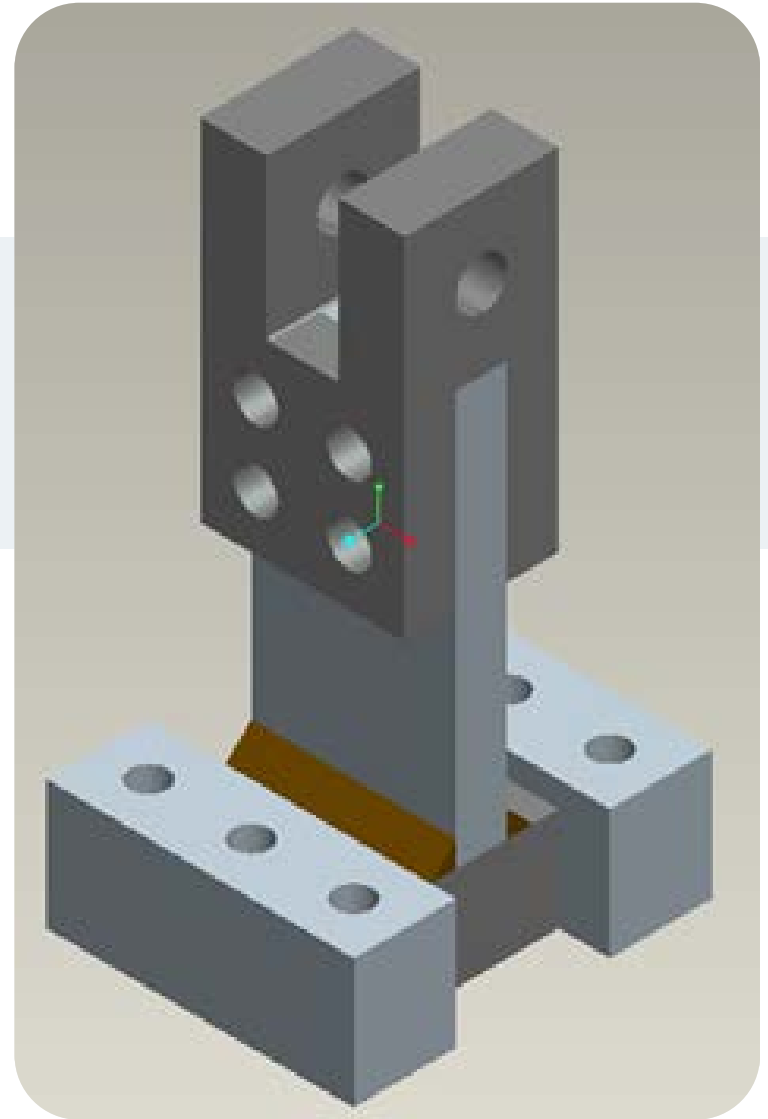


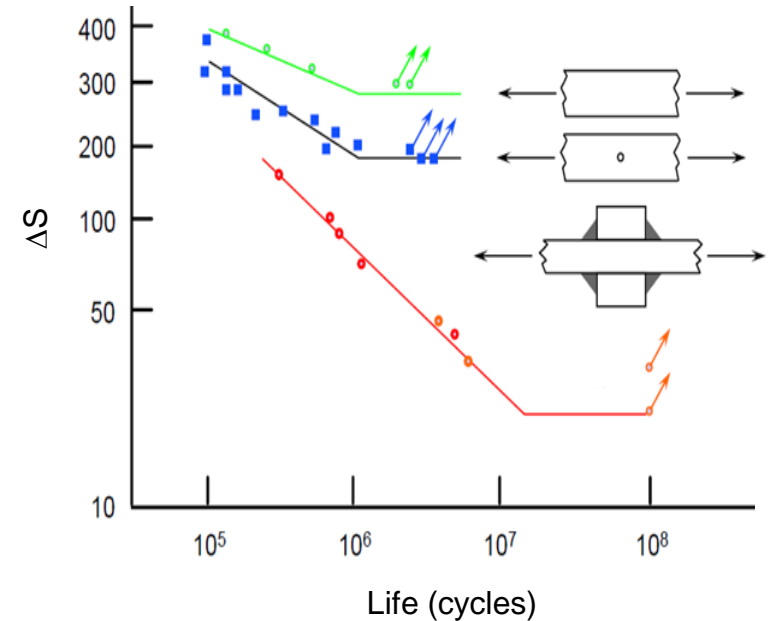
# Fatigue Simulation of Welds Using the Total-Life Method

**Dr Andrew Halfpenny**  
*Director of Technology*



- Weld fatigue properties much lower than parent plate due to:

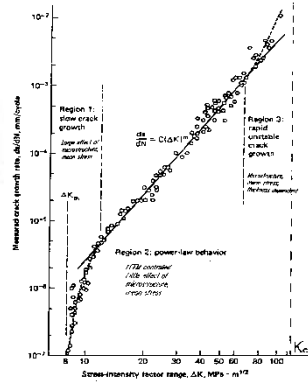
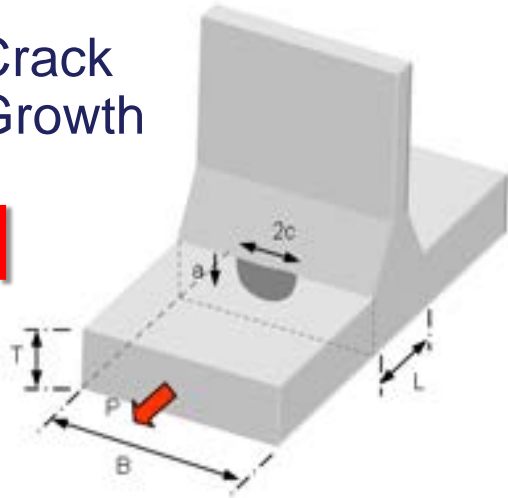
- Weld geometry:
  - Large stress concentrations factors
  - Existing crack initiation sites
- High tensile residual stresses
- Non-uniform material distribution
  - Deposited weld metal
  - Heat-affected zone in parent metal



- Parent metal strength not reflected in weld fatigue strength
- Weld fatigue behavior is primarily crack growth

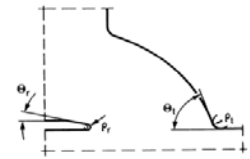
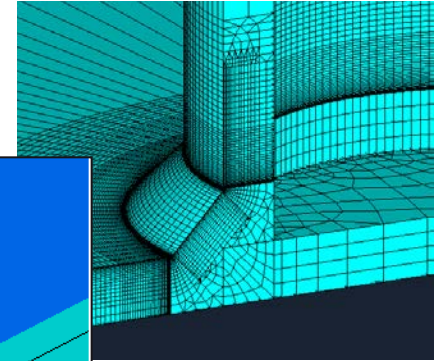
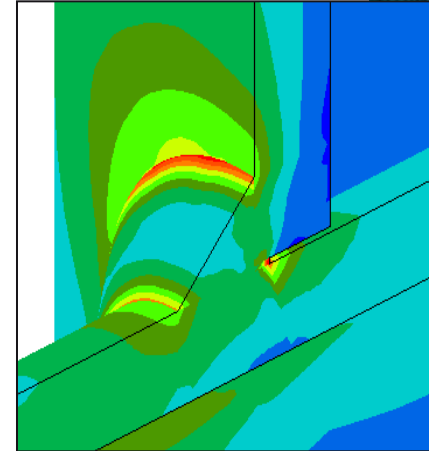
## Crack Growth

1



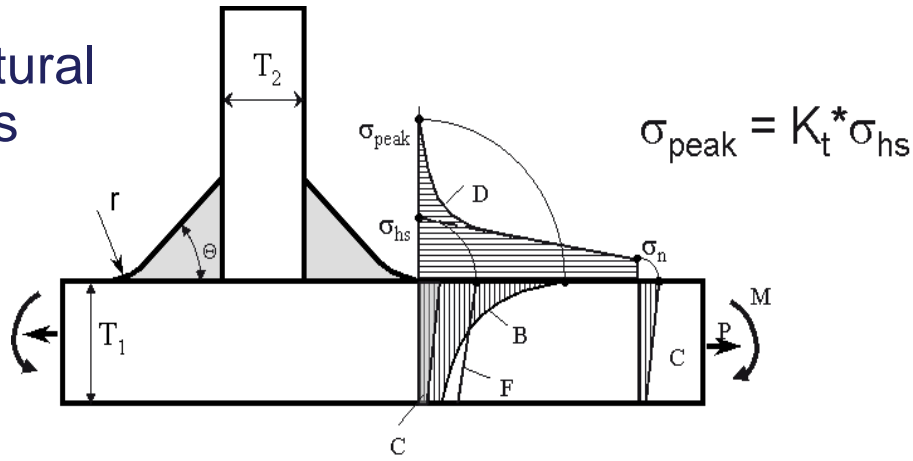
## Local Notch Stress

2



## Structural Stress

3



[www.hbmprensncia.com](http://www.hbmprensncia.com)

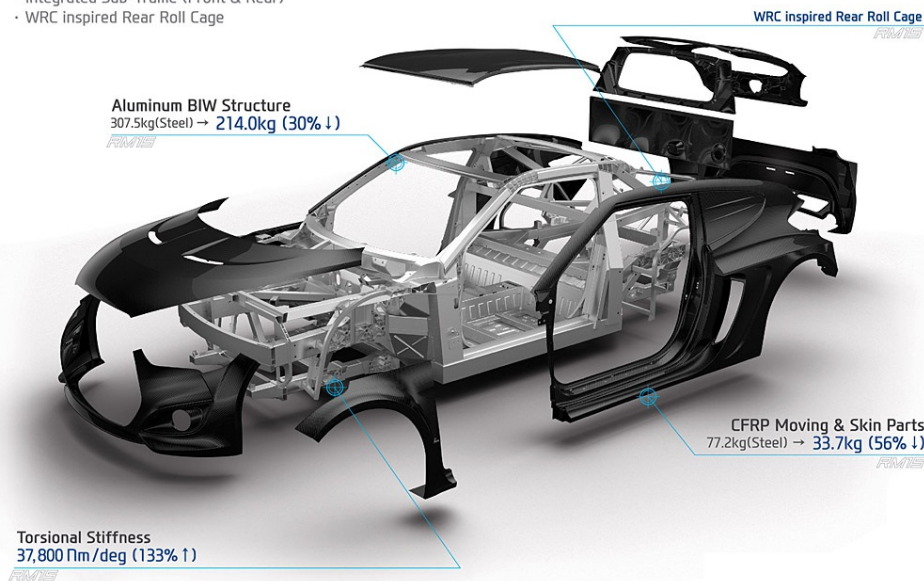
Online webinar, October 16, 2018:

*"Fatigue of Welds using nCode DesignLife"*

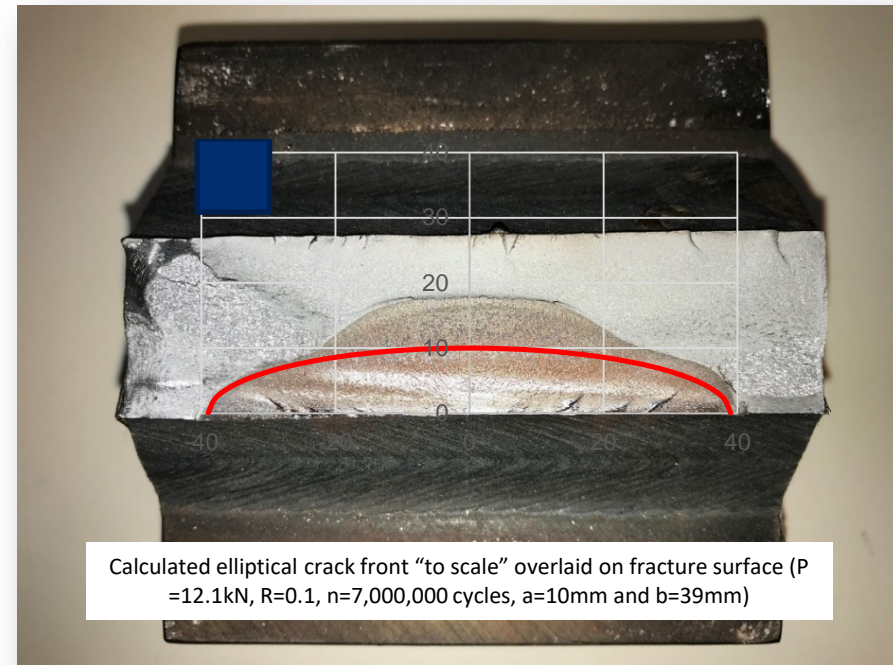
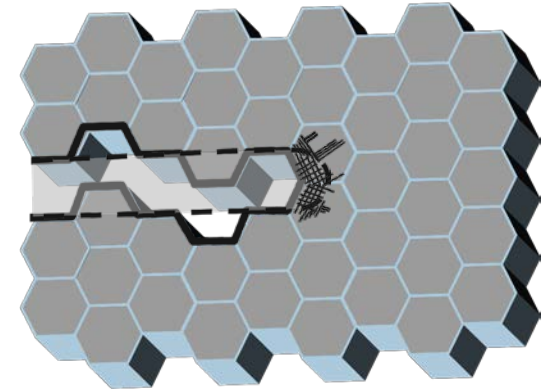
- Improve accuracy of weld fatigue life simulation
- Account for 'designed' welds – lightweight & thick-weld vehicle structures  
*e.g. stress relieving, weld dressing, etc.*
- Recognise fatigue as initiation and crack growth  
*Prof. G. Glinka, University of Waterloo, Canada*

## HYUNDAI RM15 Concept

- HLBS – Hybrid Lightweight Body Structure (Aluminum Space Frame with CFRP)
- Integrated Sub-frame (Front & Rear)
- WRC inspired Rear Roll Cage



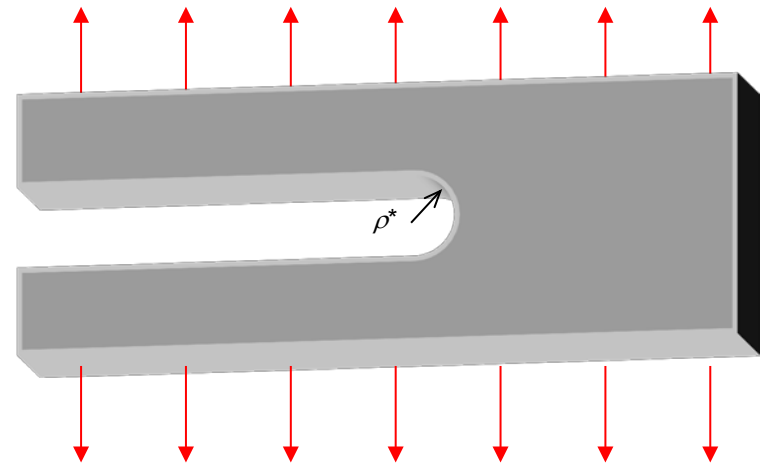
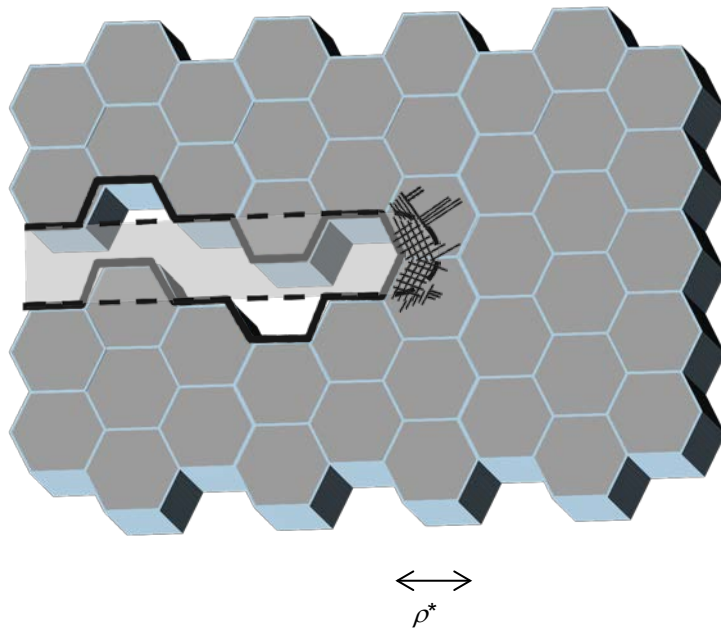
1. Fatigue/Fracture Theory
2. CAE Application
3. Case study
4. Conclusions



Calculated elliptical crack front "to scale" overlaid on fracture surface ( $P = 12.1\text{kN}$ ,  $R=0.1$ ,  $n=7,000,000$  cycles,  $a=10\text{mm}$  and  $b=39\text{mm}$ )

## *Progressive crack growth: sequence of successive initiation failures*

- High stress at crack-tip causes slip planes and progressive weakening of the grain
- Stress intensity increases as the crack grows so failure of each grain occurs more quickly
- Effective radius of crack tip  $\rho^*$   $\approx$  grain size



- 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)

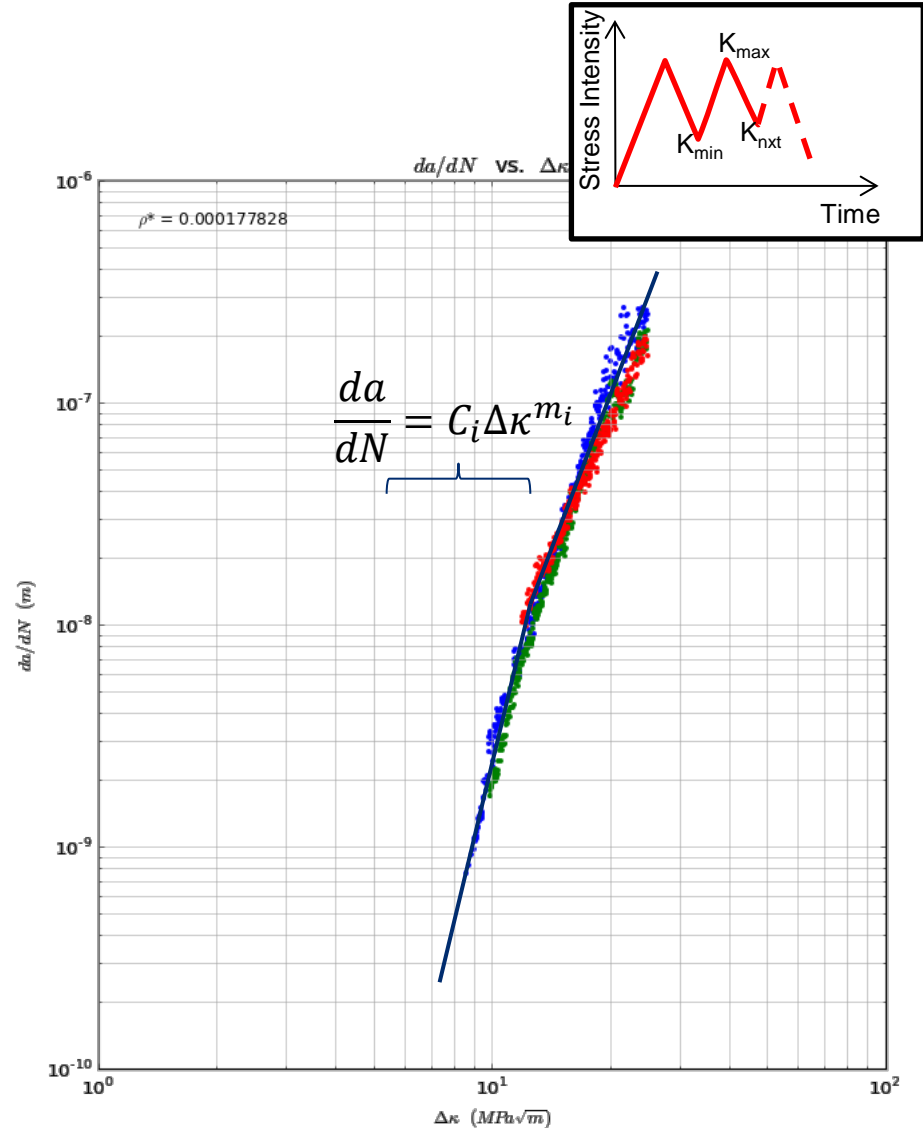
$$\Delta\kappa = K_{max}^p (K_{max} - K_{min})^{1-p}$$

- $K$  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'

$$C_f = \left(1 + \frac{1}{2} \sqrt{\frac{\rho^*}{a}}\right)$$



- Crack growth rate  $\frac{da}{dN}$  is a function of the 'crack-tip driving force'  $\Delta\kappa$

$$\frac{da}{dN} = C\Delta\kappa^m$$



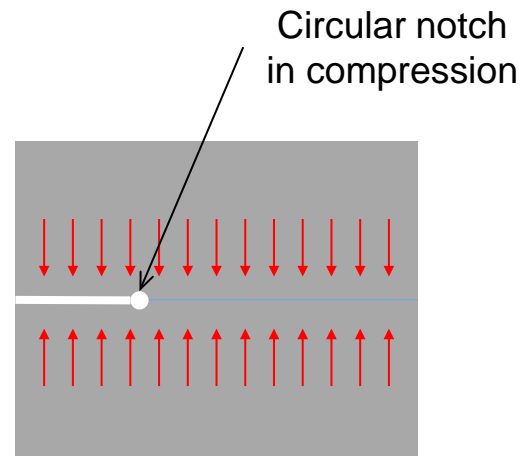
- $\Delta\kappa$  is a function of the R ratio

$$\Delta\kappa = \begin{cases} \sigma_{min} & \text{if } \sigma_{min} \geq 0 \\ K_t \sigma_{min} & \text{if } \sigma_{min} < 0 \end{cases}$$

- $K$  is a function of crack length at the tip of the crack

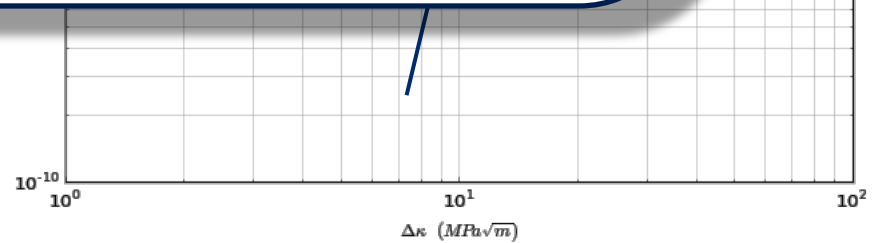
Crack closure model:

where  $K_t$  is the notch correction, typically of the range  $2 \leq K_t \leq 3$



- $C_f$  is the 'small crack correction'

$$C_f = \left(1 + \frac{1}{2}\sqrt{\frac{\rho^*}{a}}\right)$$

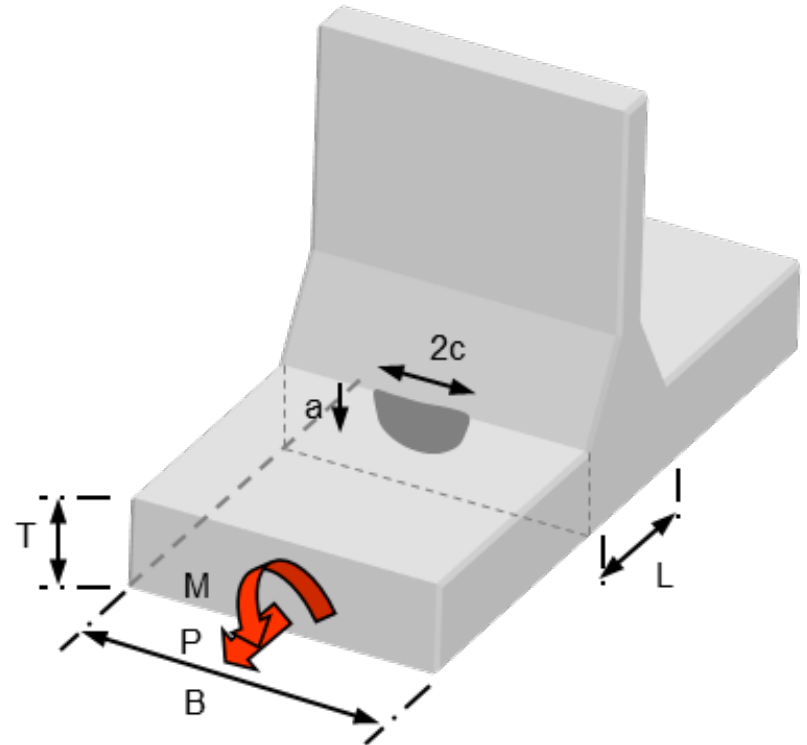


$$K = \sigma C_f Y \sqrt{\pi a} + K_r$$



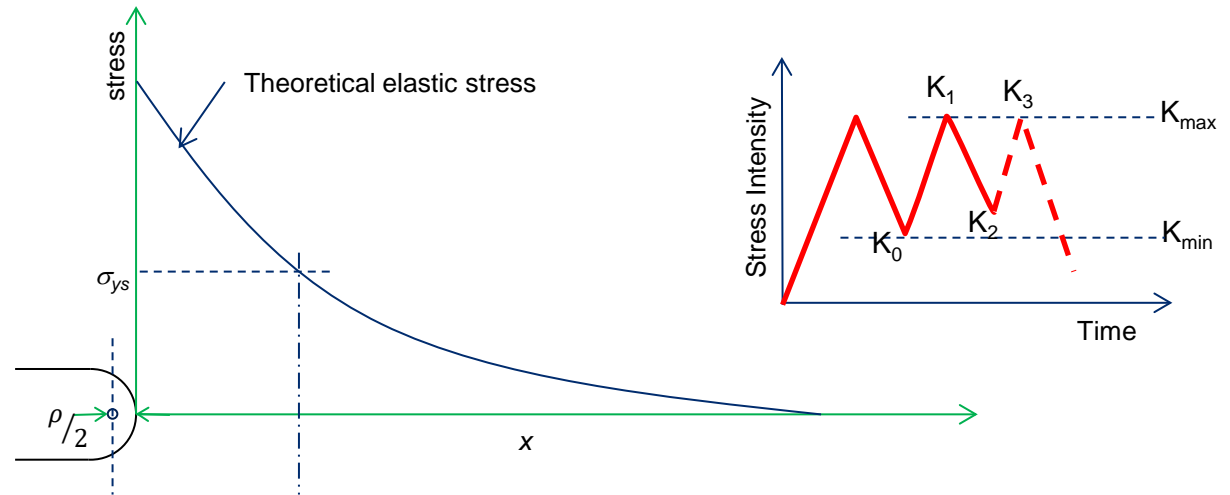
$Y = f(\text{geometry, stress profile})$

- 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



Crack-tip opening

$\overrightarrow{K_0 K_1}$



Multiaxial crack-tip stress profile based on Creager-Paris law for blunt cracks:

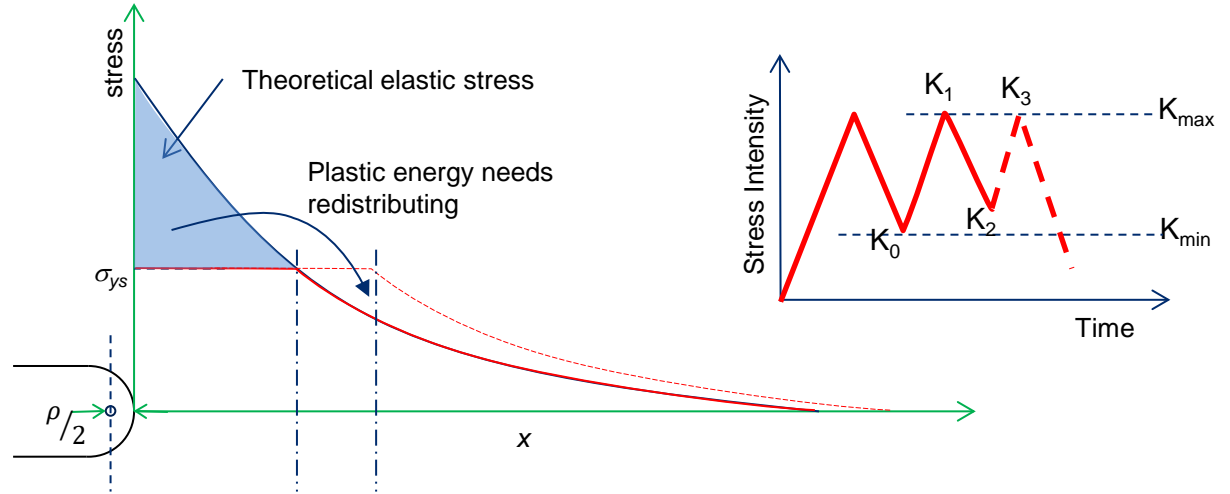
$$s_x(r, \theta) = \frac{K}{\sqrt{2\pi r}} \left[ \cos\left(\frac{\theta}{2}\right) \left( 1 - \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) \right) - \frac{\rho^*}{2r} \cos\left(\frac{3\theta}{2}\right) \right]$$

$$s_y(r, \theta) = \frac{K}{\sqrt{2\pi r}} \left[ \cos\left(\frac{\theta}{2}\right) \left( 1 + \sin\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) \right) + \frac{\rho^*}{2r} \cos\left(\frac{3\theta}{2}\right) \right]$$

$$v(r, \theta) = \frac{K}{\sqrt{2\pi r}} \left[ \sin\left(\frac{\theta}{2}\right) \cos\left(\frac{\theta}{2}\right) \sin\left(\frac{3\theta}{2}\right) - \frac{\rho^*}{2r} \sin\left(\frac{3\theta}{2}\right) \right]$$

Crack-tip opening

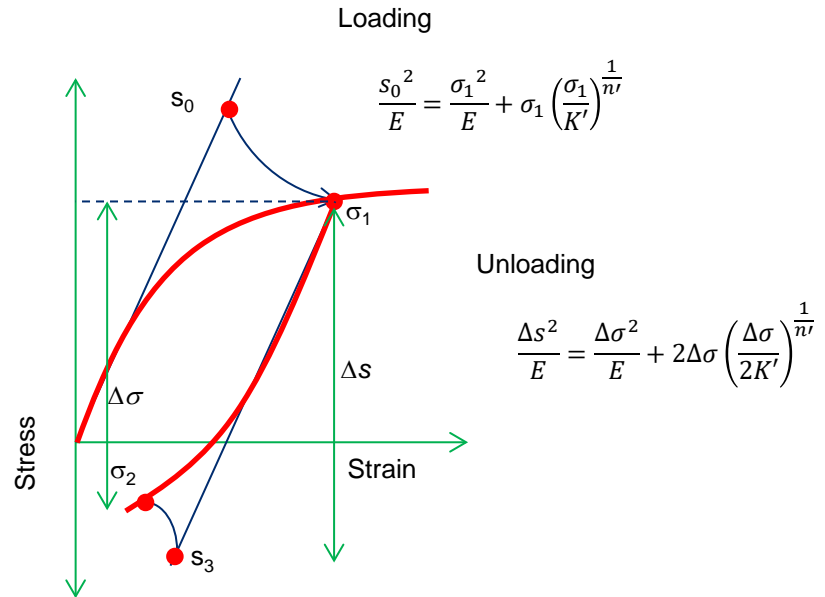
$$\overrightarrow{K_0 K_1}$$



Crack-tip closing

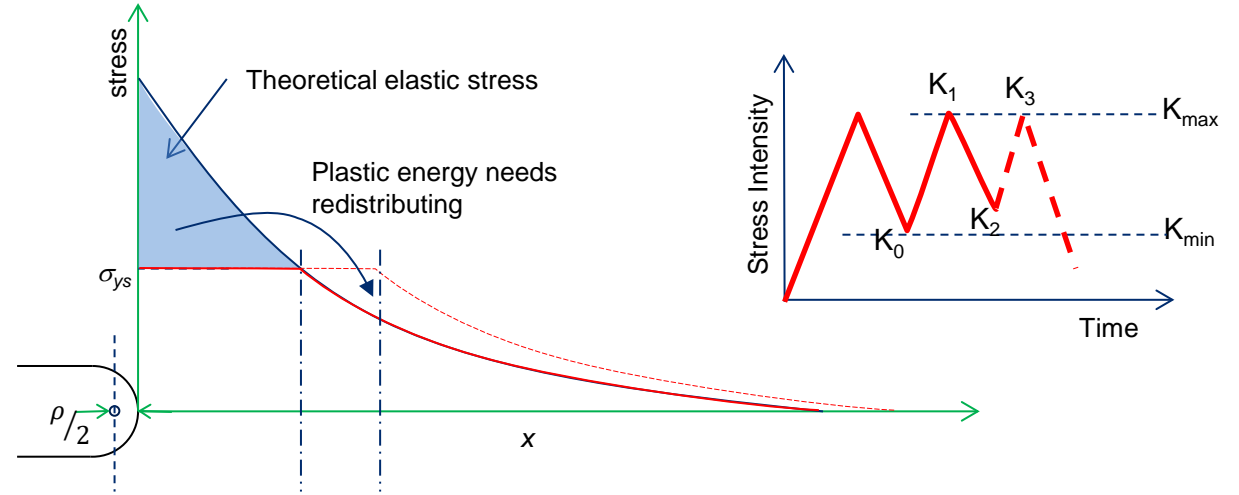
$$\overrightarrow{K_1 K_2}$$

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



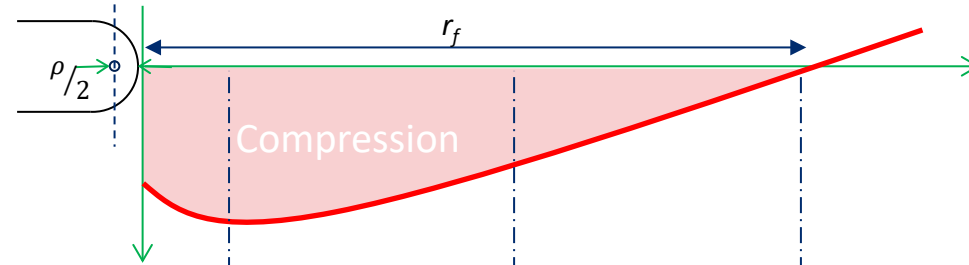
Crack-tip opening

$$\overrightarrow{K_0 K_1}$$

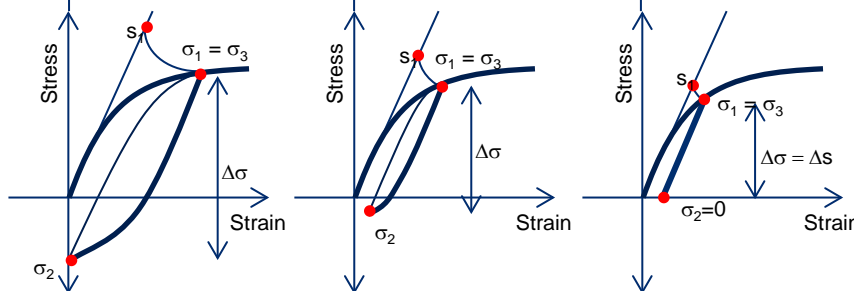


Crack-tip closing

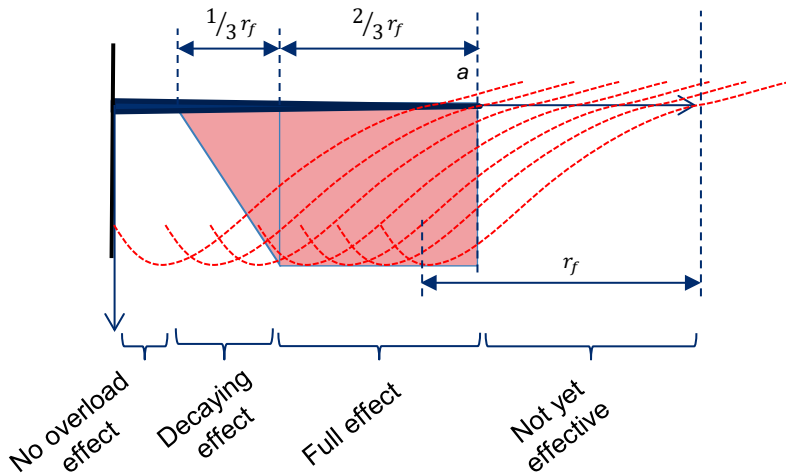
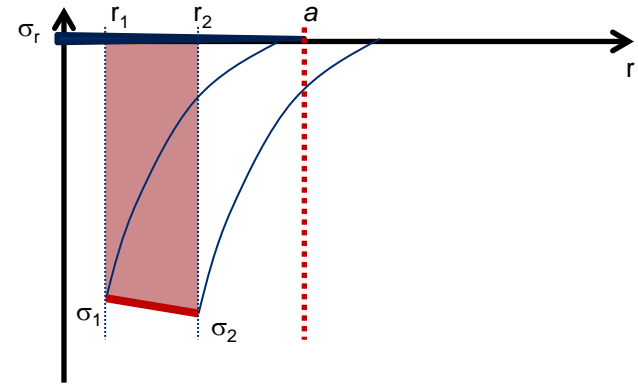
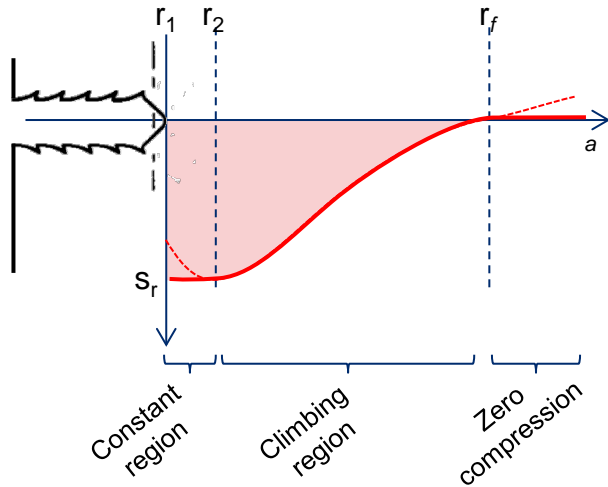
$$\overrightarrow{K_1 K_2}$$



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



Current Overload Cycle



Stress intensity arising from compressive wake determined using Glinka's Stress Weight Function:

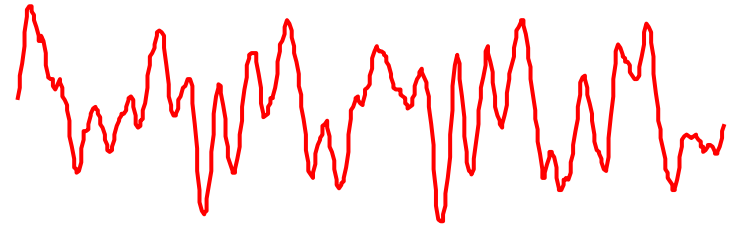
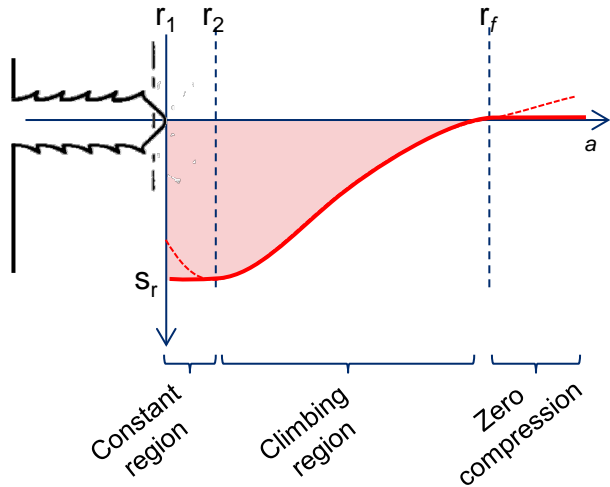
$$K_r = \int_{r_1}^{r_2} \frac{2\sigma_r(r)}{\sqrt{2\pi(a-r)}} dr$$

This retards the crack growth:

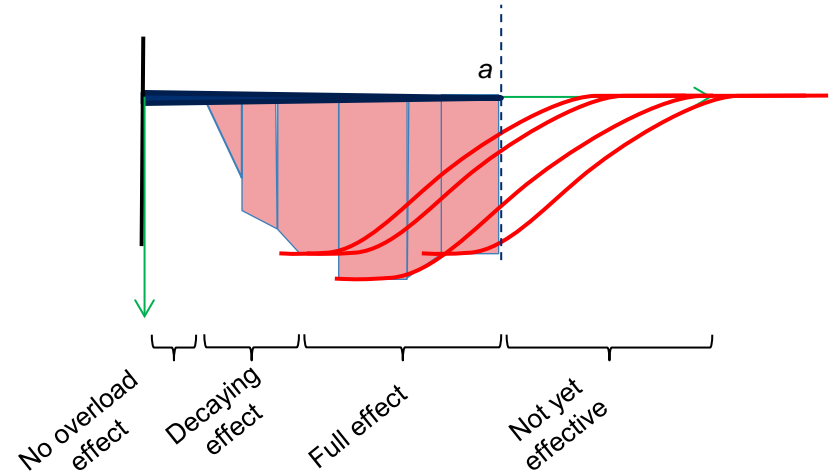
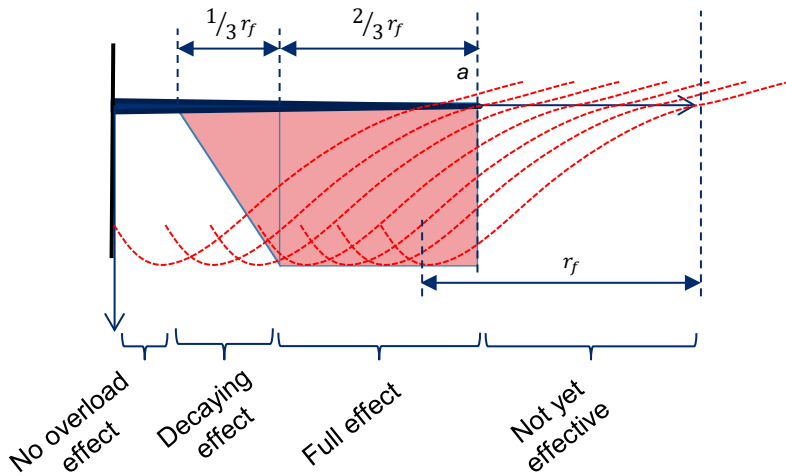
$$K = \sigma C_f Y \sqrt{\pi a} + K_r$$

Compressive wake from constant-amplitude loading

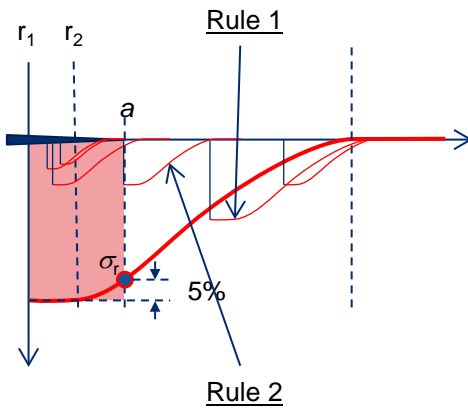
Current Overload Cycle



Compressive wake from variable-amplitude loading



Compressive wake from constant-amplitude loading

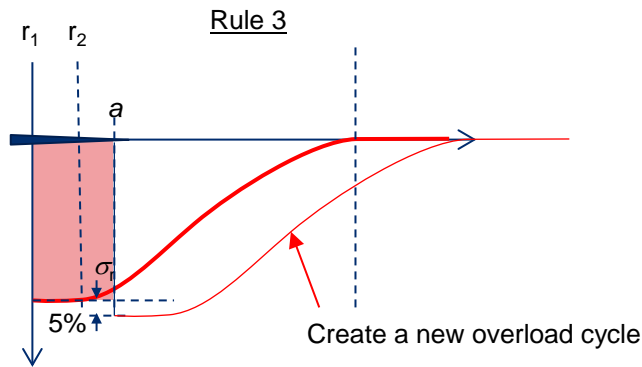


## Rule 1:

- Residual compression from cycle exceeds previous overload
- ∴ Start new overload

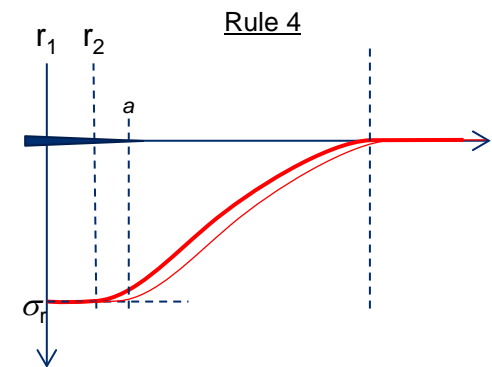
## Rule 2:

- Residual compression from cycle is less than previous overload
- ∴ Keep previous overload



## Rule 3:

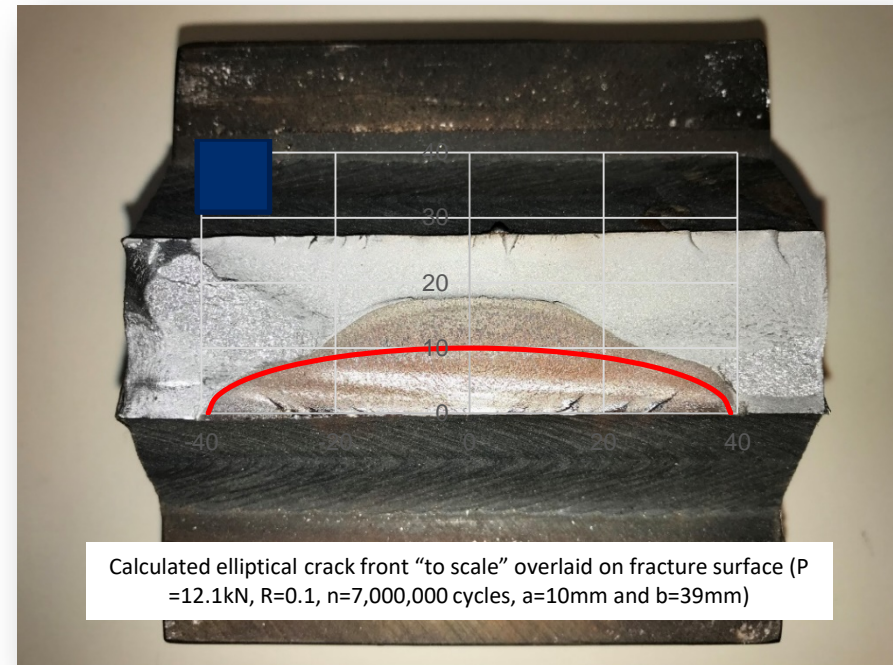
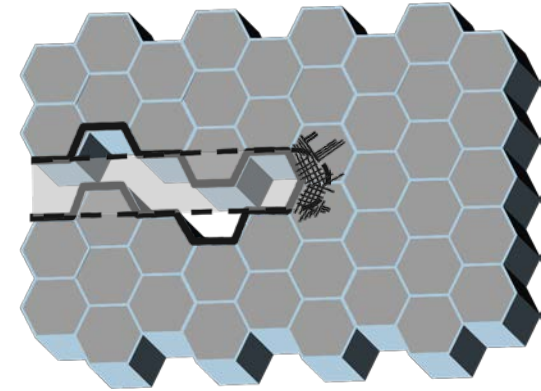
- Residual compression from cycle exceeds previous overload
- ∴ Start new overload



## Rule 4:

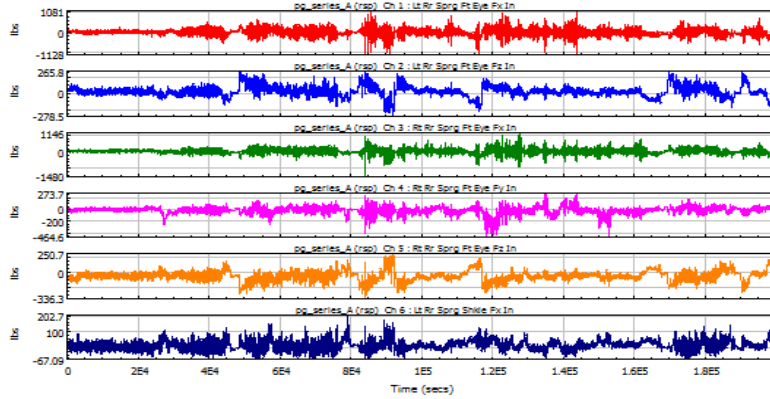
- Residual compression from cycle is approximately the same as the previous overload
- ∴ Extend overload zone

1. Fatigue/Fracture Theory
2. CAE Application
3. Case study
4. Conclusions

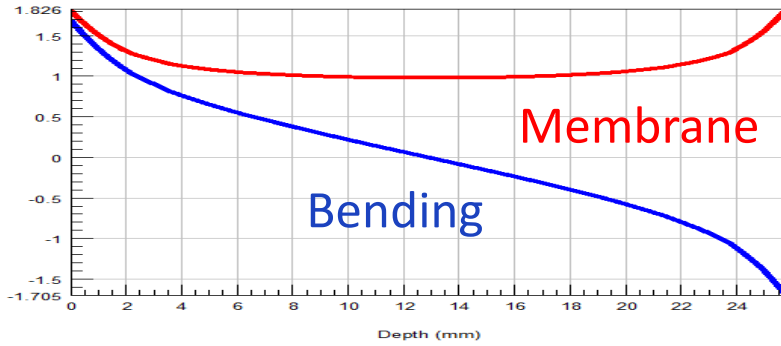


Calculated elliptical crack front "to scale" overlaid on fracture surface ( $P = 12.1\text{kN}$ ,  $R=0.1$ ,  $n=7,000,000$  cycles,  $a=10\text{mm}$  and  $b=39\text{mm}$ )

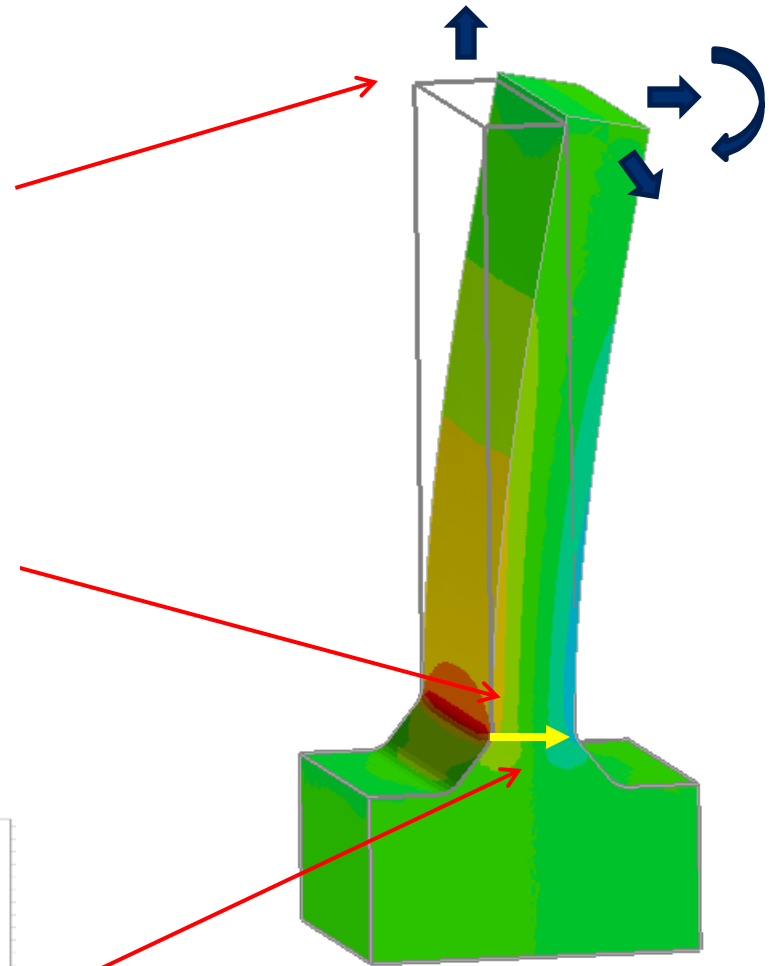
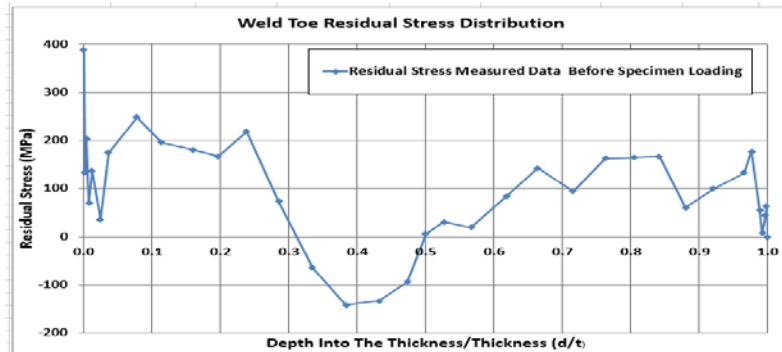
Applied structural stress histories

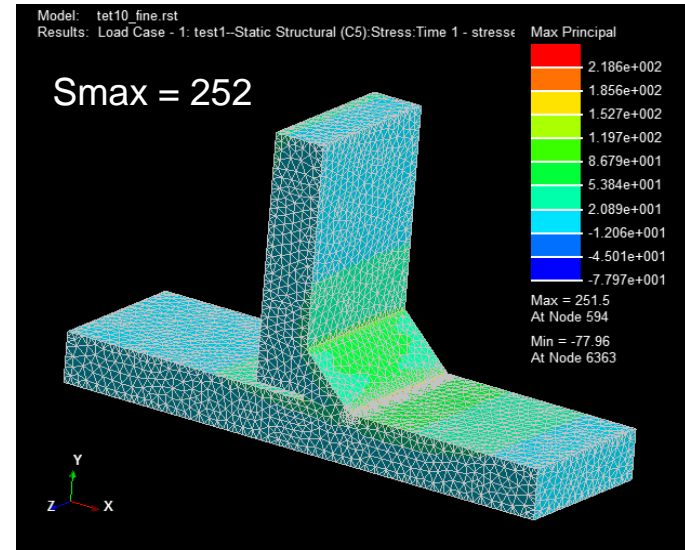
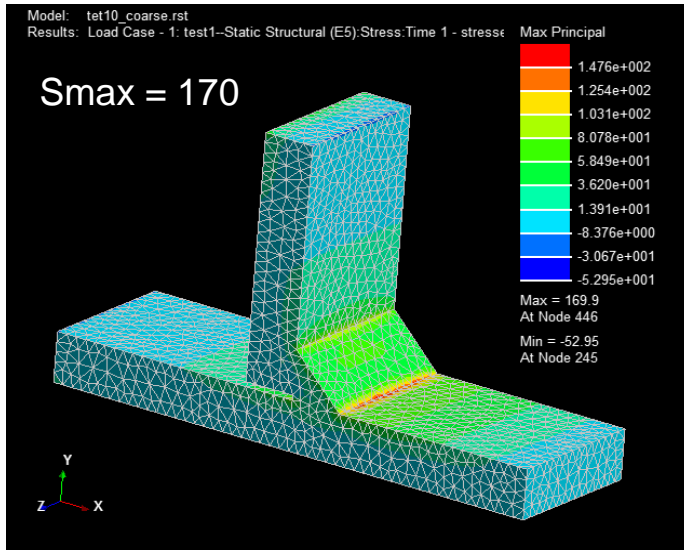
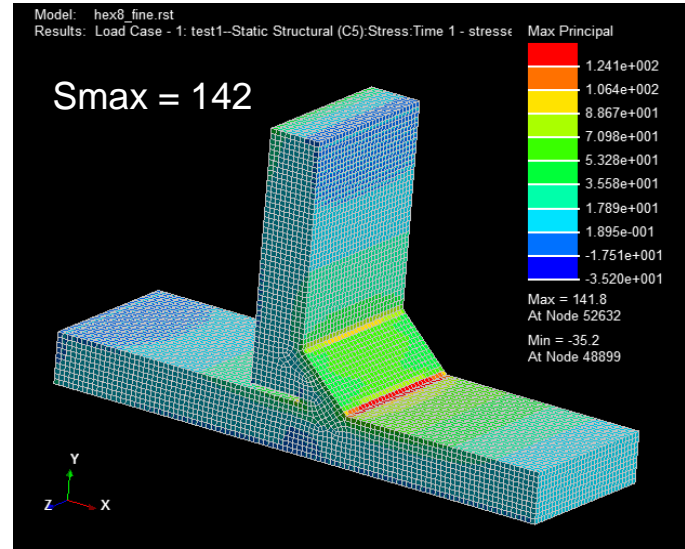
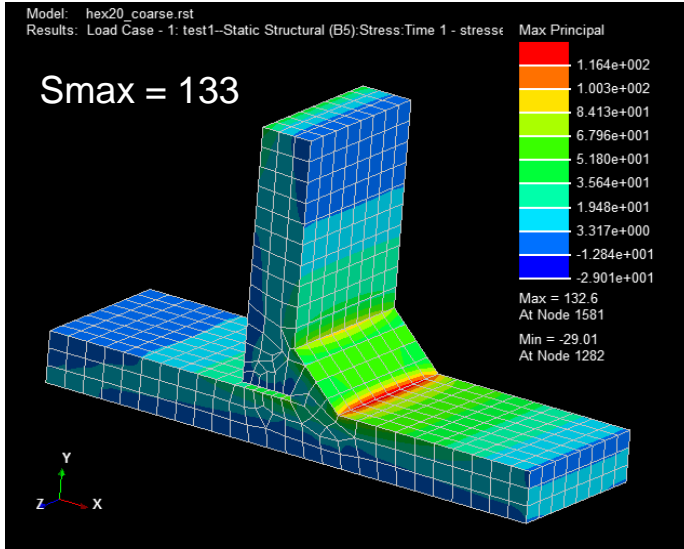


Through-thickness Kt profiles



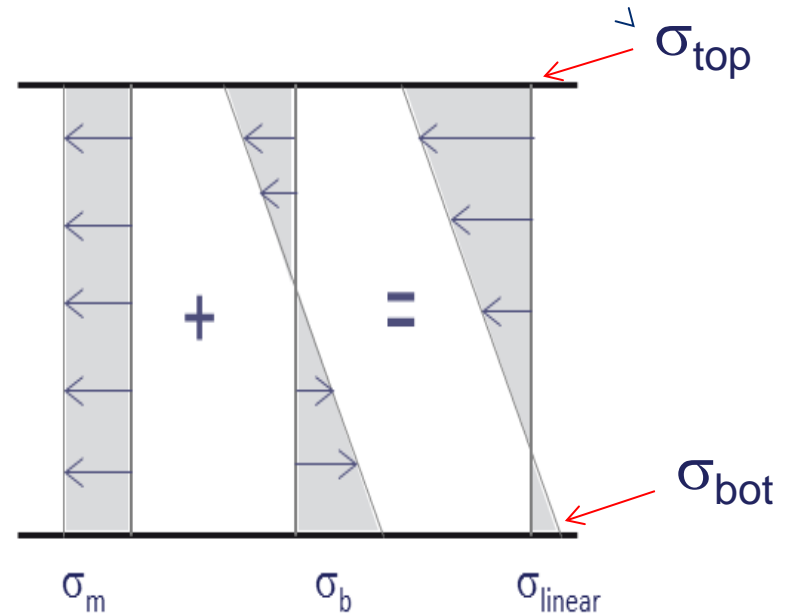
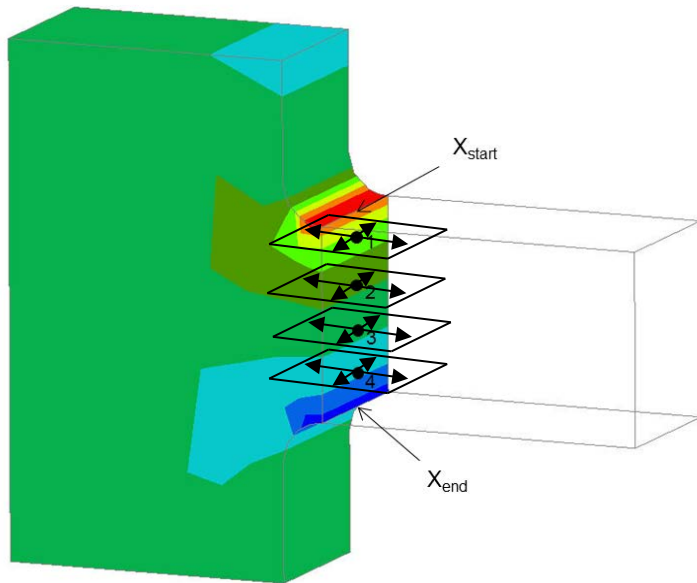
Residual Stress profile



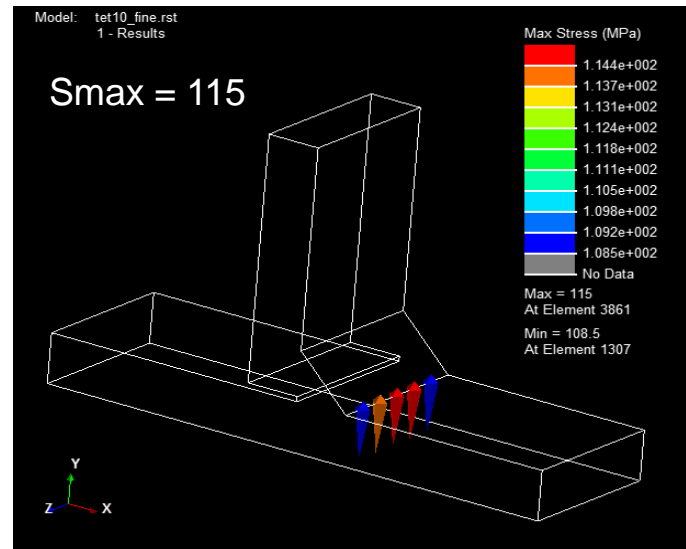
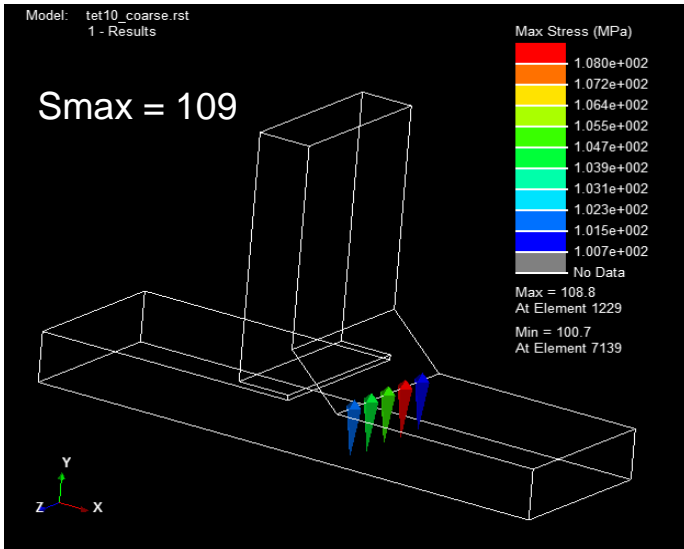
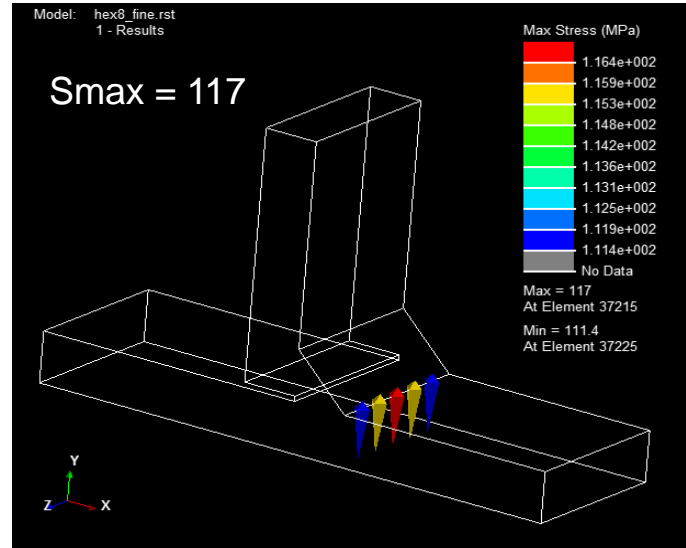
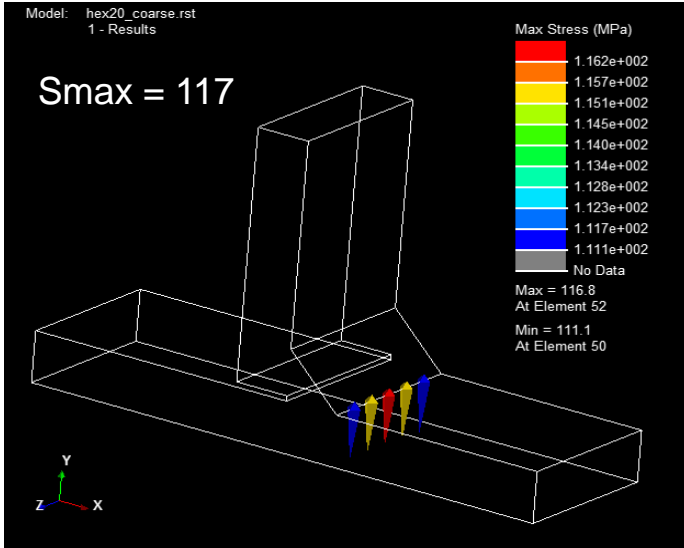


$$\sigma_m = \frac{1}{t} \int_0^t \sigma \, dx$$

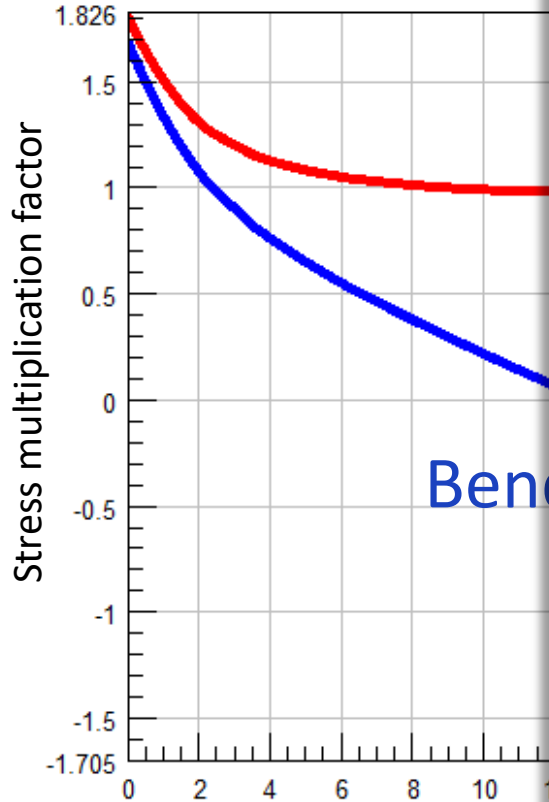
$$\sigma_b = \frac{6}{t^2} \int_0^t \sigma \left[ \frac{t}{2} - x \right] dx$$



The linearized stress is a 2D tensor,  $S_{tt}$ ,  $S_{ee}$ ,  $S_{et}$

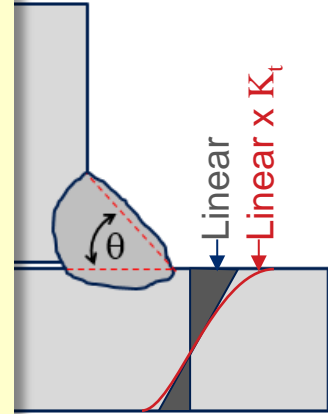


- Kt Stress profiles and Weight functions are used to calculate stress intensity factors
- Built-in empirical fillet weld geometry
- User input dimensions



## New for 2019:

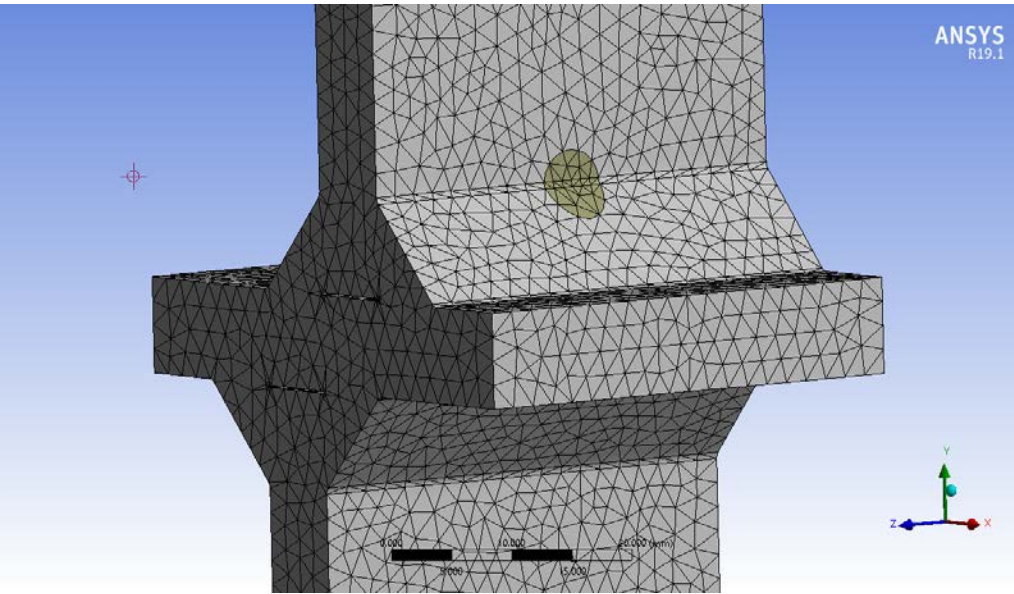
- Can be applied to shell elements as well as solids making it compatible with all standard seam weld capabilities
- New sub-modelling feature to calculate Kt profiles



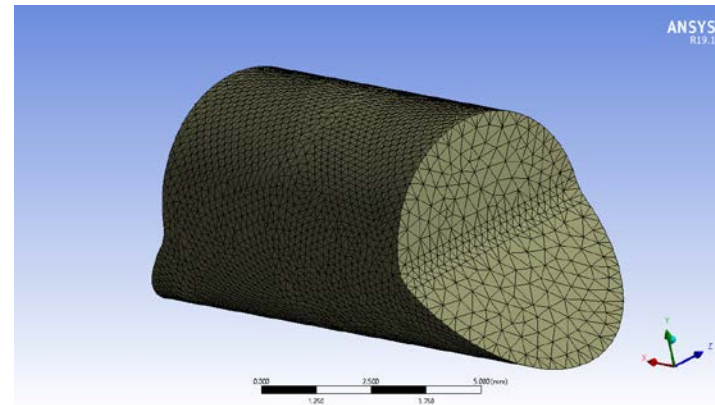
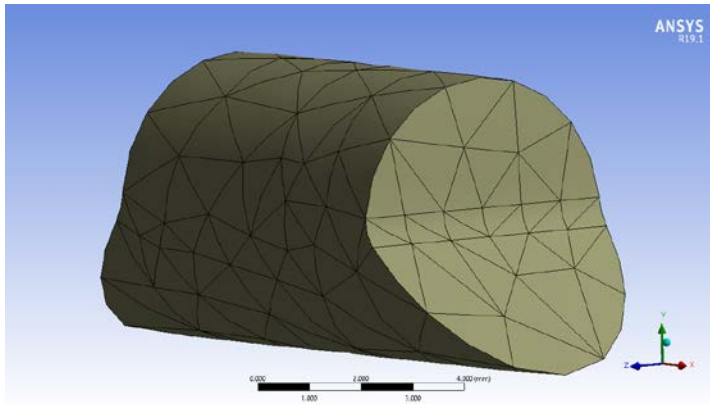
ly fatigue cracks  
rotational  
Southampton.

De

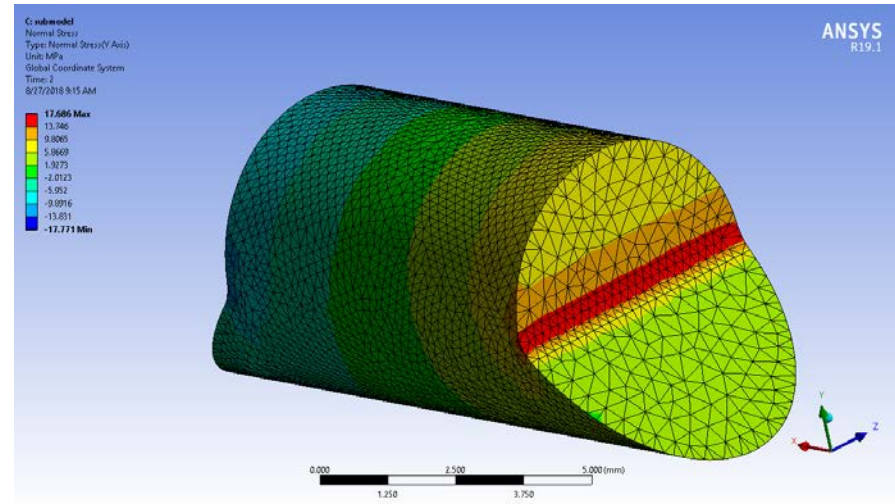
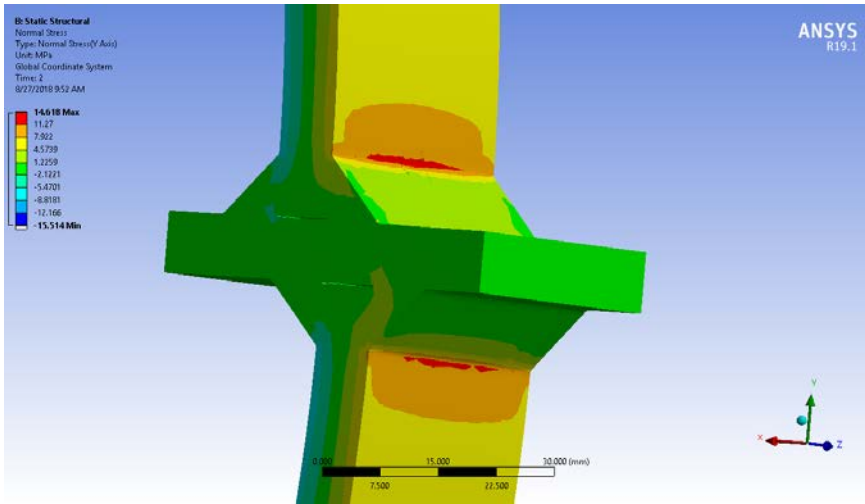
- Python scripting



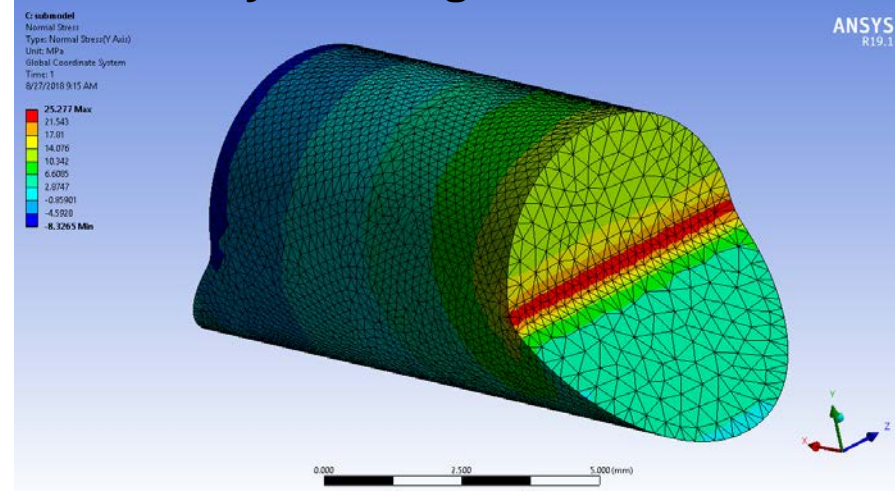
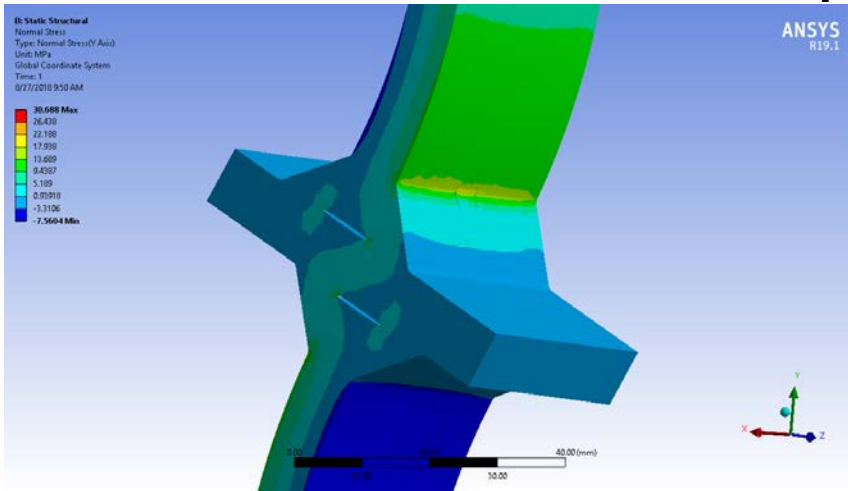
- Coarse model can be used for actual WholeLife calculation, but a refined model is required to obtain Kt and/or stress profile
- Here a refined submodel has been employed for that purpose



## Load case 1: predominantly membrane



## Load case 2: predominantly bending



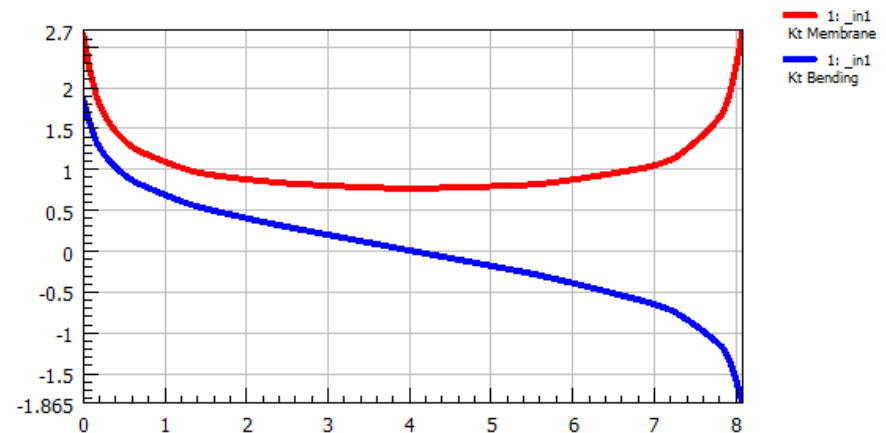
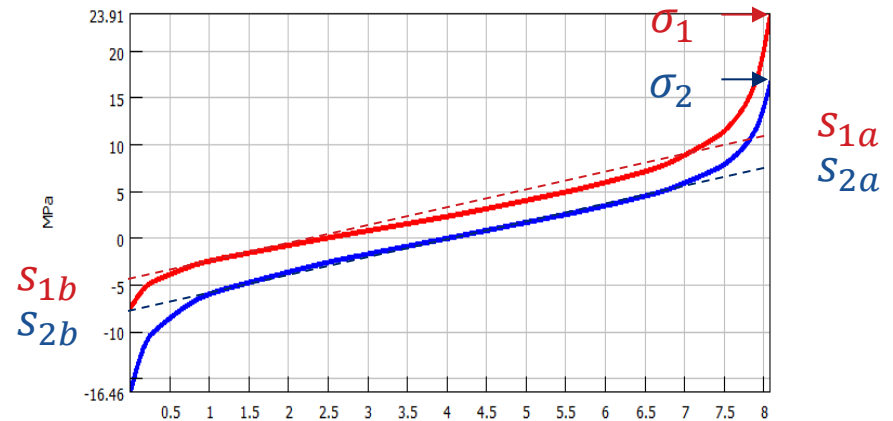
## Breakout model

- Calculate detailed stresses  $\sigma_1$  and  $\sigma_2$
- Calculate structural stresses  $s_1$  and  $s_2$
- Calculate unit Transformation matrix separating **membrane** and **bending** components

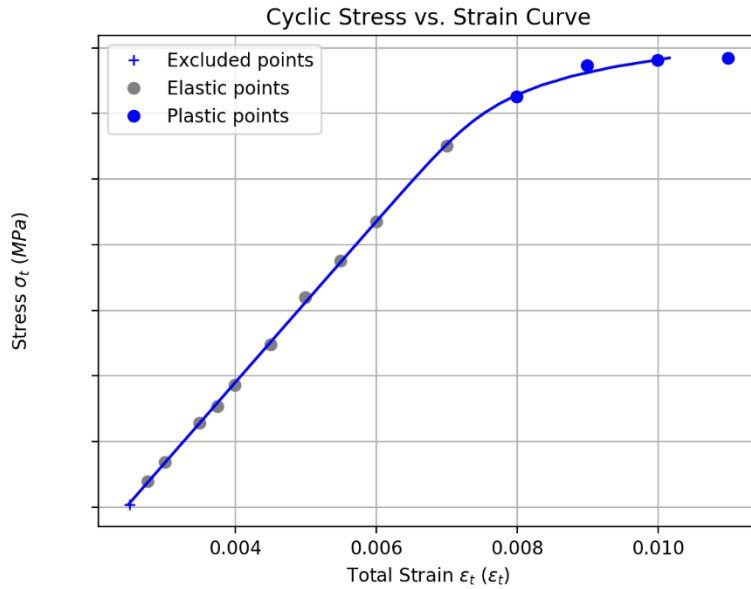
$$[T] = \begin{bmatrix} s_{1a} & s_{2a} \\ s_{1b} & s_{2b} \end{bmatrix}^{-1} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

- Apply Transform to calculate Kt for membrane and bending

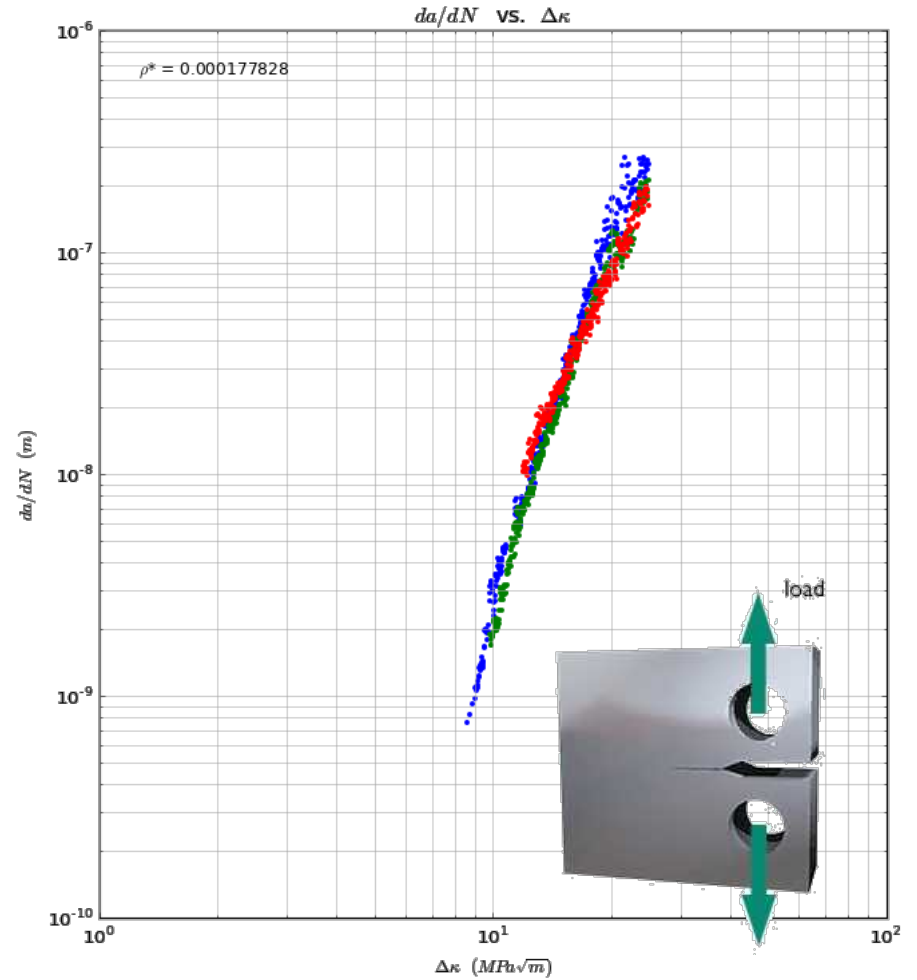
$$\begin{bmatrix} K_{t\ mem} \\ K_{t\ bend} \end{bmatrix} = [T]^T \begin{bmatrix} \sigma_1 & \sigma_2 \end{bmatrix}$$



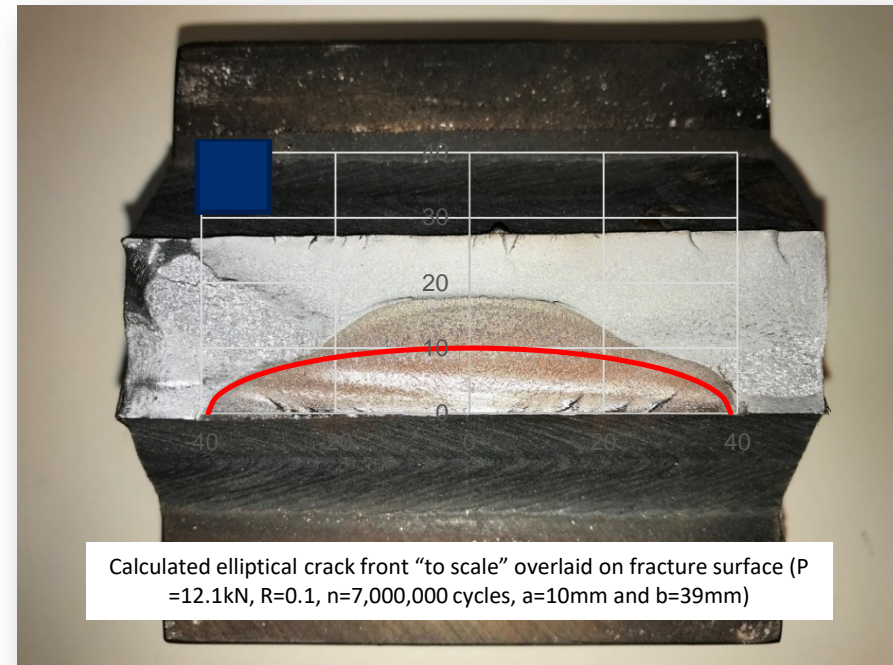
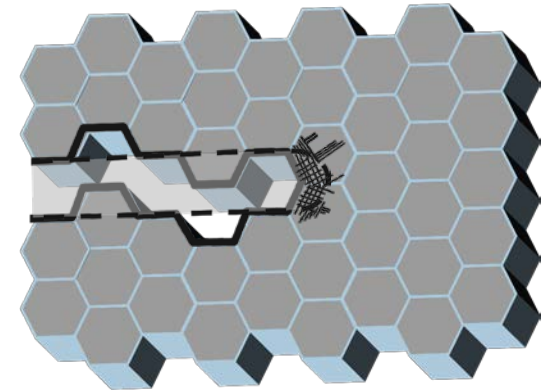
## Ramberg-Osgood from EN analysis



## LEFM crack growth properties at several R ratios



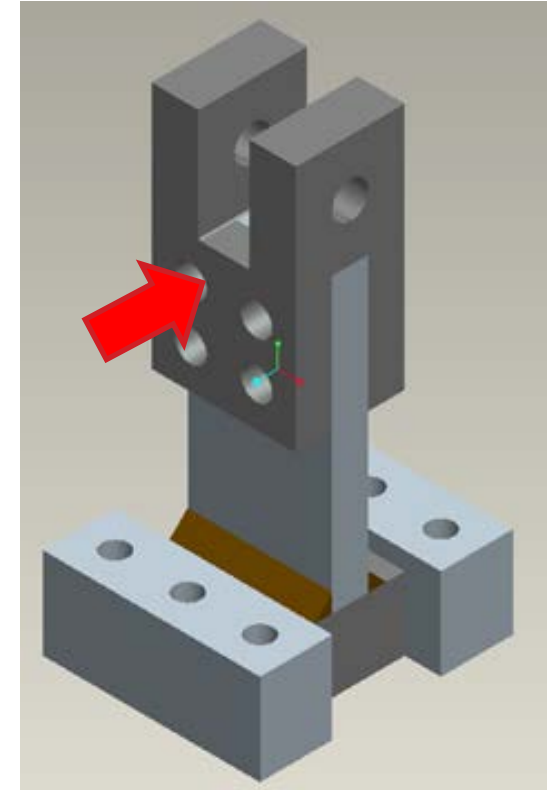
1. Fatigue/Fracture Theory
2. CAE Application
3. Case study
4. Conclusions



Calculated elliptical crack front "to scale" overlaid on fracture surface ( $P = 12.1\text{kN}$ ,  $R=0.1$ ,  $n=7,000,000$  cycles,  $a=10\text{mm}$  and  $b=39\text{mm}$ )

## SAE Fatigue Design & Evaluation (FD&E) Committee

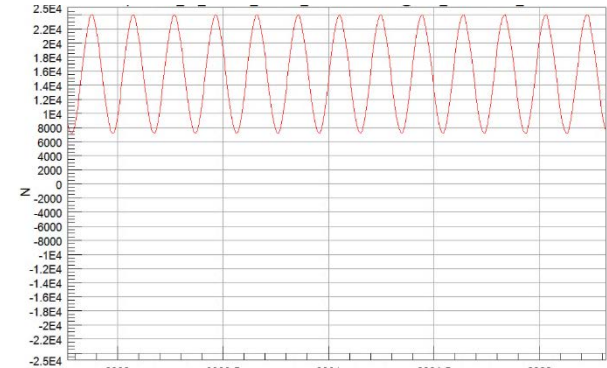
### *TOTAL LIFE FATIGUE PROJECT*



[www.fatigue.org/projects/total-life-project](http://www.fatigue.org/projects/total-life-project)

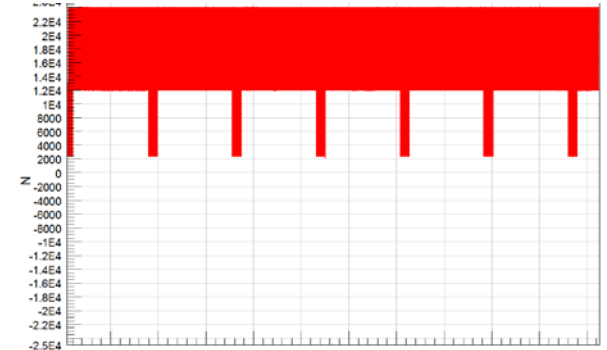
**Constant amplitude**

- 24kN, R = 0.3
- 24kN, R = 0.1
- 18kN, R = 0.1
- 10.8 kN, R = -1



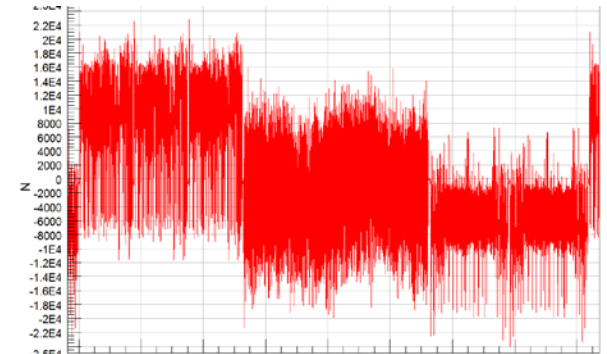
**Block load**

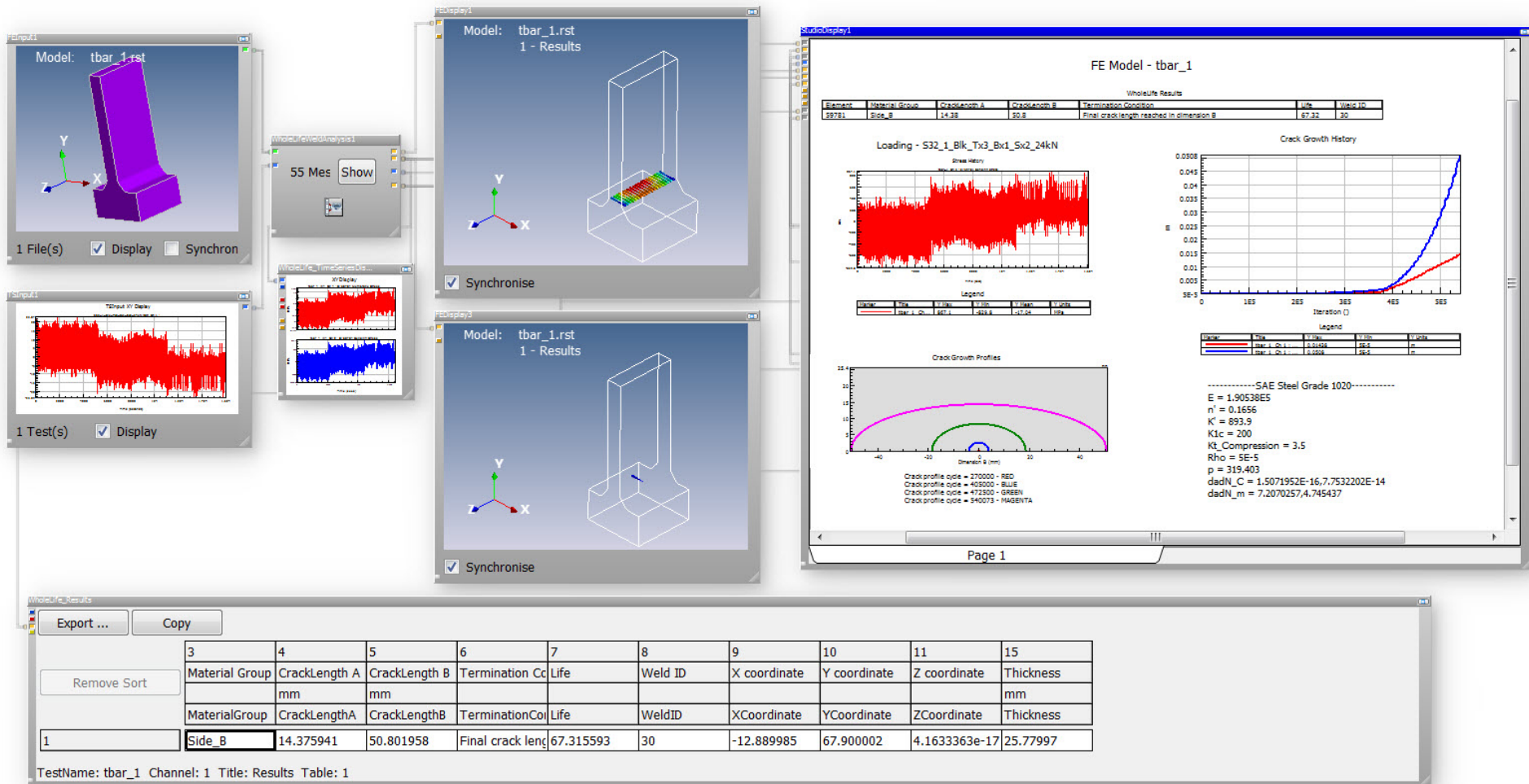
- 24kN, variable-amplitude, block-load

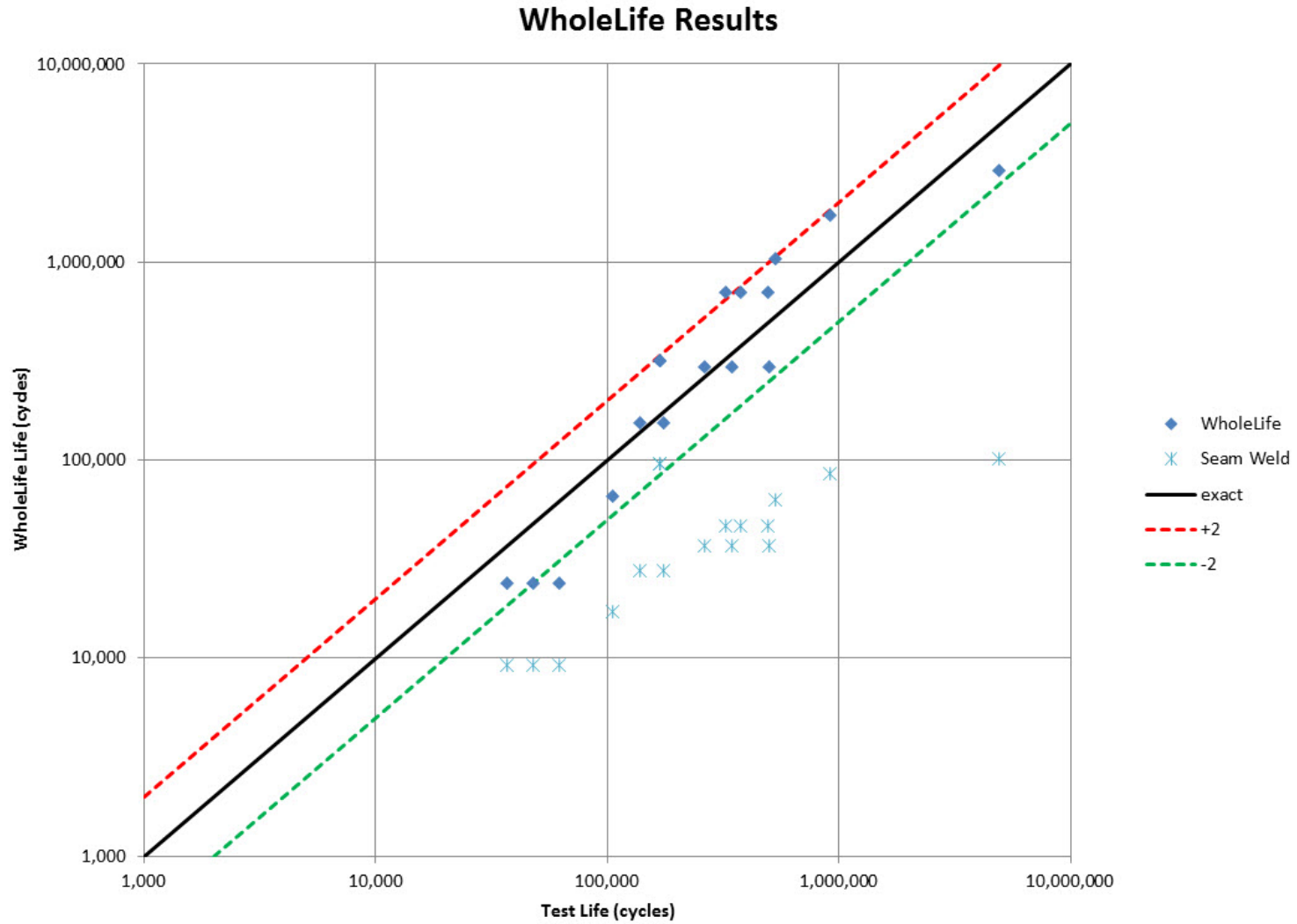


**Random**

- 24kN, variable amplitude, time history file







## Challenge

- Improve accuracy of weld fatigue life simulation
- Account for 'designed' welds as used in lightweight & thick-weld vehicle structures e.g. stress relieving, weld dressing, etc.
- Recognize fatigue as initiation and crack growth

*Prof. G. Glinka, University of Waterloo, Canada*

## Results

- Method showed outstanding correlation with independent SAE tests – “total-life” method

## Solution - WholeLife

- Accommodates complex weld geometries, residual stresses & multiaxial loading
- Uses standard FE mesh models – *shells & solids*
- Easy-to-use sub-modelling feature
- Uses fracture mechanics with advanced crack-tip cyclic plasticity modeling – *insensitive to initial crack length*
- Uses structural stress weld methods to locate critical failure sites



# nCode 'WholeLife'

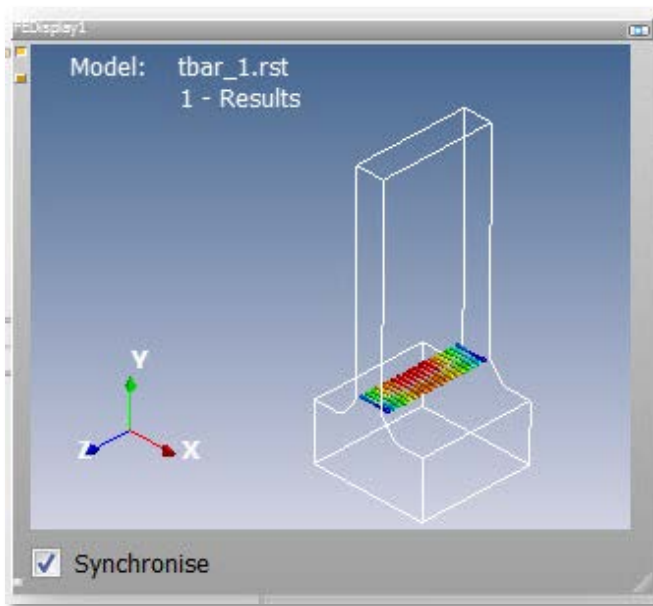
[www.hbmprenscia.com](http://www.hbmprenscia.com)

Dr Andrew Halfpenny

Director of Technology – nCode Products

T: +44 (0)7968 288760

E: [andrew.halfpenny@hbm.com](mailto:andrew.halfpenny@hbm.com)



WholeLife V???.pptx

