Fatigue Assessment of Retrofitted Metal Structures Using Local Approaches

KASRA GHAHREMANI, PH.D.

PRESENTATION AT THE SAE FD&E COMMITTEE MEETING

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Kasra Ghahremani

Ph.D. in Civil Engineering - Structures and Mechanics Engineering from the *University of Waterloo*, ON, Canada

Thesis: Fatigue Assessment of Repaired Highway Bridge Welds Using Local Approaches

Advisors: T. Topper & S. Walbridge

Currently Diagnostics Engineer at *Walter P Moore*, Houston, Texas

Outline

1) Fatigue of Metal Structures
2) Analysis of Impact Treated Weld Joints
3) Local Stress Design Concept for Fatigue Design

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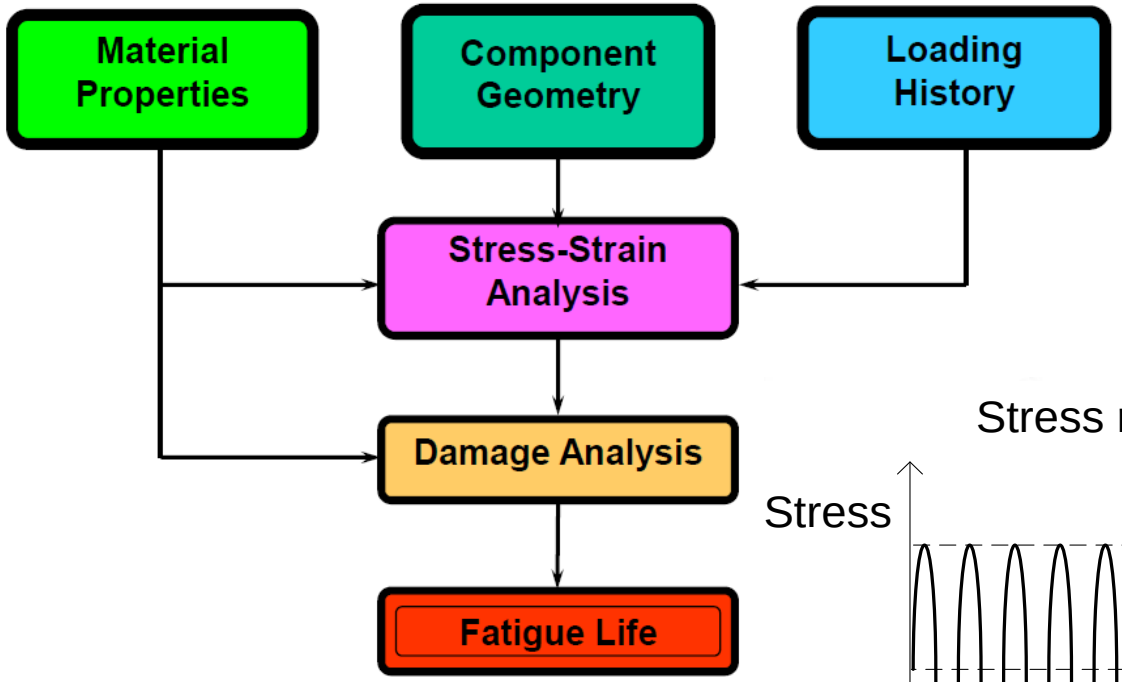
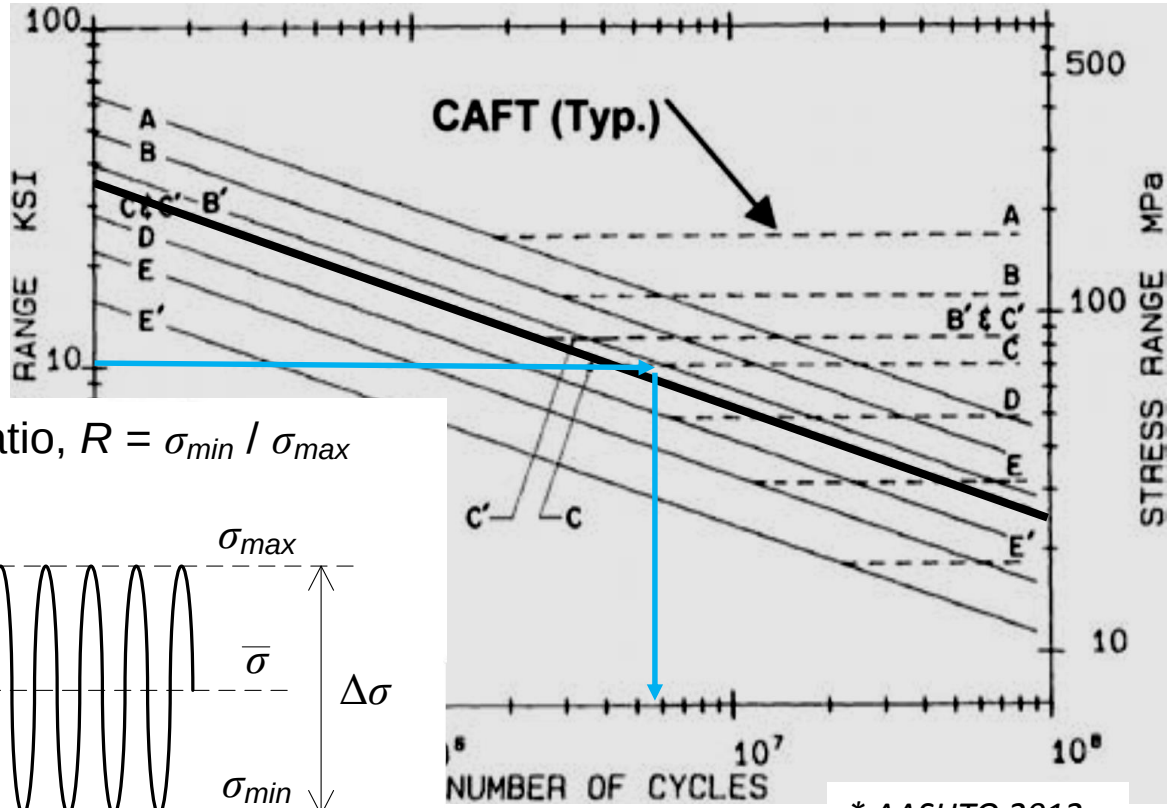
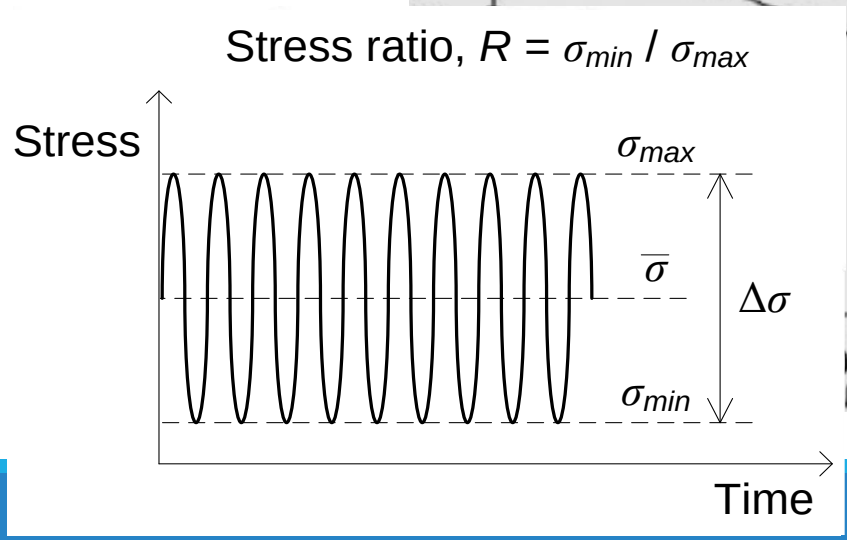
1) *Fatigue of Metal Structures*
2) Analysis of Impact Treated Weld Joints
3) Local Stress Design Concept for Fatigue Design

Fatigue of Metal Structures
Fatigue life analysis



Nominal Stress-Life (*S-N*) Approach





** AASHTO 2012*

Fatigue of Metal Structures
Fatigue improvement

HFMI treatment tool

HFMI: High Frequency Mechanical Impact Treatment

Before HFMI

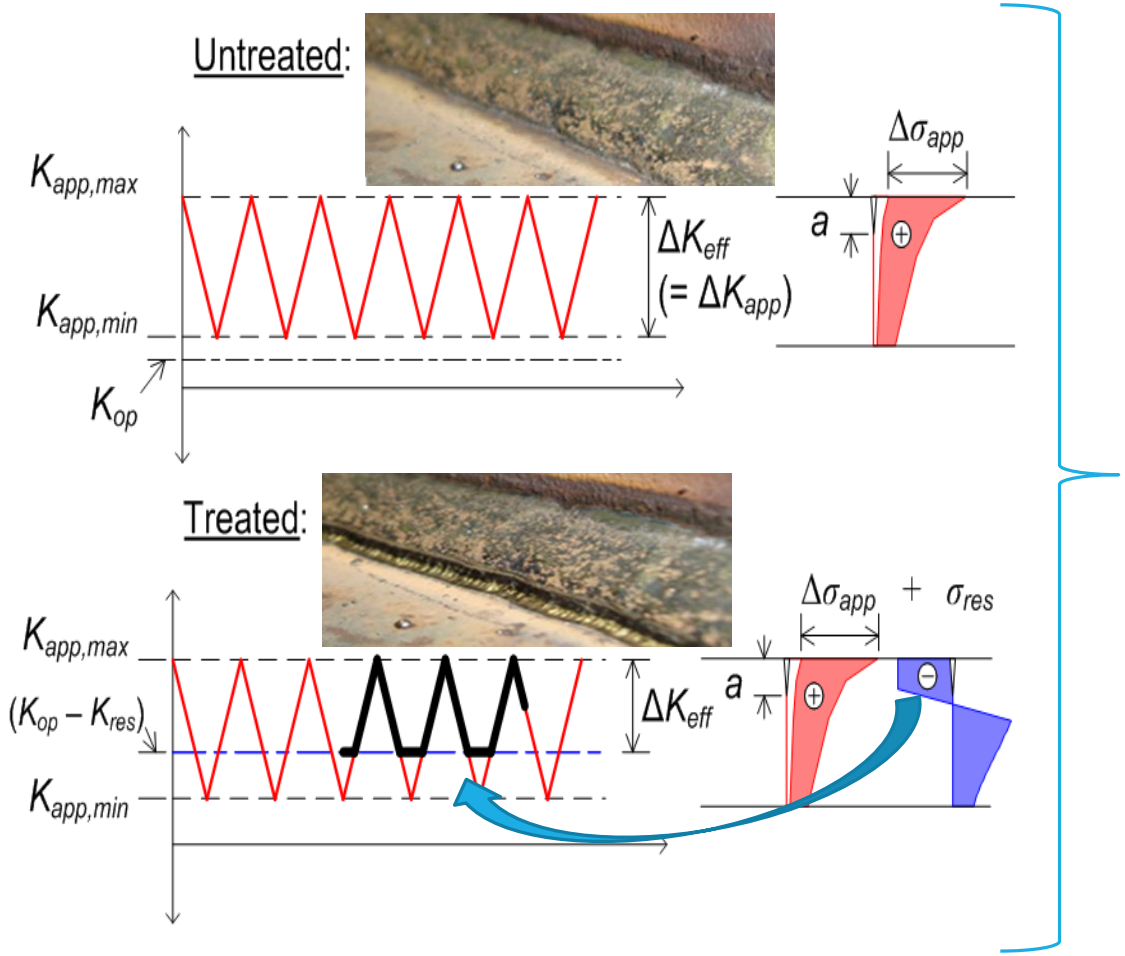
After HFMI

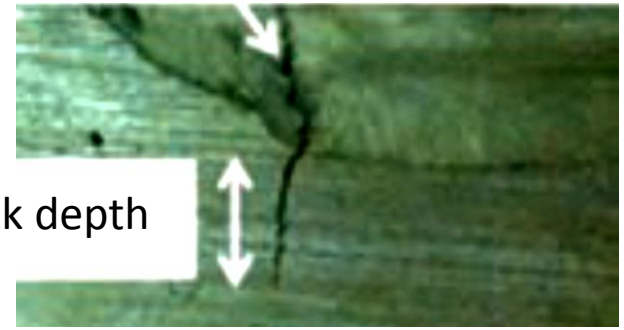
Fatigue enhancement techniques

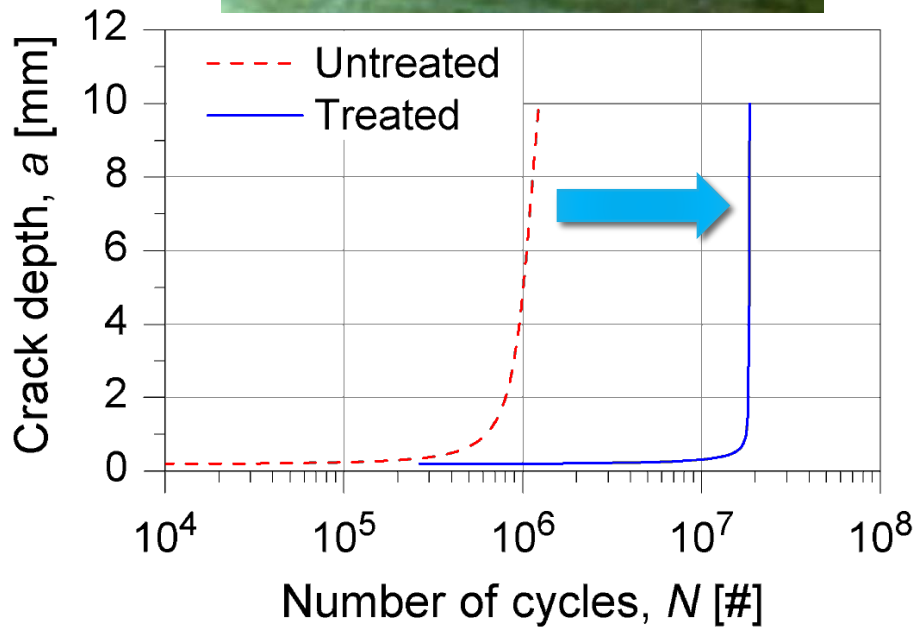
Residual stress-based post-weld treatments (peening methods)

delay the growth of fatigue cracks by introducing a compressive residual stress field near the surface

HFMI treatments
How they work







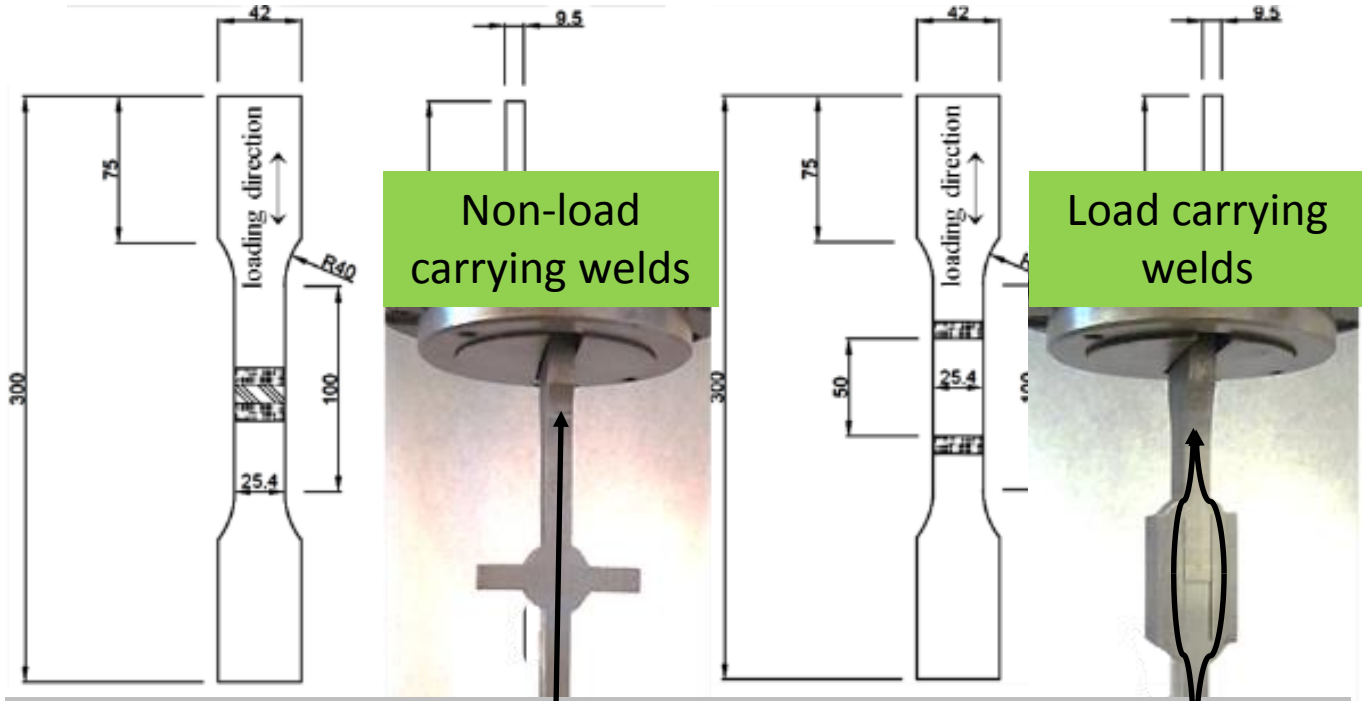
Outline

1) Fatigue of Metal Structures
2) *Analysis of Impact Treated Weld Joints*
3) Local Stress Design Concept for Fatigue Design

Impact Treatments
High cycle fatigue studies

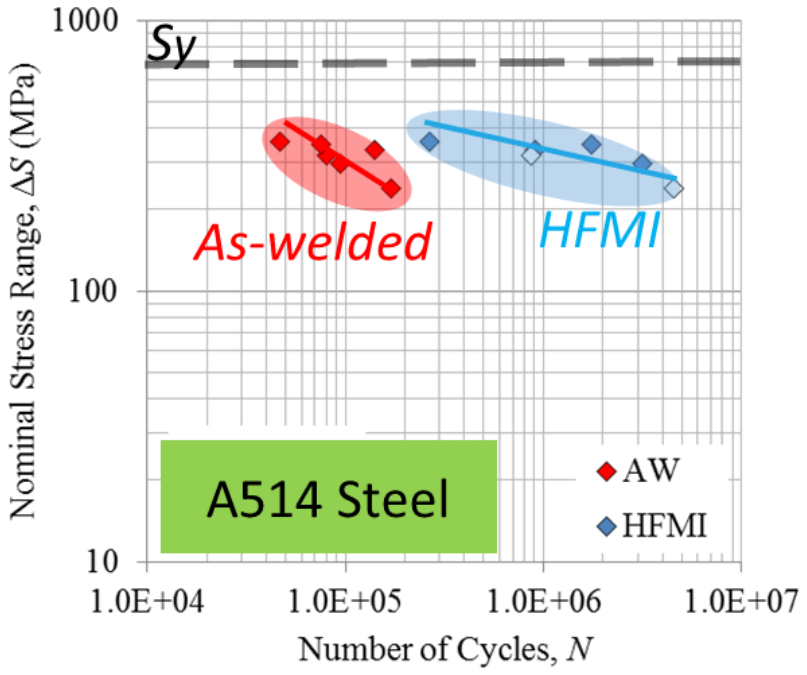
Objectives:

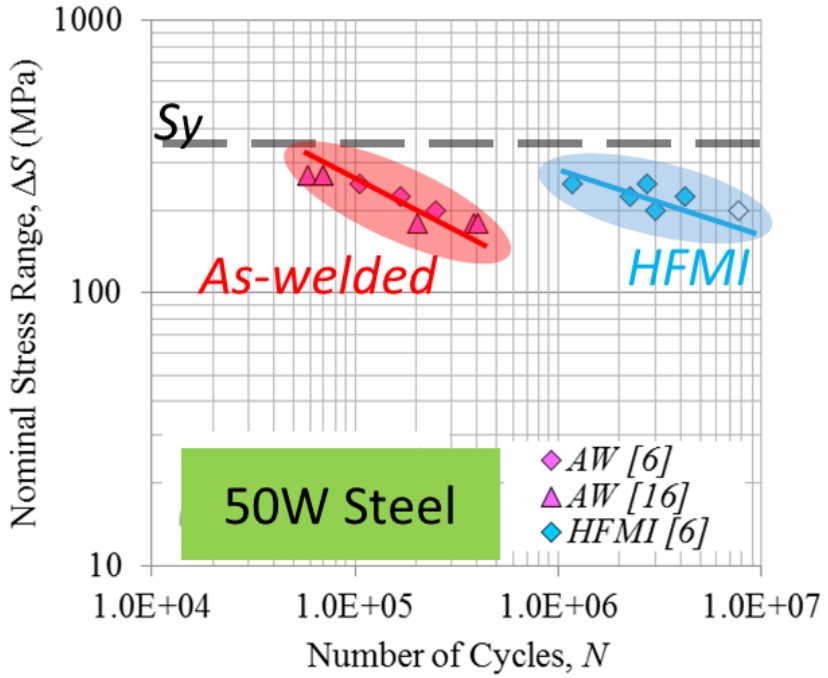
1. Study the effectiveness of HFMI treatments under in-service loading conditions for different metals
2. Develop recommendations for design of treated weld joints

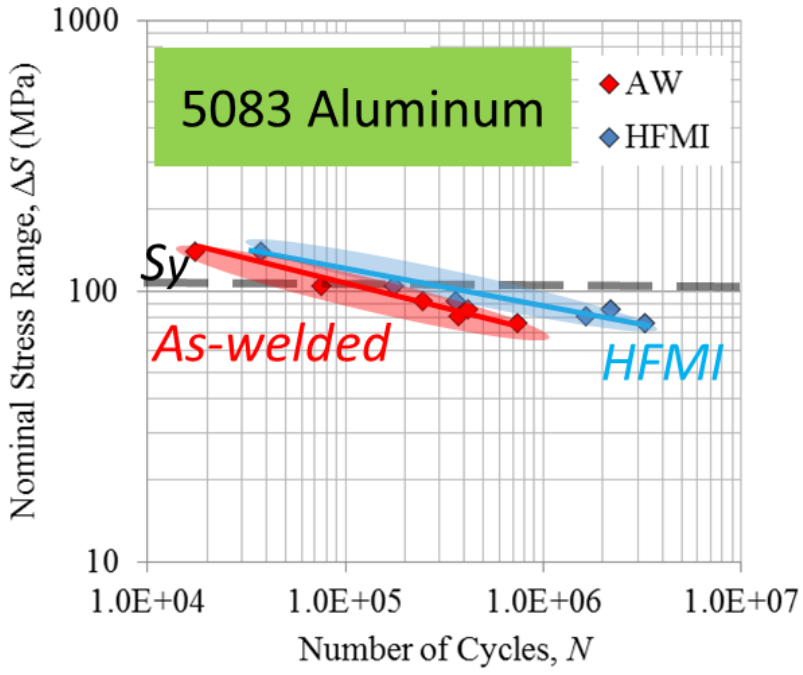


Structural Steel (50W), High Strength Steel (ASTM A514), Structural Aluminum (5083-H321)

Impact Treatments
Experimental results (CA)



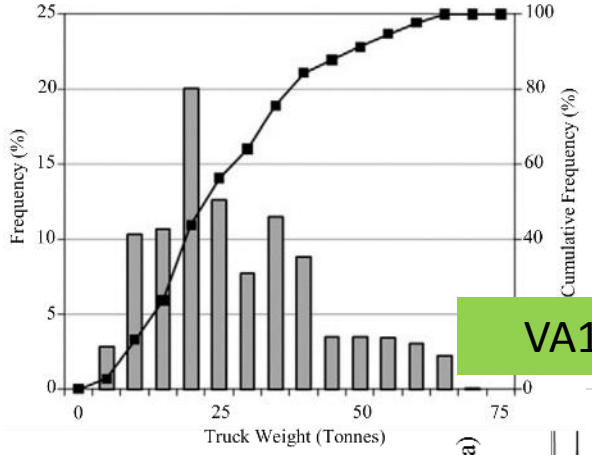




HFMI treatment effectiveness increases with an increase in the material strength

Impact Treatments
Variable Amplitude (VA) Loading Spectrum

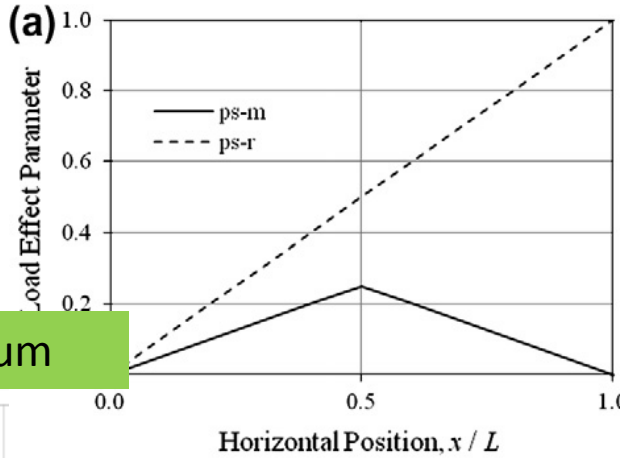
Truck weight histogram



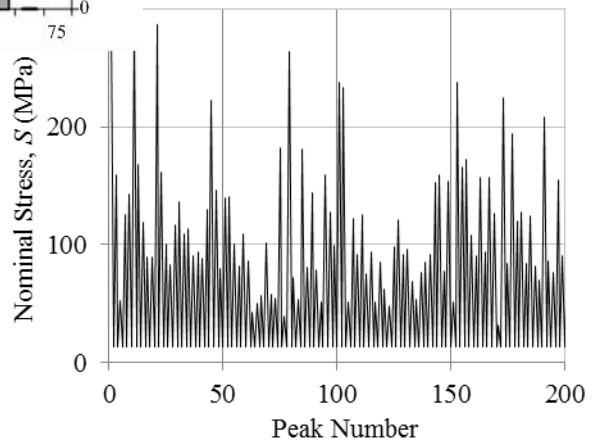
10,195 Cycles

$$\Delta S_{eq} = \left(\Sigma \Delta S_i^s \cdot y_i\right)^{1/s}$$

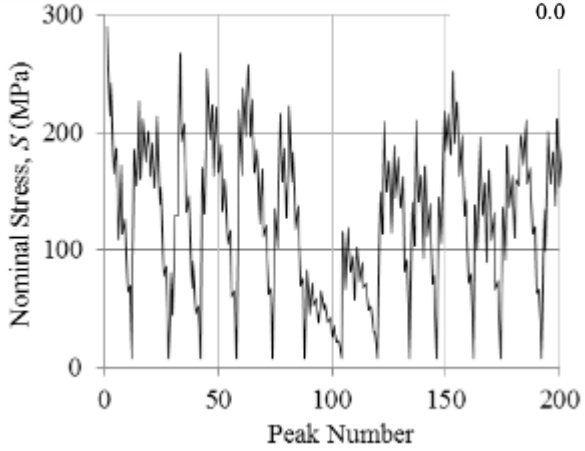
Influence lines



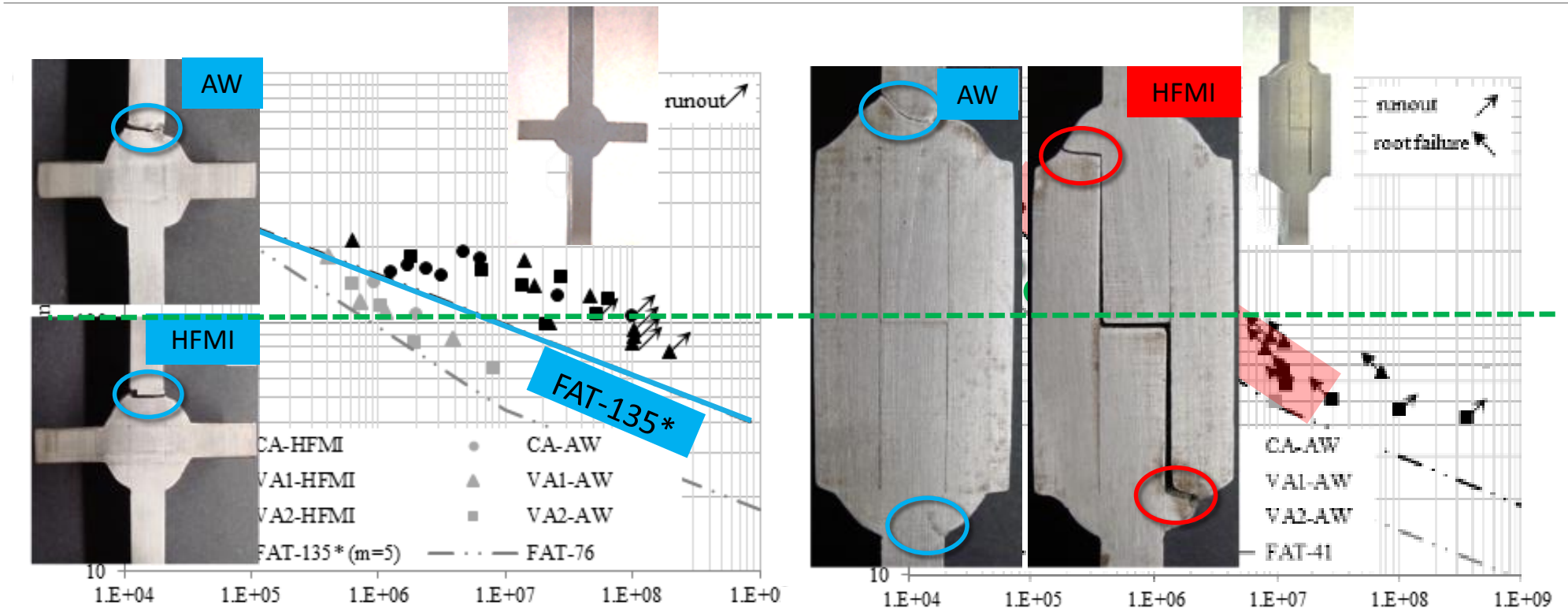
VA1 loading spectrum



VA2 loading spectrum



Impact Treatments
Experimental results (50W steel)



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The maximum applied stress should be limited to a ***local*** stress value

Impact Treatments
Strain-based fracture mechanics analysis

Effective Strain-Life Model + **Strain-based Fracture Mechanics Model** + **Crack Closure Models**

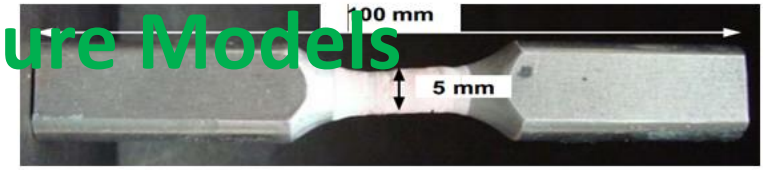
$$\Delta\varepsilon_{eff} = \frac{A}{E}\left(2N_f\right)^e + \Delta\varepsilon_i$$

$$\frac{da}{dN} = C(\Delta K_{eff} - \Delta K_i)^m$$

$$\Delta K_{eff} = K_{max} - MAX\left(K_{op}, K\right$$

$$K = Y \cdot E \cdot \varepsilon \cdot \sqrt{\pi \cdot a}$$

$$\sigma_{el} = k_p \cdot S$$



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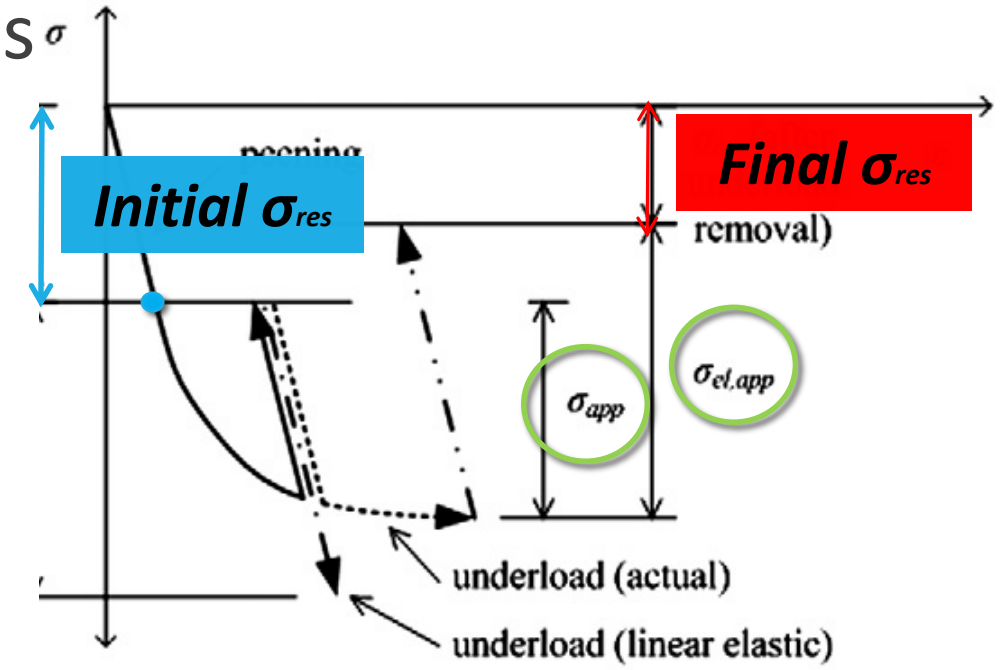
Impact Treatments
Why strain-based fracture mechanics?

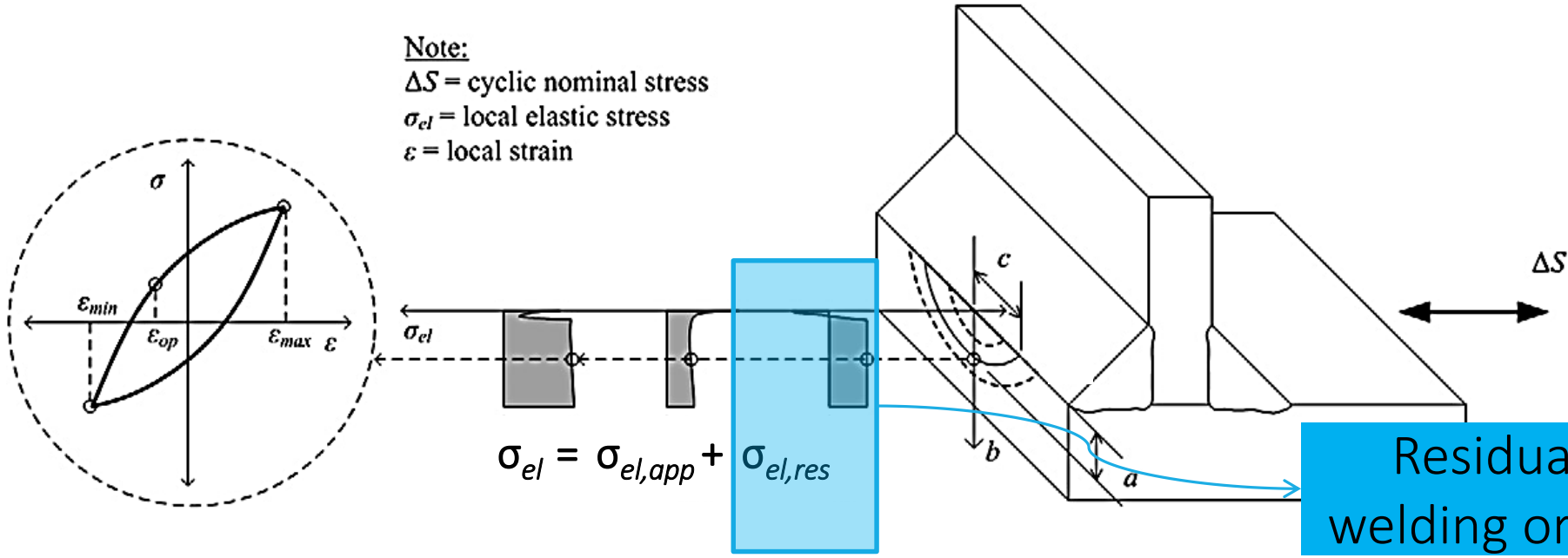
SBFM captures and tracks the effects of:

- residual stress relaxation due to increasing plasticity at higher stress levels
- significant non-linear material response
- reducing the crack opening stress level



Impact Treatments
Strain-based fracture mechanics analysis

The analysis consists of cyclically loading the material at various depth below the surface of the weld notch to determine the strain parameters for each completed cycle



Residual stress due to welding or HFMI treatment

Fracture Mechanics Model (SBFM)
Input parameters

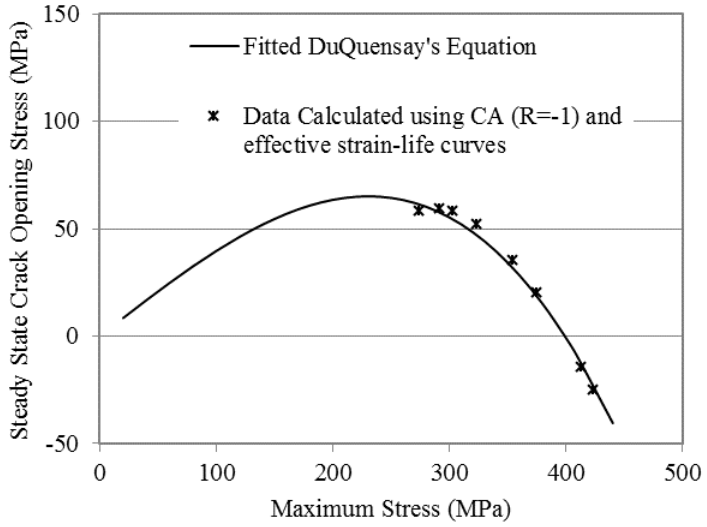
- *Material constants: E, Sy, σy, K', n'*
- Crack closure/ opening stress paran
- Crack growth parameters: C, m, ΔK
- Initial crack size
- Elastic stress concentration
- Residual stresses

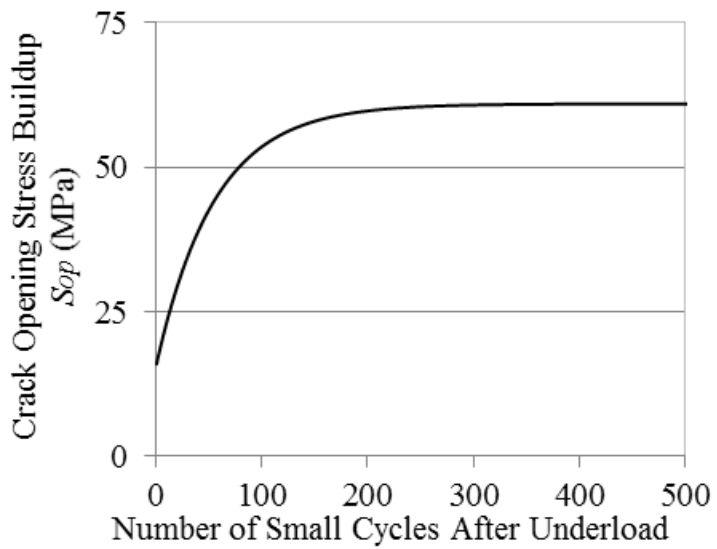
Monotonic and cyclic material testing

Fracture Mechanics Model (SBFM)
Input parameters

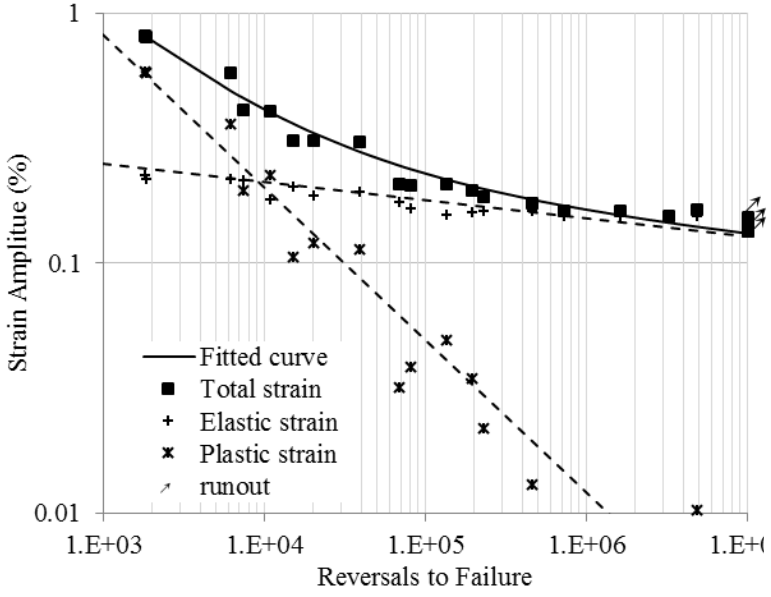
- Material constants: E, Sy, σy, K', n'
- *Crack closure/ opening stress parameters: θ, φ, μ*
- Crack growth paran
- Initial crack size
- Elastic stress conce
- Residual stresses

Effective strain-life model



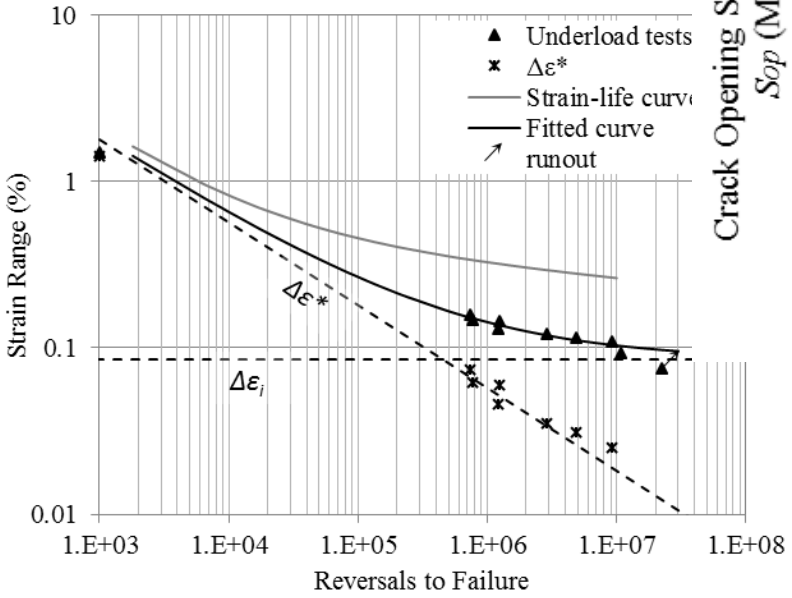


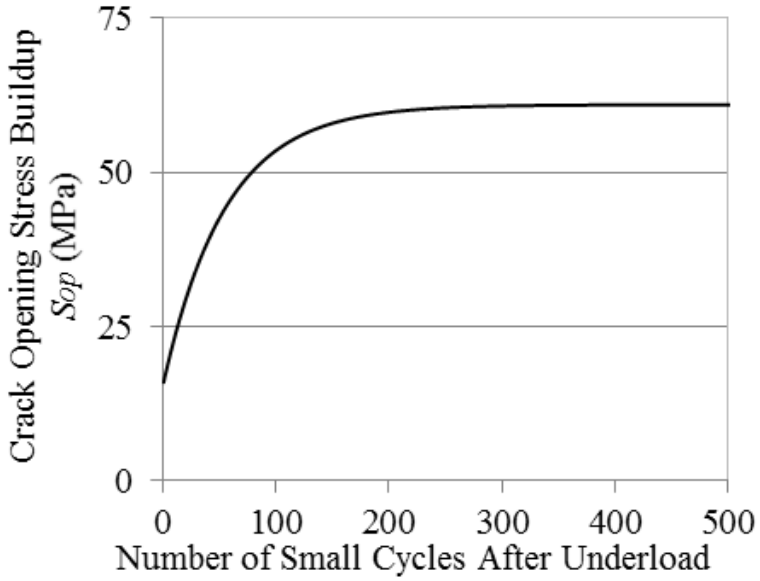
Fracture Mechanics Model (SBFM)
Smooth specimens testing results



21 CA (R=-1) tests

9 underload tests

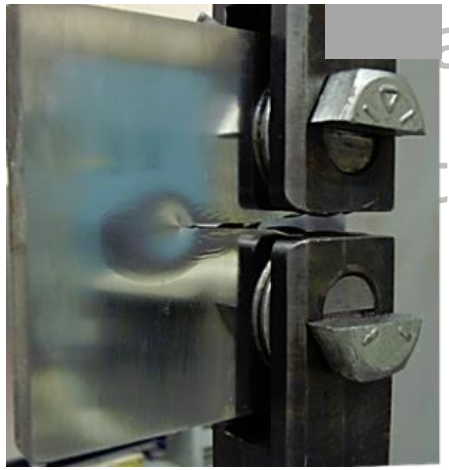


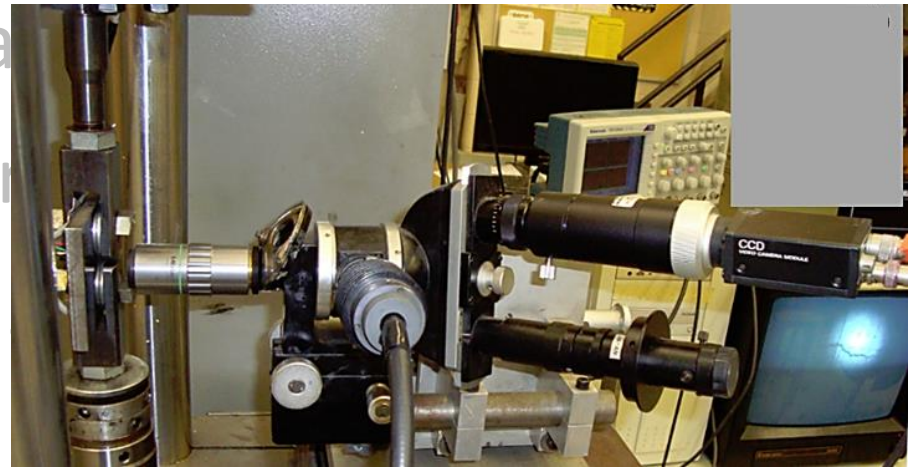


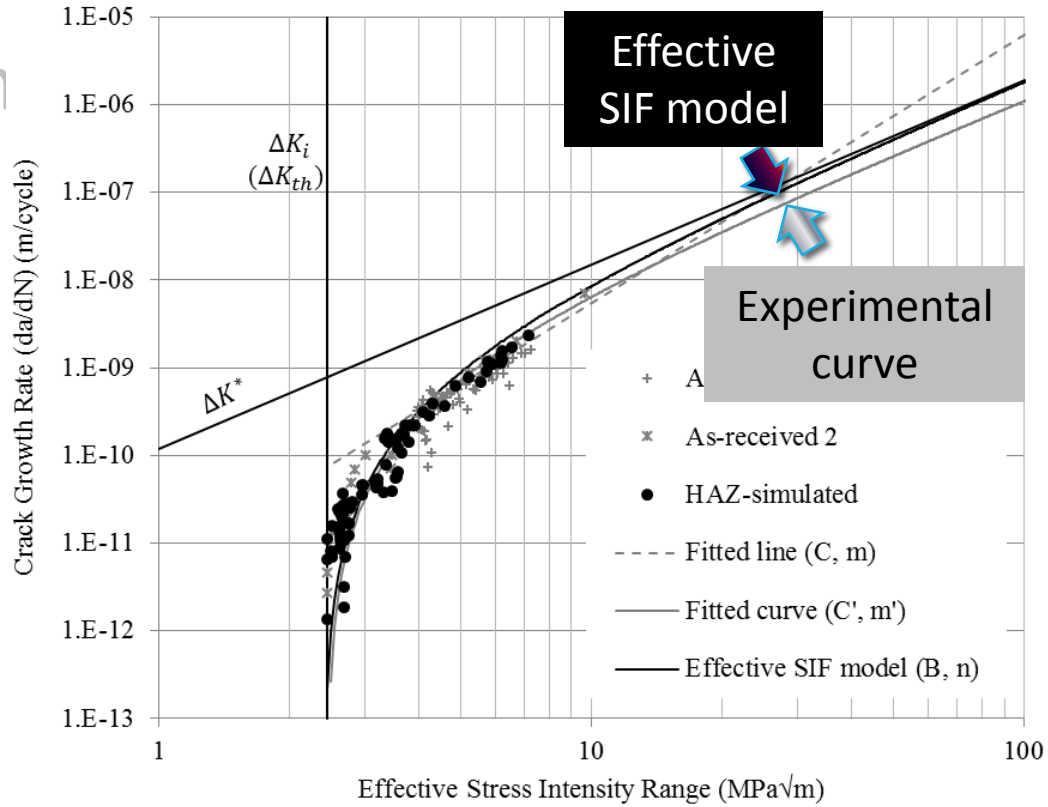
8 overload tests

Fracture Mechanics Model (SBFM)
Input parameters

- Material constants: E, Sy, σy, K', n'
- Crack closure/ opening stress param
- *Crack growth parameters: C, m, ΔKi*

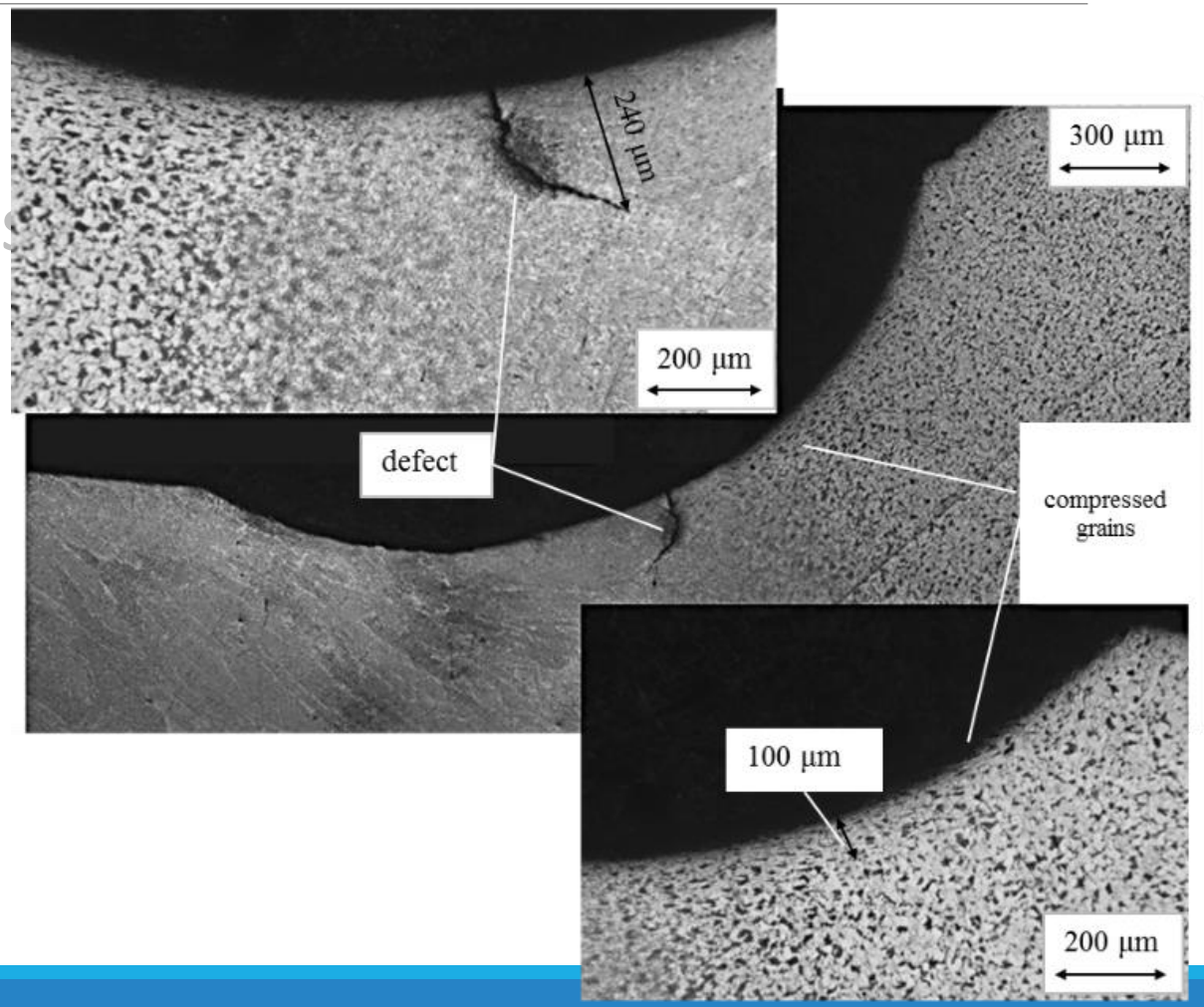






Fracture Mechanics Model (SBFM)
Input parameters

- Material constants: E, Sy, σy,
- Crack closure/ opening stress
- Crack growth parameters: C,
- *Initial crack size*
- Elastic stress concentration
- Residual stresses



Fracture Mechanics Model (SBFM)
Input parameters

- Material constants: E, Sy, σy, K', n'
- Crack closure/ opening stress parameters: θ, ϕ, μ
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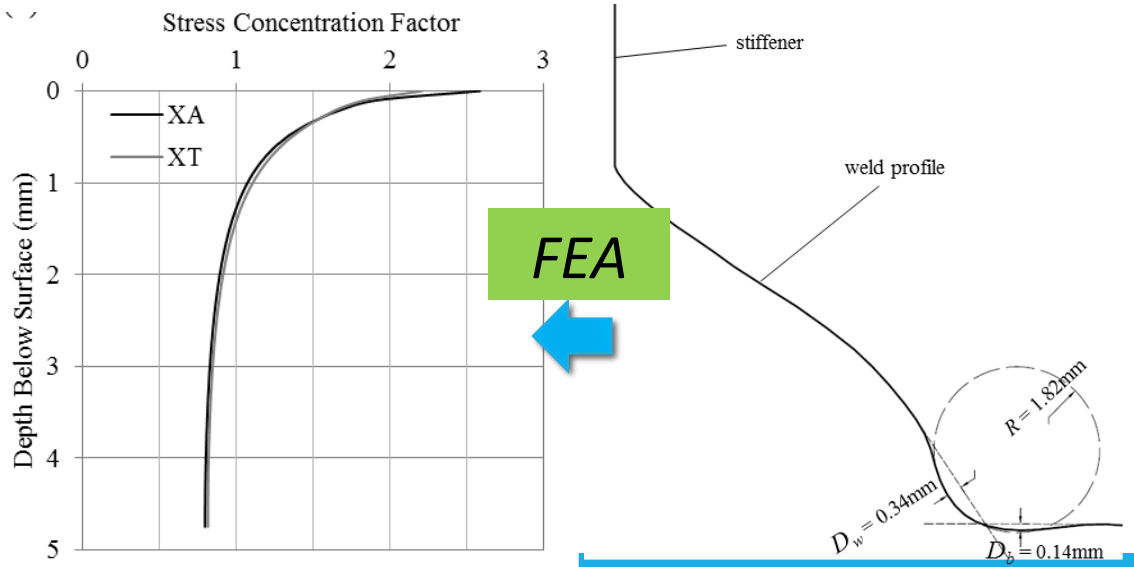
- Initial crack size
- *Elastic stress concentration*
- Residual stresses



Fracture Mechanics Model (SBFM)
Input parameters

- Material constants
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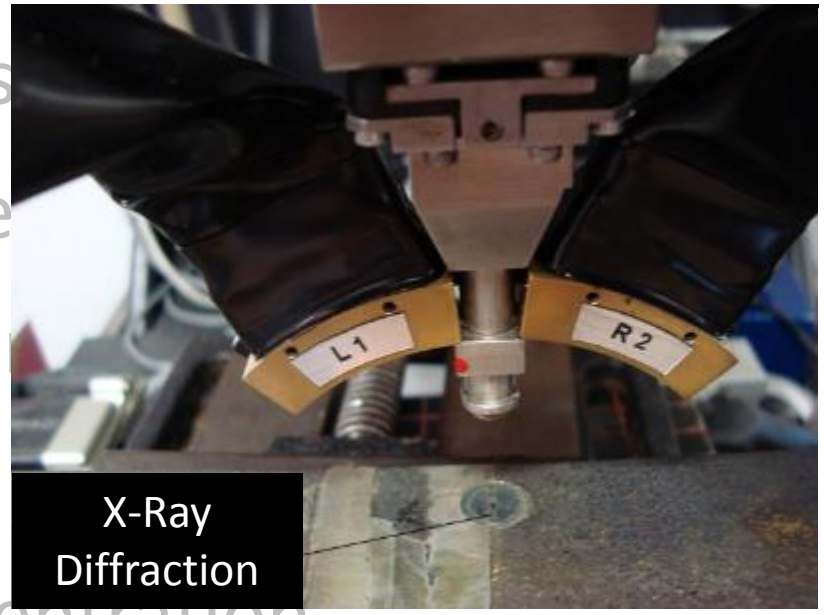
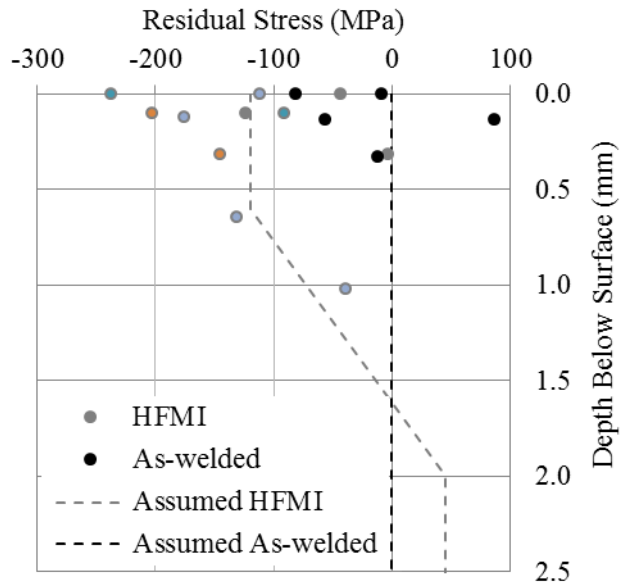
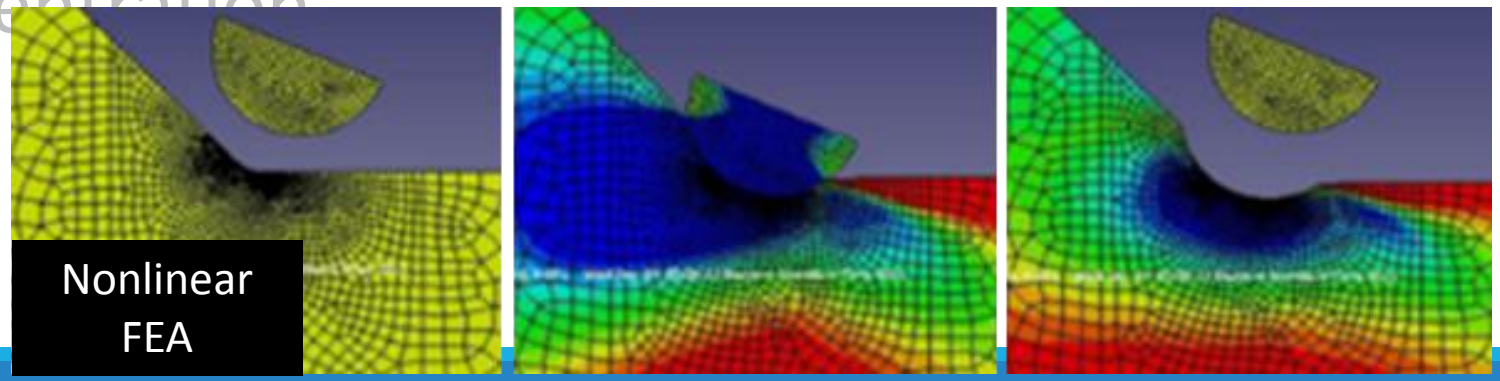
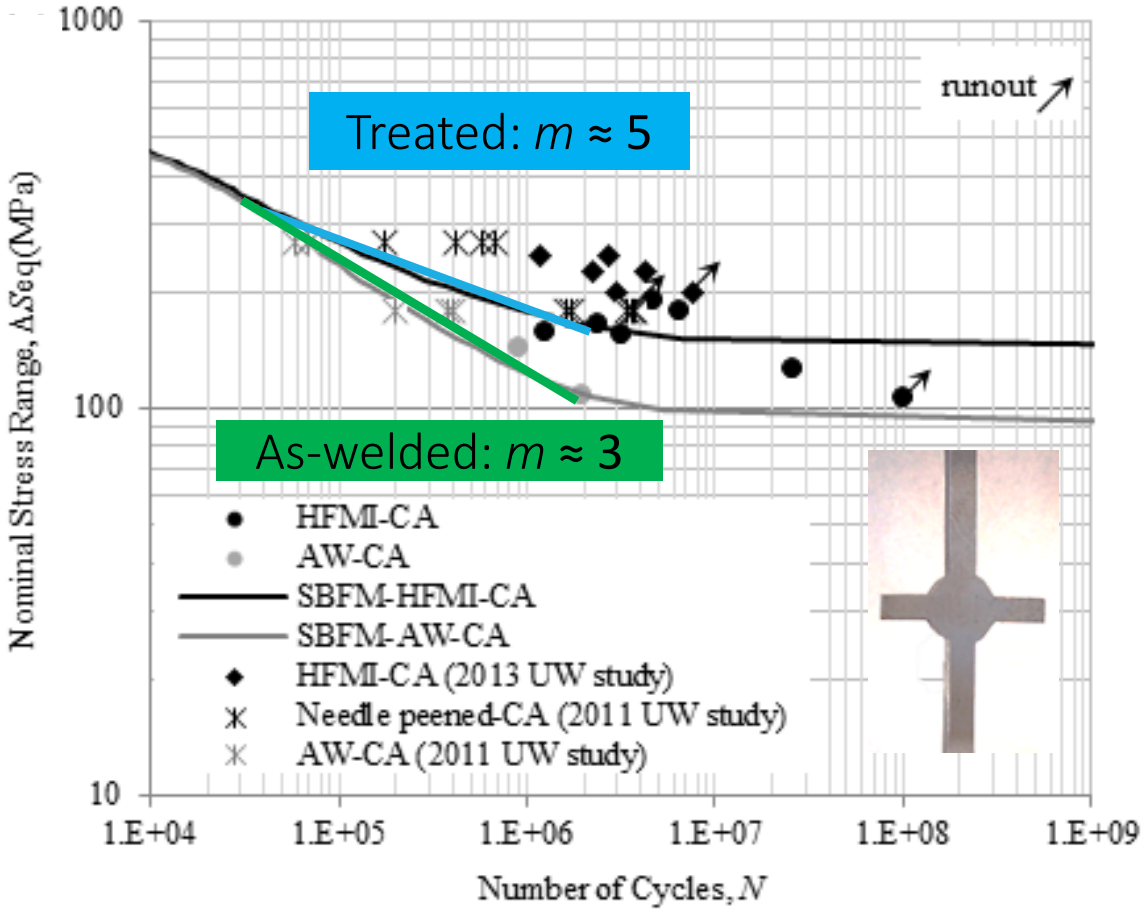
- *Residual stresses*



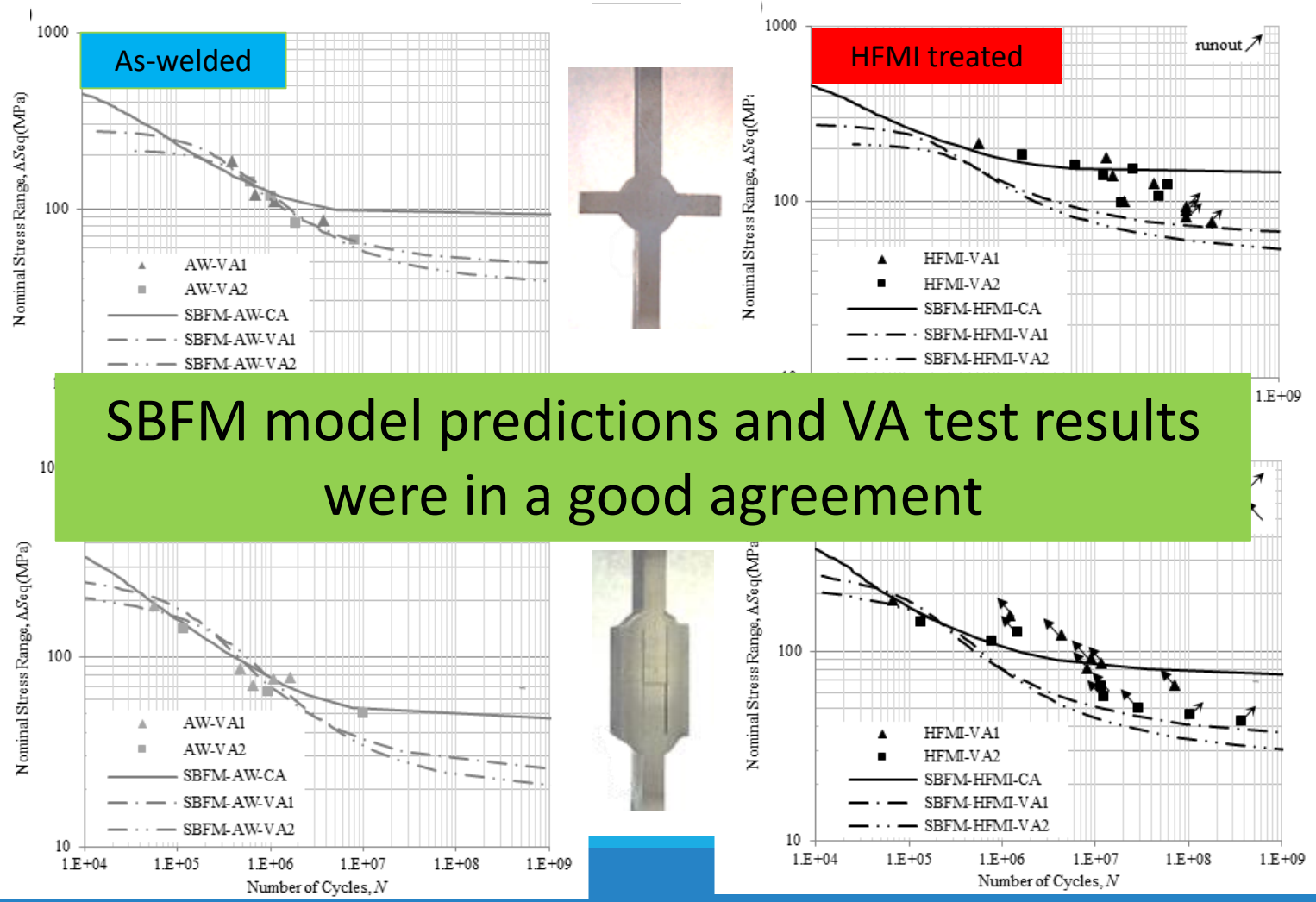




Fracture Mechanics Analysis (SBFM)
CA results



Fracture Mechanics Analysis (SBFM)
VA results



SBFM model predictions and VA test results were in a good agreement

Fracture Mechanics Analysis (SBFM)
Simulations for other load histories

Envelopes for *20* VA loading histories corresponding to simulations for other influence lines and bridge spans

Design recommendations for impact treated weld toes:

1- Single-sloped *S-N* design curves with m=5

2- No fatigue improvement under in-service loading for $N < 10^6$

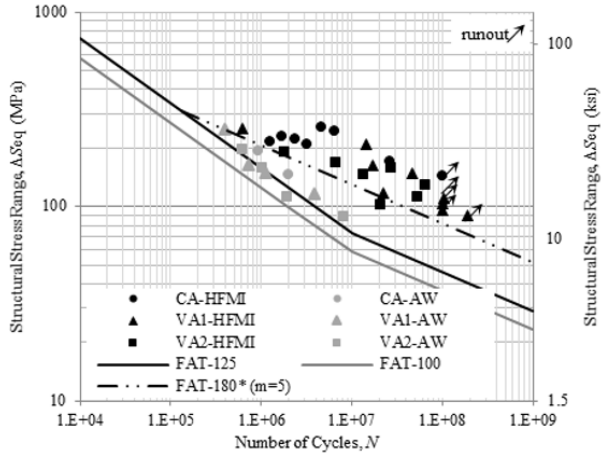
3- Limit the structural (local) maximum stress to $1.15f_y$

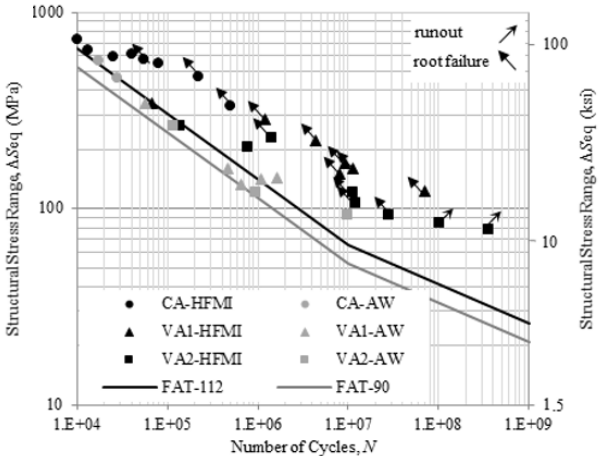
Outline

1) Fatigue of Metal Structures
2) Analysis of Impact Treated Weld Joints
3) *Local Stress Design Concept for Fatigue Design*

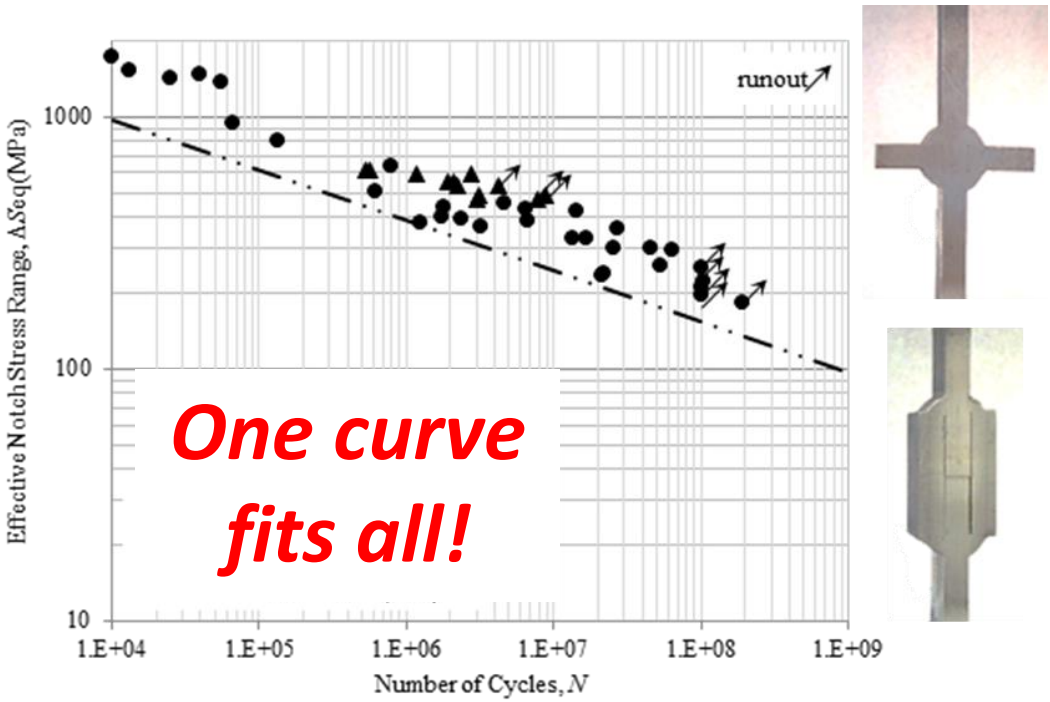
Local Stress Approach
Definitions for the local stress

Structural Stress





Effective Notch Stress



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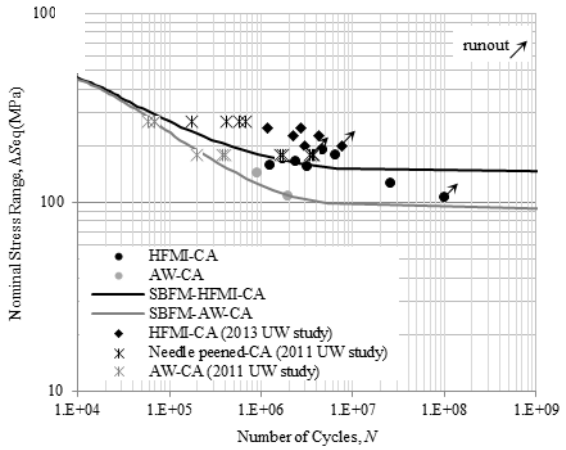
Local Stress Approach
A methodology to generate *S-N* curves

- Material testing
- Effective strain-life model
- Residual stress state
- Geometry measurements
- Elastic FE analysis

SBFM analysis

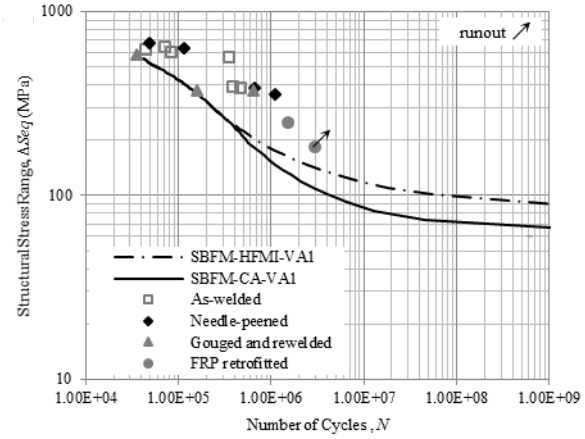


Small-scale fatigue tests

Local stress coefficient

$\times K_{st}$

Generate the local (e.g. structural) stress S-N curve



Publications

1. **K. Ghahremani**, S. Walbridge, & T. Topper. "A Methodology for Variable Amplitude Fatigue Analysis of Structural Welds Based on Fracture
2. R. Ranja … Fatigue Behavio
3. **K. Ghah** … Amplitude Loading
4. **K. Ghah** … echanical Impact (… ges 391-400.
5. M. Safa … Element Analysis
6. **K. Ghah** … sing FRP Angles",
7. R. Tehra … Performance of Ultras
8. **K. Ghah** … Retrofitted Steel Hig
9. **K. Ghah** … ariable Amplitu

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A methodology for variable amplitude fatigue analysis of HFMI treated welds based on fracture mechanics and small-scale experiments

Kasra Ghahremani *, Scott Walbridge, Tim Topper

Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, ON, Canada

Questions…

Results – Design recommendations

Effective notch stress