Fatigue Simulation of Welds Using the Total-Life Method

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Challenge/project scope

- 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**
Challenge/project scope

1. Crack Growth

2. Local Notch Stress

3. Structural Stress

\[ \sigma_{\text{peak}} = K_t \sigma_{hs} \]

Online webinar, October 16, 2018:
“Fatigue of Welds using nCode DesignLife”

www.hbmprenscia.com
Challenge/project scope

- 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
1. Fatigue/Fracture Theory

2. CAE Application

3. Case study

4. Conclusions

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

- 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 ‘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 Model $\frac{da}{dN}$

- 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 stress intensity and R ratio

  \[ \Delta \kappa = K_m d_m^{p} \frac{K_m - K_m}{1 - p} \]

- $K$ is a function of stress $\sigma$, geometry $Y$, crack length $d$, and the residual stress field at the tip of the crack

  \[ K = \sigma C_f Y \pi d + K_r \]

- $C_f$ is the ‘small crack correction’

  \[ C_f = \left( 1 + \frac{1}{2} \sqrt{\frac{R}{a}} \right) \]

- Crack closure model:

  \[ \sigma_{min} = \begin{cases} \sigma_{min} & \text{if } \sigma_{min} \geq 0 \\ K_t \sigma_{min} & \text{if } \sigma_{min} < 0 \end{cases} \]

  where $K_t$ is the notch correction, typically of the range

  \[ 2 \leq K_t \leq 3 \]
Universal Weight Function (UWF) Solutions

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

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

- 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
Cyclic Crack-tip Plasticity Model $K_r$

Crack-tip opening

\[ K_0 K_1 \]

\[ \sigma_{ys} \]

\[ \rho \]

\[ x \]

Theoretical elastic stress

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

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

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

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

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:

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

$$\frac{\Delta s^2}{E} = \frac{\Delta \sigma^2}{E} + 2\Delta \sigma \left(\frac{\Delta \sigma}{2K^1}\right)^\frac{1}{m}$$
Cyclic Crack-tip Plasticity Model $K_r$

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:
Cyclic Crack-tip Plasticity Model $K_r$ - Crack retardation

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:

$$K = \sigma C_f Y \sqrt{\pi a} + K_r$$
Cyclic Crack-tip Plasticity Model $K_r$ - Crack retardation

Current Overload Cycle

Compressive wake from constant-amplitude loading

Compressive wake from variable-amplitude loading

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Cyclic Crack-tip Plasticity Model $K_r$ - Memory rules

**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
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Inputs to a WholeLife Weld Calculation

- Applied structural stress histories
- Through-thickness Kt profiles
- Residual Stress profile

- Membrane
- Bending

Weld Toe Residual Stress Distribution

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Stresses Calculated Directly by the Finite Element Model

Smax = 133
Max = 132.6
At Node 1591
Min = -25.04
At Node 1242

Smax = 142
Max = 141.8
At Node 5232
Min = -35.2
At Node 4899

Smax = 170
Max = 169.9
At Node 446
Min = -62.35
At Node 246

Smax = 252
Max = 261.5
At Node 584
Min = -77.56
At Node 2603
Structural Stresses in Solid FE Models from Trough Thickness Integration

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

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

The linearized stress is a 2D tensor, \( S_{tt}, S_{ee}, S_{et} \)
Structural Stress from Through Thickness Integration

Smax = 117

Smax = 109

Smax = 115
Kt Profiles

- 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
Submodel Used for Kt Profiles Calculation

- 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
Two Stress States on Detailed Submodel

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 $K_t$ for membrane and bending

$$\begin{bmatrix} K_{t\text{,mem}} \\ K_{t\text{,bend}} \end{bmatrix} = [T]^T \begin{bmatrix} \sigma_1 \\ \sigma_2 \end{bmatrix}$$
WholeLife Material Data

Ramberg-Osgood from EN analysis

LEFM crack growth properties at several R ratios

Cyclic Stress vs. Strain Curve

- Excluded points
- Elastic points
- Plastic points

Graph showing da/dN vs. Δκ with a slope of 0.000177828.
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Description of SAE FD&E Committee Total Life Project

SAE Fatigue Design & Evaluation (FD&E) Committee

TOTAL LIFE FATIGUE PROJECT

www.fatigue.org/projects/total-life-project
SAE Case Study – *specimen loading*

**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
SAE Case Study – *DesignLife analysis*
Correlation with Test – Comparison with Standard Solid Seam Weld Analysis

WholeLife Results

- WholeLife
- Seam Weld
- exact
- +2
- -2

Test Life (cycles)

WholeLife Life (cycles)
### Summary

#### 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*

#### 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

#### Results

- Method showed outstanding correlation with independent SAE tests – “total-life” method
nCode ‘WholeLife’

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