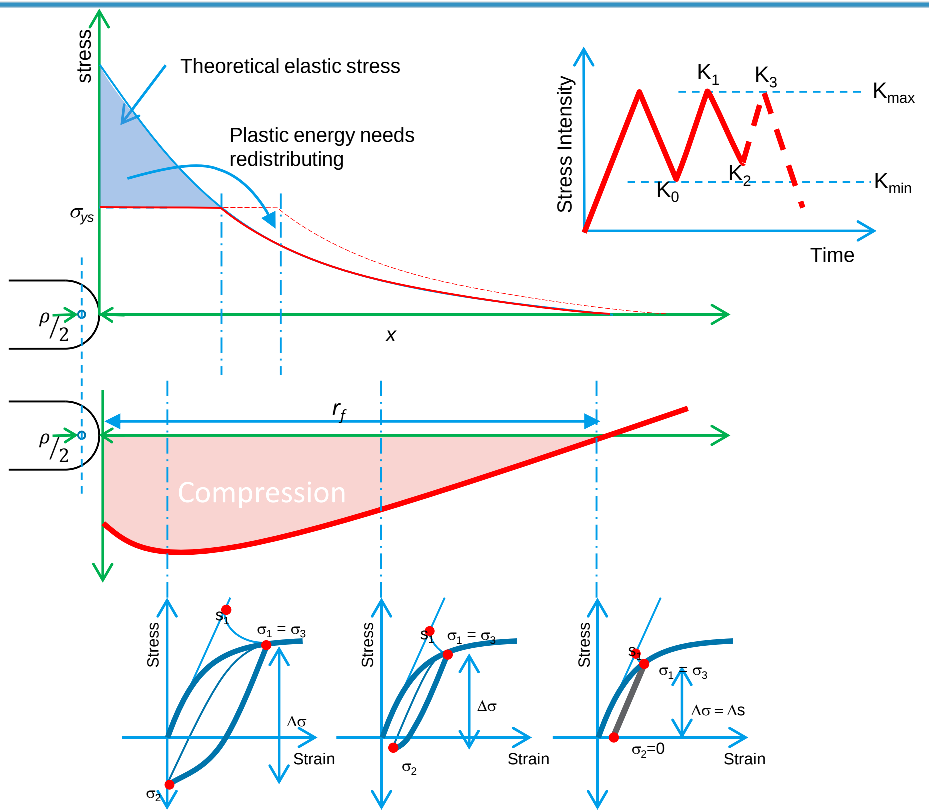
Crack-tip opening

$\overrightarrow{K_0 K_1}$

Crack-tip closing

$\overrightarrow{K_1 K_2}$

Crack-tip plasticity is based on multiaxial Neuber-Ramberg-Osgood cyclic plasticity model with plastic redistribution:



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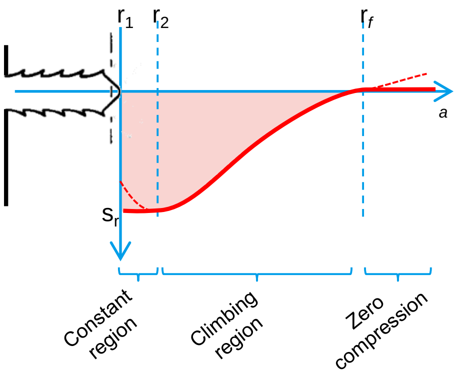
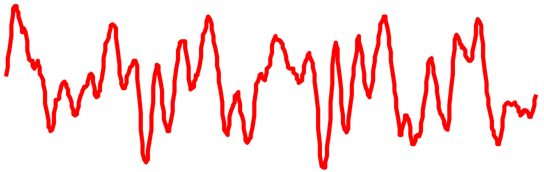
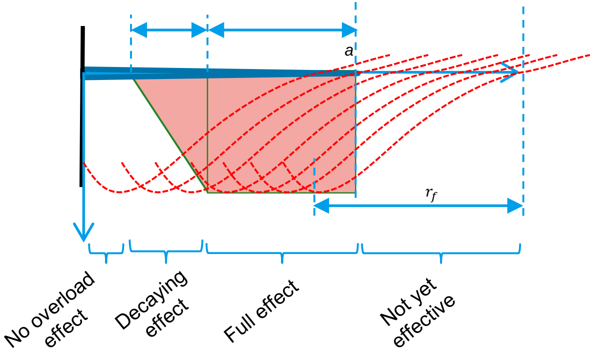
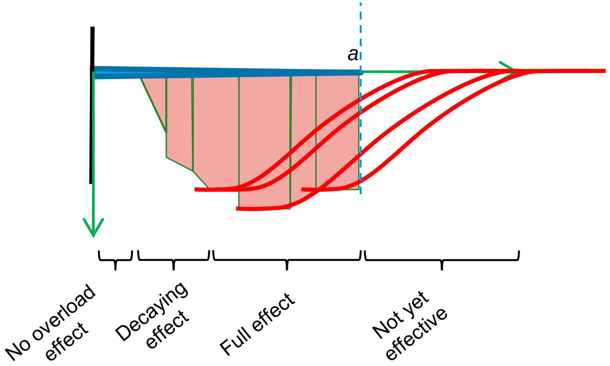
# Cyclic Crack-tip Plasticity Model $K_r$ - *Crack retardation*



Compressive wake from variable-amplitude loading




Compressive wake from constant-amplitude loading

# Summary

- **Strain life serves us well but it doesn't quantify useful life**
- **Total life provides a better measure of useful life**
- **Crack size vs cycles better defines useful life than cycles to initiation**
- **Total life provides ability to quantify improvements in the life of weldments due to geometry and residual stress**

Supporting details for this summary are in the referenced papers presented in this session

# Following papers document Total Life Project

- Accounting For Geometry And Residual Stresses In Weld Fatigue: A Strain Energy Density Approach To Total Life Of Welded T-specimens
- FD&E Total Life T-sample Residual Stress Analytical Predictions And Measured Results
- Testing Of Welded And Machined A36 Steel T-joint Configuration Specimens
- A Finite Element Based Methodology For Combined Crack Initiation And Crack Growth Prediction In Welded Structures
- Comparison of Total Fatigue Life Predictions of Welded and Machined A36 Steel T-Joints
- Crack Initiation and Propagation Fatigue Life Prediction for an A36 Steel Welded Plate Specimen

# Thank you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