GREAT DESIGNS IN STEEL

A GENERALIZED STRESS PARAMETER APPROACH FOR FATIGUE LIFE PREDICTION OF WELDED JOINTS

Xiao Wu, Siva Vayugundla, Hong-Tae Kang

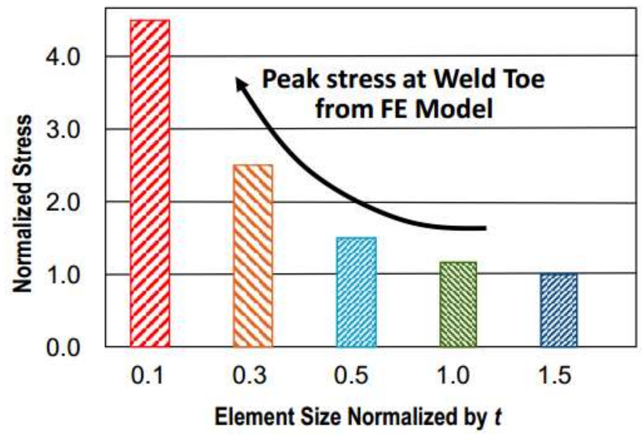
A/SP Fatigue Committee Members

CONTENTS

- Objective
- Part I. Method Development
  - Stress intensity factors
  - Fracture mechanics-based generalized stress parameter (GSP) approach
  - Comparison with structural stress methods
- Part II. Validation and Application
  - Consolidation of coupon fatigue test results
  - Life prediction of welded component
- Conclusions

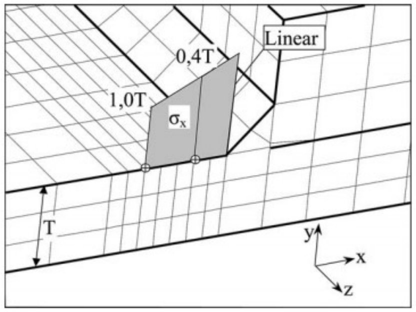
OBJECTIVE

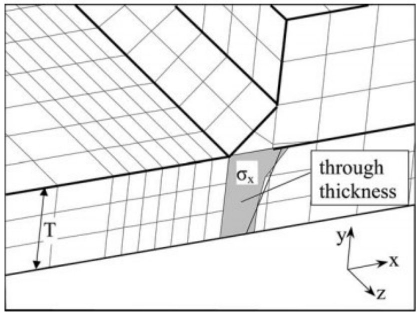
- Background:
  - Fatigue failure is a common failure mechanism in welded joints, which are often the weakest areas due to stress concentration



- Current methods:
  1. FEA stress output (mesh-sensitive)
  2. Stress intensity factor (time-consuming)
  3. Structural stress
     - Linear surface extrapolation
     - Linearization through thickness
     - Nodal force-based structural stress

Only considers global geometry effect





[1] Battelle structural stress training, 2016
[2] Finite element methods for structural hot spot stress determination—a comparison of procedures

OBJECTIVE

- To develop and validate a fatigue life prediction model for welded joints
  - CAE effectiveness
  - Including the effects of local weld geometric parameters on fatigue life prediction
  - Comparable to current methods

Part I. Method Development

WORKFLOW

1. $K = (Y_m \sigma_m + Y_b \sigma_b)\sqrt{\pi a}$

3. $\frac{da}{dN} = C(\Delta K)^m$

Structural stress σ

SIF K

Fatigue life N

2. Weight function

STRESS INTENSITY FACTORS

Relations between SIF and structural stress:

$$K = (Y_m \sigma_m + Y_b \sigma_b)\sqrt{\pi a}$$

Y_m and Y_b are geometric correction factors under pure tension and pure bending, respectively

$$\sigma_m = \sigma_s - \sigma_b = (1 - r_b)\sigma_s$$

$$\sigma_b = r_b \sigma_s$$

SIF can be calculated from stress through Y_m and Y_b, vice versa.

σ_s: structural stress

r_b: bending ratio (=σ_b/σ_s)

[4] D. Radaj, C.M. Sonsino, W. Fricke, Fatigue assessment of welded joints by local approaches, Woodhead publishing, 2006.

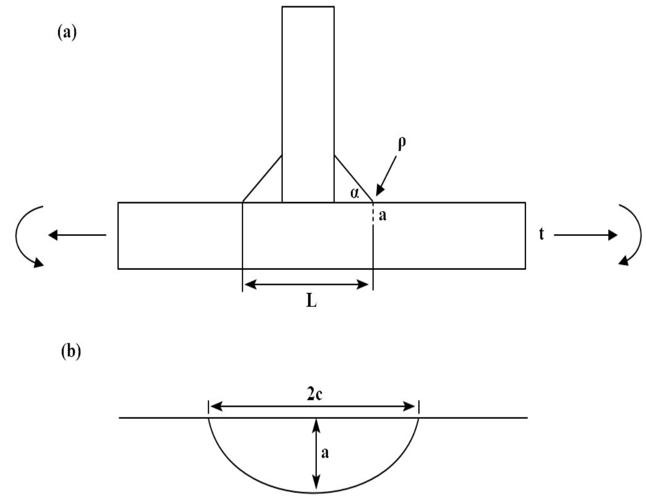
STRESS INTENSITY FACTORS

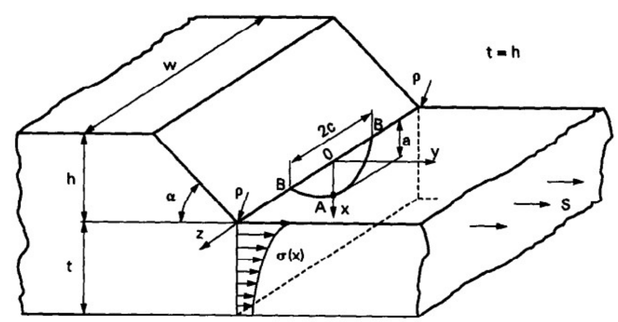
SIFs are calculated using weight function method

$$K = \int_0^a \sigma(x) m\left(x, \frac{a}{t}, \frac{a}{c}, \alpha\right) dx$$

$m\left(x, \frac{a}{t}, \frac{a}{c}, \alpha\right)$ is the weight function provided by Niu and Glinka

$\sigma(x)$ is the normal stress distribution on the un-cracked cross-section at the critical point of the welded plate. Mode I failure is assumed





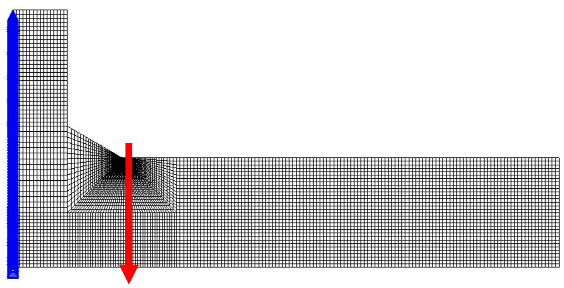
[5] X. Niu, G. Glinka, Theoretical and experimental analyses of surface fatigue cracks in weldments, in: Surface-Crack Growth: Models, Experiments, and Structures, ASTM International, 1990.

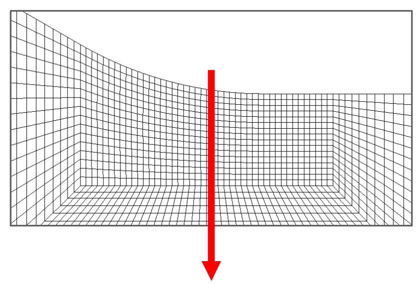
STRESS INTENSITY FACTORS

FEA stress analysis

Weld angle $\alpha = 30°, 45°$, and $60°$ and weld toe radius $\rho/t = 0.1, 0.3$, and 0.5

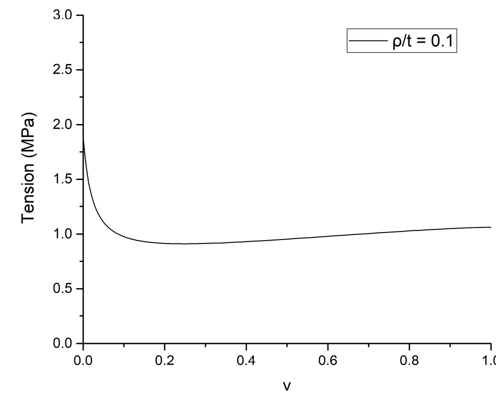
$$K = \int_0^a \sigma(x) m\left(x, \frac{a}{t}, \frac{a}{c}, \alpha\right) dx$$



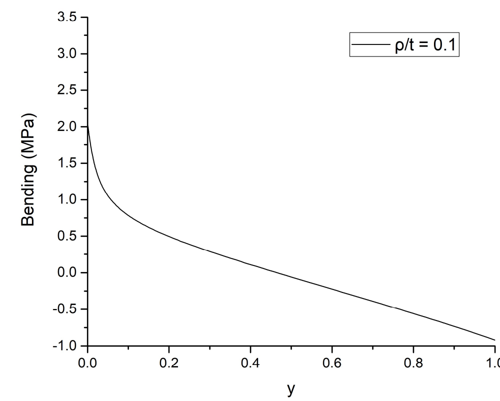


Stress distribution at weld toe

Tension



Bending



STRESS INTENSITY FACTORS

Consider two cases:

1. Tension only

$$K = \int_0^a \sigma(x) m\left(x, \frac{a}{t}, \frac{a}{c}, \alpha\right) dx$$

$$K = Y_m \sigma_m \sqrt{\pi a}$$

Y_m is obtained

2. Bending only

$$K = \int_0^a \sigma(x) m\left(x, \frac{a}{t}, \frac{a}{c}, \alpha\right) dx$$

$$K = Y_b \sigma_b \sqrt{\pi a}$$

Y_b is obtained

STRESS INTENSITY FACTORS

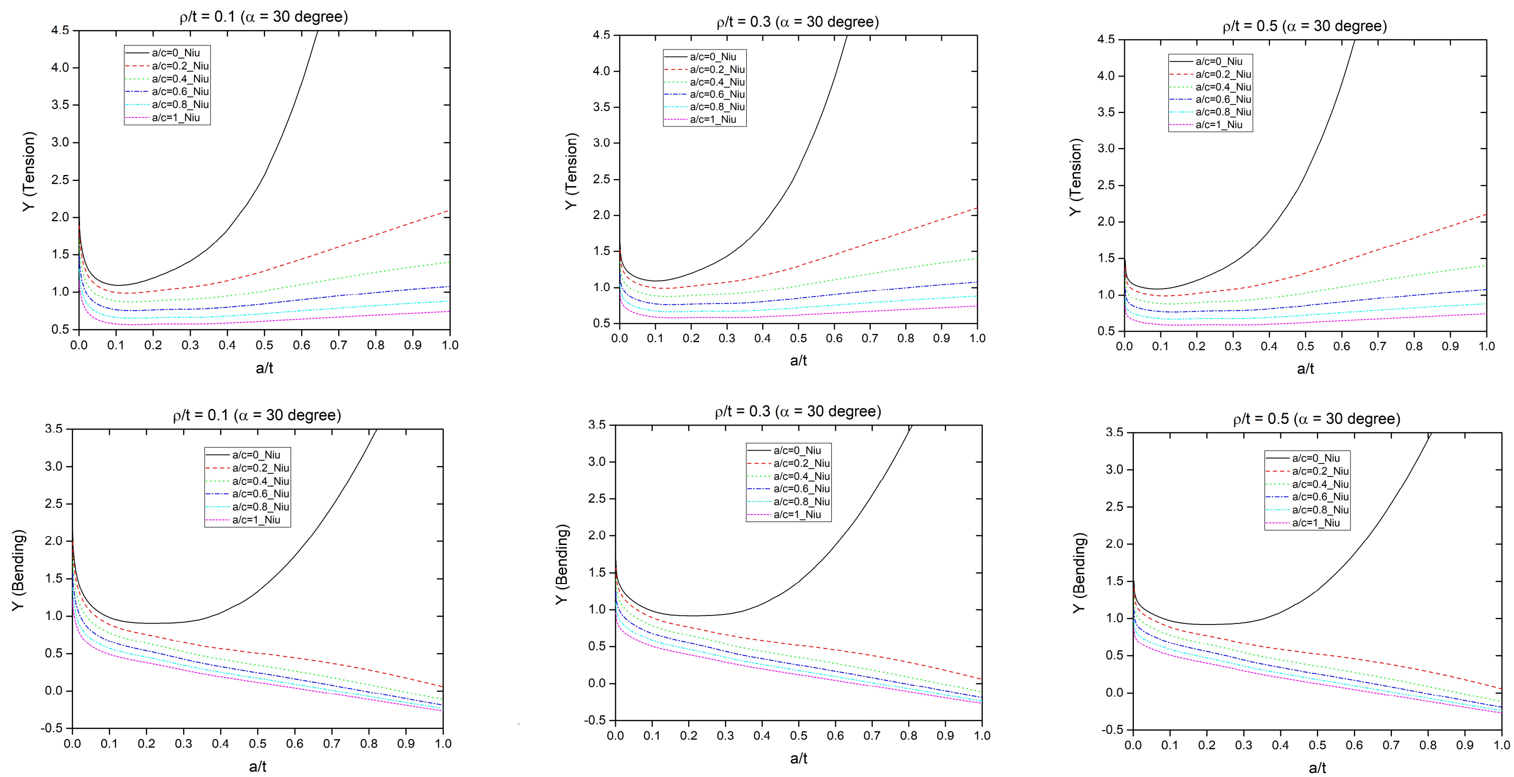
Distribution of Y_m and Y_b ($\alpha = 30°$)

a/c=0_Niu
a/c=0.2_Niu
a/c=0.4_Niu
a/c=0.6_Niu
a/c=0.8_Niu
a/c=1_Niu

(a) $\rho/t = 0.1$ (b) $\rho/t = 0.3$ (c) $\rho/t = 0.5$

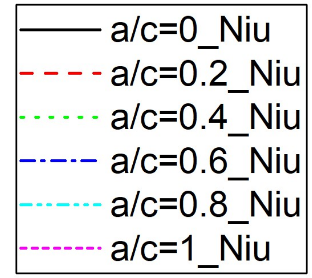
Y_m

Y_b



STRESS INTENSITY FACTORS

Distribution of Y_m and Y_b ($\alpha = 45°$)

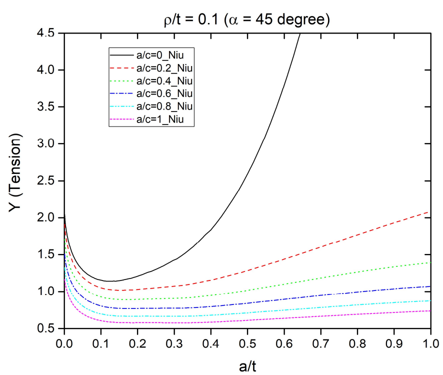


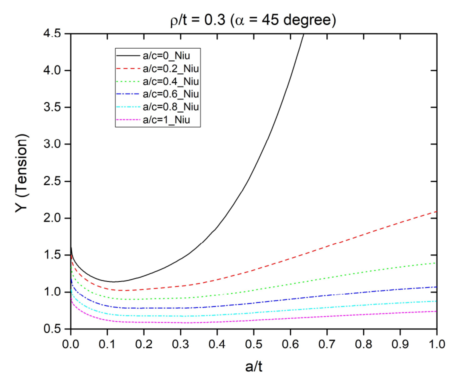
(a) $\rho/t = 0.1$

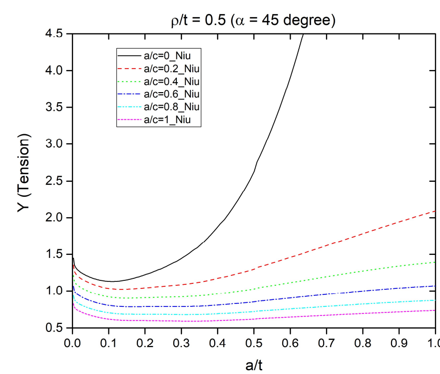
(b) $\rho/t = 0.3$

(c) $\rho/t = 0.5$

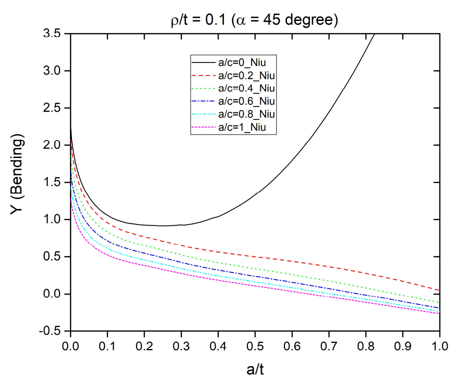
Y_m

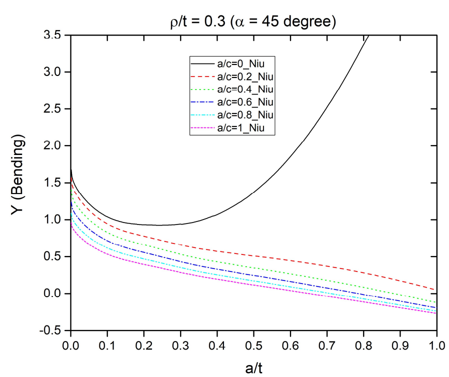


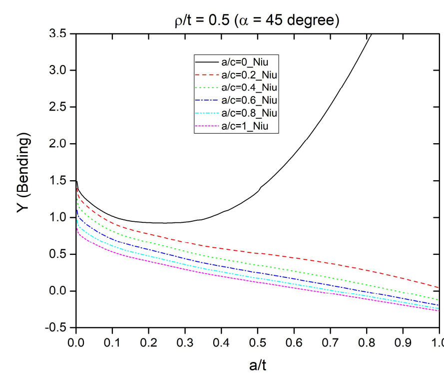




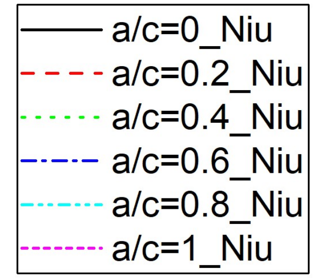
Y_b







STRESS INTENSITY FACTORS

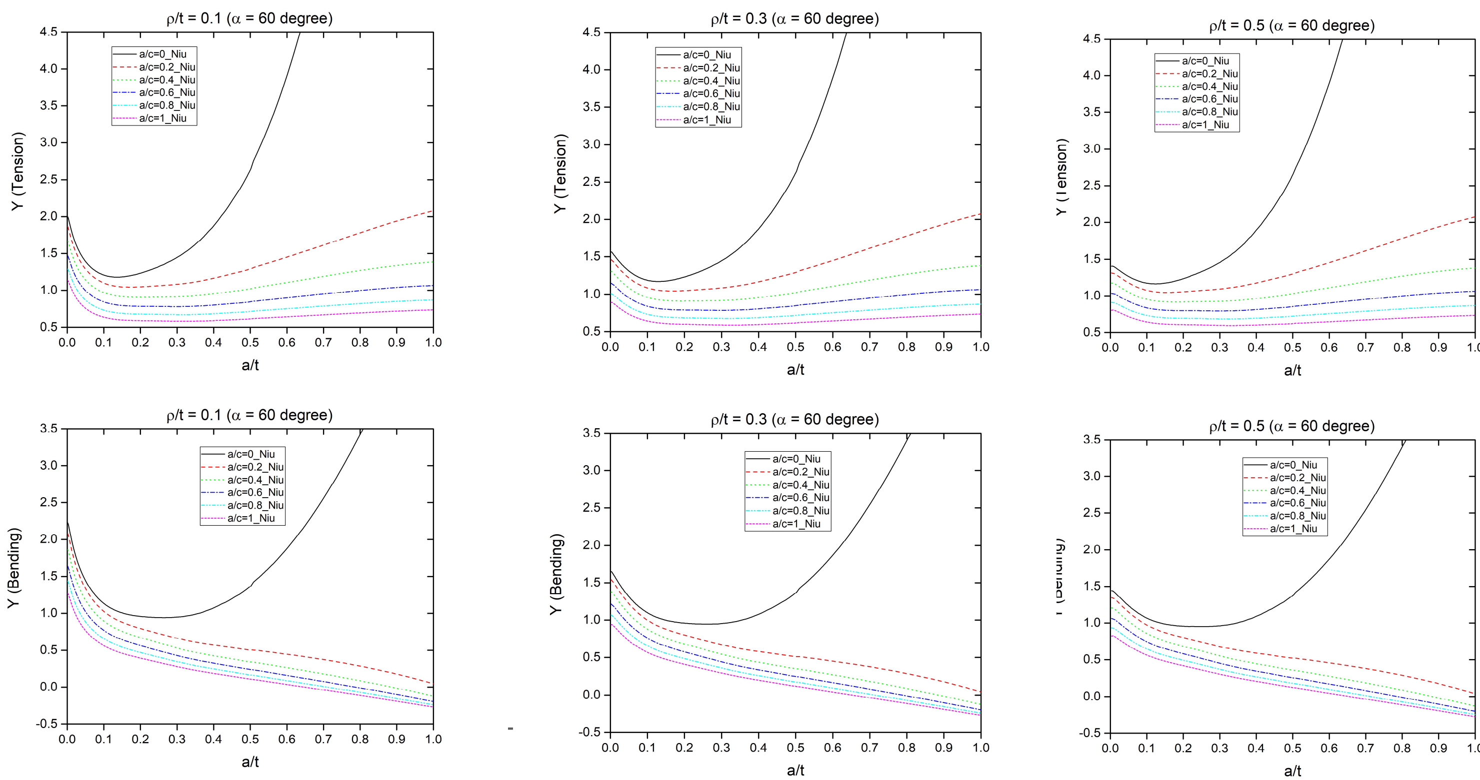


Distribution of Y_m and Y_b ($\alpha = 60°$)

(a) $\rho/t = 0.1$ (b) $\rho/t = 0.3$ (c) $\rho/t = 0.5$

Y_m

Y_b



GENERALIZED STRESS PARAMETER APPROACH

GDIS

Fatigue life can be estimated by integrating the Paris' Law

$$\frac{da}{dN} = C(\Delta K)^m$$
$$\Delta K = (Y_m \Delta\sigma_m + Y_b \Delta\sigma_b)\sqrt{\pi a}$$

$$N = \int \frac{1}{C(\Delta K)^m} da = \frac{1}{C} \cdot t^{1-\frac{m}{2}} \cdot (\Delta\sigma_s)^{-m} \cdot \int \frac{1}{\left(\sqrt{\frac{\pi a}{t}}\,[Y_m(1-r_b) + Y_b r_b]\right)^m} d\left(\frac{a}{t}\right)$$

$$= \frac{1}{C} \cdot t^{1-\frac{m}{2}} \cdot (\Delta\sigma_s)^{-m} \cdot I$$

$I = \int \frac{1}{\left(\sqrt{\frac{\pi a}{t}}[Y_m(1-r_b)+Y_b r_b]\right)^m} d\left(\frac{a}{t}\right)$ is the crack propagation integral

GENERALIZED STRESS PARAMETER APPROACH

Note:

1. $I = \int \frac{1}{\left(\sqrt{\frac{\pi a}{t}}[Y_m(1-r_b)+Y_b r_b]\right)^m} d\left(\frac{a}{t}\right)$

2. Y_m and Y_b are in terms of weld angle α, weld toe radius $\frac{t}{\rho}$ and crack aspect ratio $\frac{a}{c}$

We have

$$\Delta S = \frac{t^{\frac{m-2}{2m}}}{I\left(r_b, \alpha, \frac{\rho}{t}, \frac{a}{c}\right)^{\frac{1}{m}}} \Delta\sigma_s$$

Thickness effect

Global geometric effect

Loading mode effect

Local geometric effect

[4] S. Maddox, Assessing the significance of flaws in welds subject to fatigue, Welding Journal, 53 (1974).

GENERALIZED STRESS PARAMETER APPROACH

$I\left(r_b, \alpha, \frac{\rho}{t}, \frac{a}{c}\right) = \int_{a_i/t}^{a_f/t} \frac{1}{\left(\sqrt{\frac{\pi a}{t}}[Y_m(1-r_b)+Y_b r_b]\right)^m} d\left(\frac{a}{t}\right)$ is the crack propagation integral

Carrying out numerical integrations on $I\left(r_b, \alpha, \frac{\rho}{t}, \frac{a}{c}\right)^{\frac{1}{m}}$ with $a_i/t = 0.01,\ a_f/t = 0.8$, a/c assumed to be 0.25, and the fatigue crack growth factor m is taken as 3.6 for steel, a simple parametric expression is obtained by multivariate regression

Weld angle effect

$$I\left(r_b, \alpha, \frac{\rho}{t}\right)^{\frac{1}{m}} = e^{6.939 r_b - 8.174} + 0.097 r_b - 0.415\alpha + 0.066\frac{\rho}{t} + 0.496 * \alpha * \frac{\rho}{t} + 1.581$$

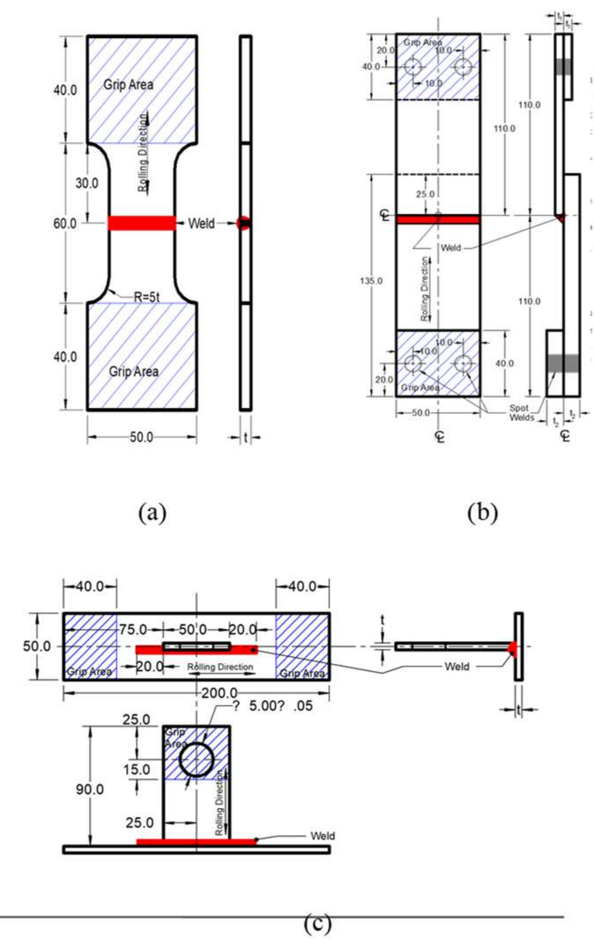
Bending ratio effect

Weld toe radius effect

Part II. Validation and Application

COUPON FATIGUE TEST RESULTS

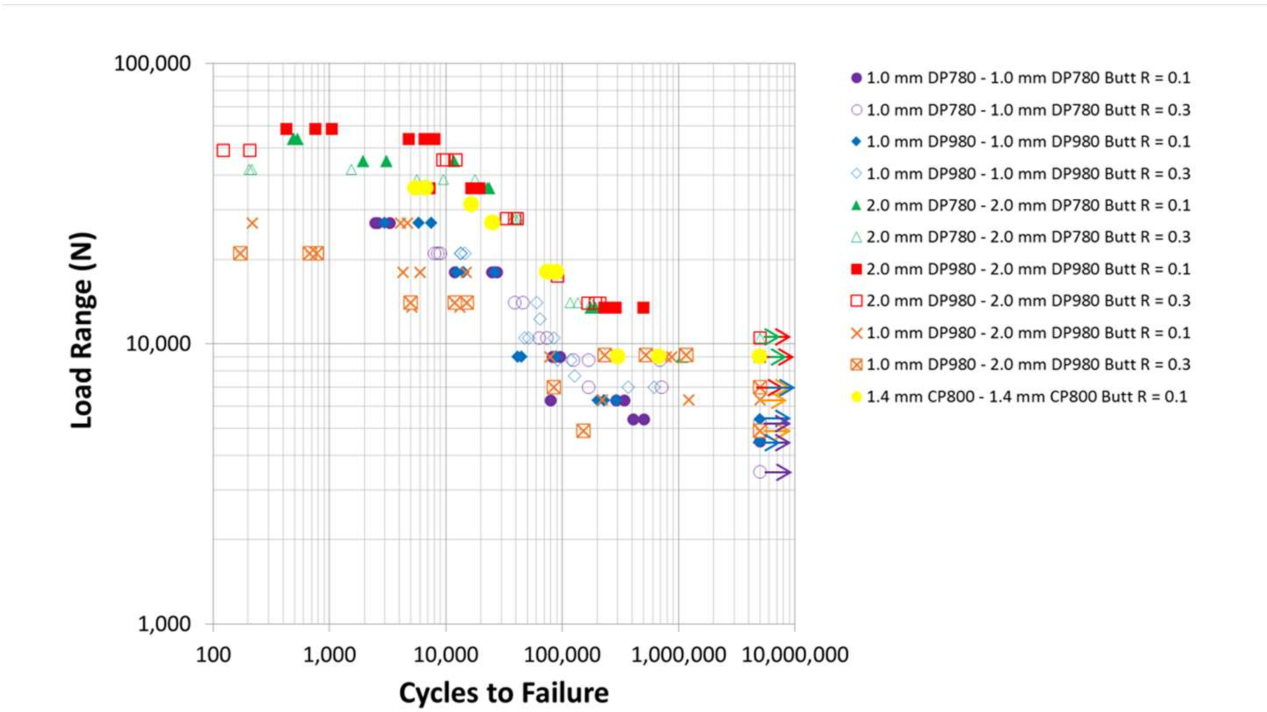
- Gas metal arc welding (GMAW)
- Advanced high strength steel (AHSS)
  - 4 different steel grades (DP780, DP980, CP800, HRPO)
  - 3 different specimen types
  - 5 equal thickness combinations
  - 2 unequal thickness combinations
  - 2 loading ratios (R=0.1 and R=0.3)

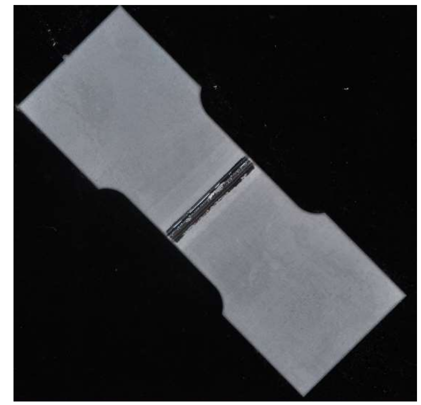


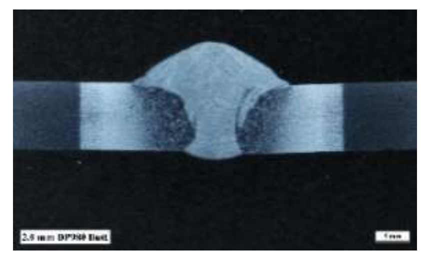
Joint types	Thickness combinations						
Butt joint	1mm-1mm	2mm-2mm	1mm-2mm	1.4mm-1.4mm	-	-	-
Lap joint	1mm-1mm	2mm-2mm	1mm-2mm	1.4mm-1.4mm	2.5mm-2.5mm	1.4mm-2.5mm	4.9mm-4.9mm
Fillet joint	1mm-1mm	2mm-2mm	1mm-2mm	1.4mm-1.4mm	2.5mm-2.5mm	-	4.9mm-4.9mm

COUPON FATIGUE TEST RESULTS

Butt Joint



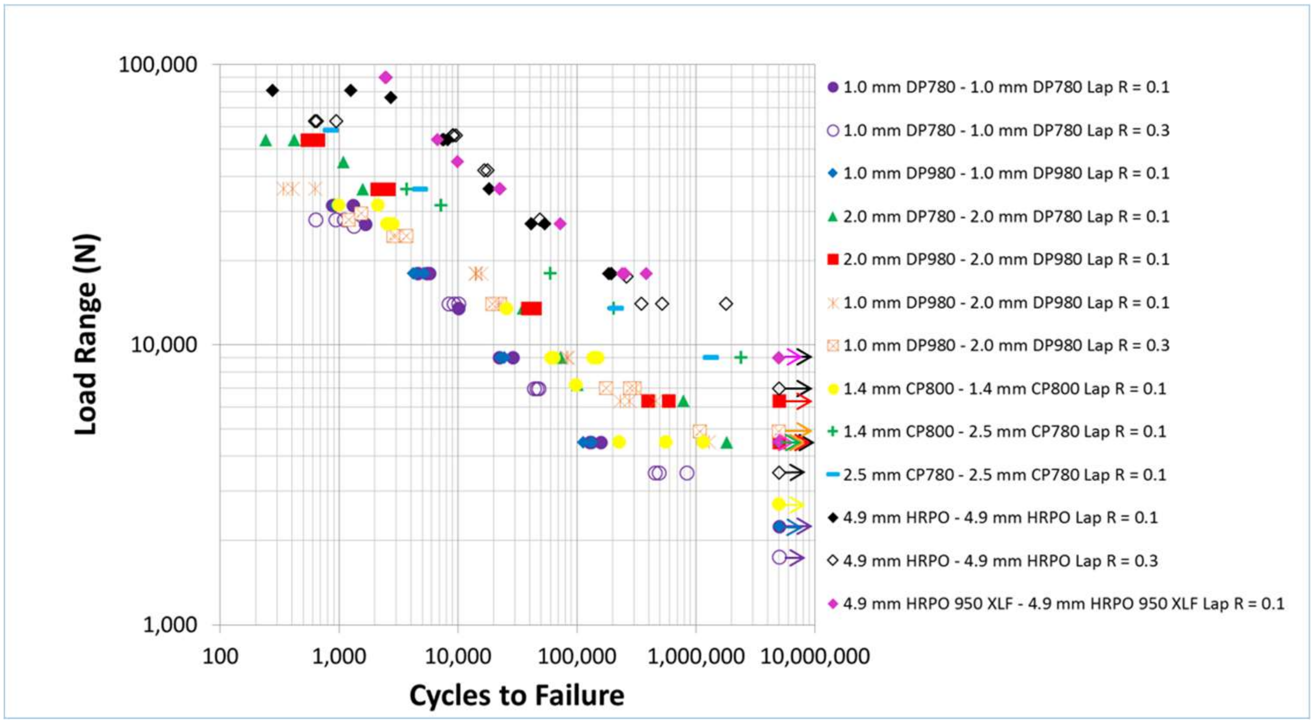


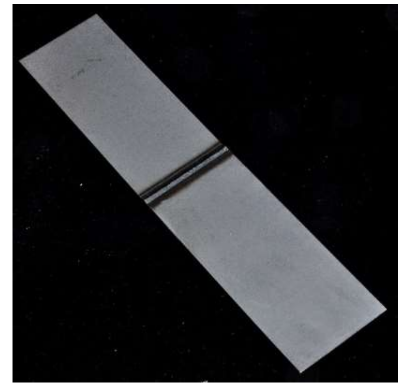


2.0 mm DP980
2.0 mm DP980

COUPON FATIGUE TEST RESULTS

Lap-Shear Joint

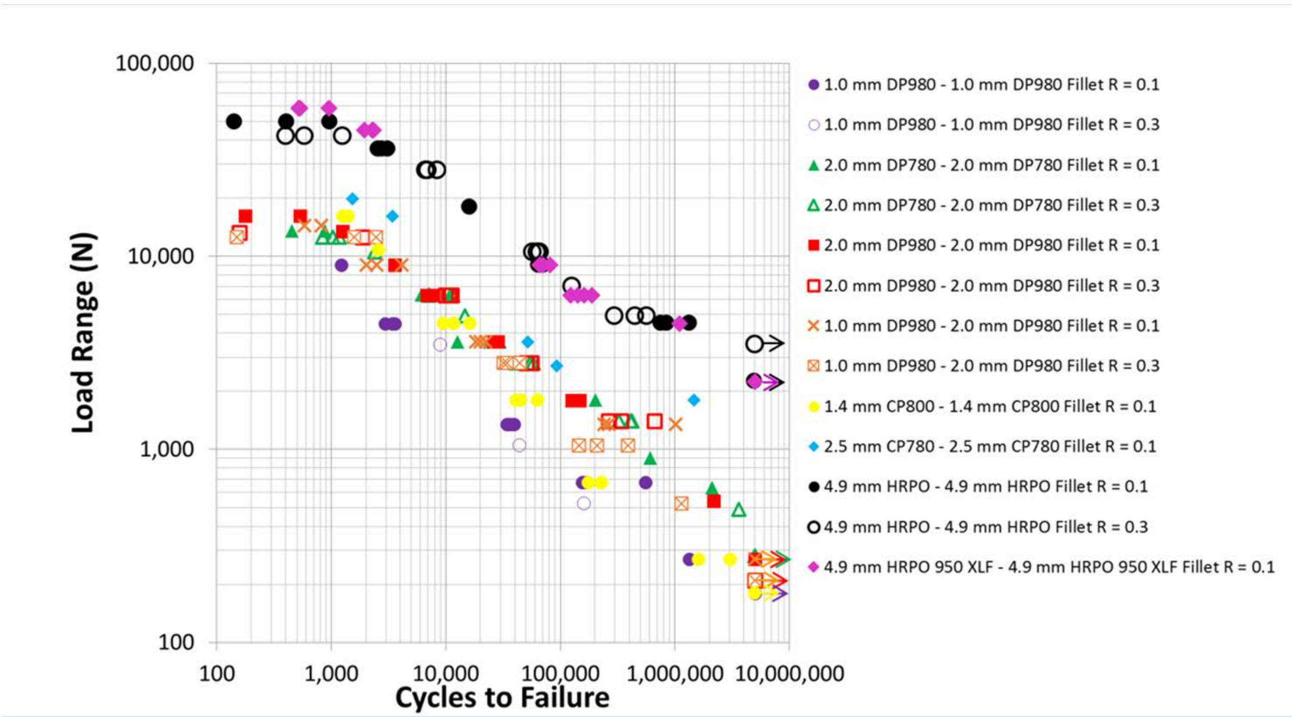


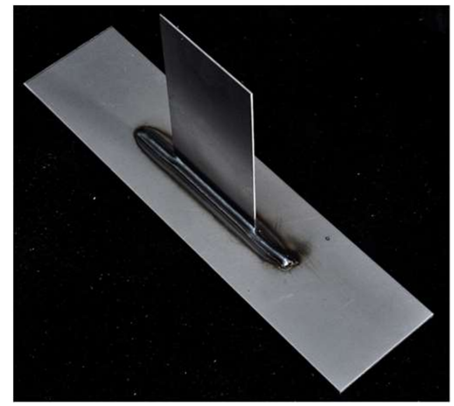


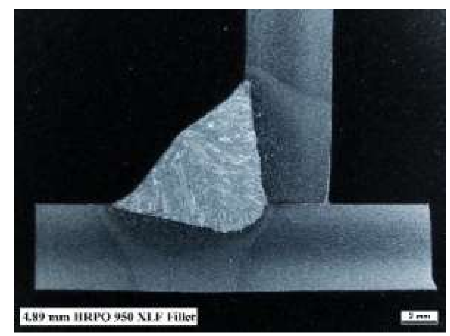
2.5 mm CP780
2.5 mm CP780

COUPON FATIGUE TEST RESULTS

Fillet Joint

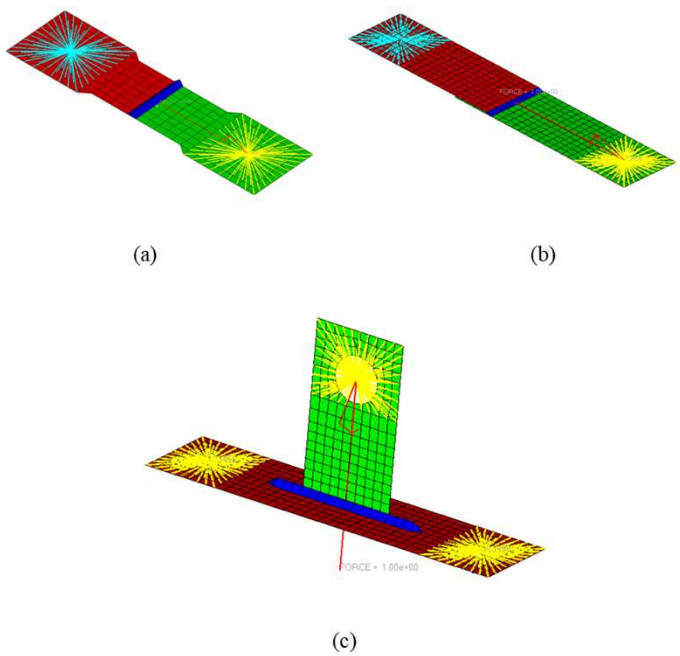




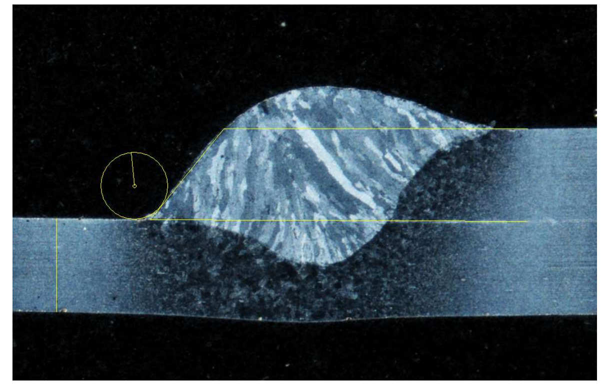


4.9 mm HRPO 950 XLF
4.9 mm HRPO 950 XLF

COUPON FATIGUE TEST RESULTS



Coarsely meshed models of (a) butt welded joint, (b) lap welded joint, and (c) fillet welded joint

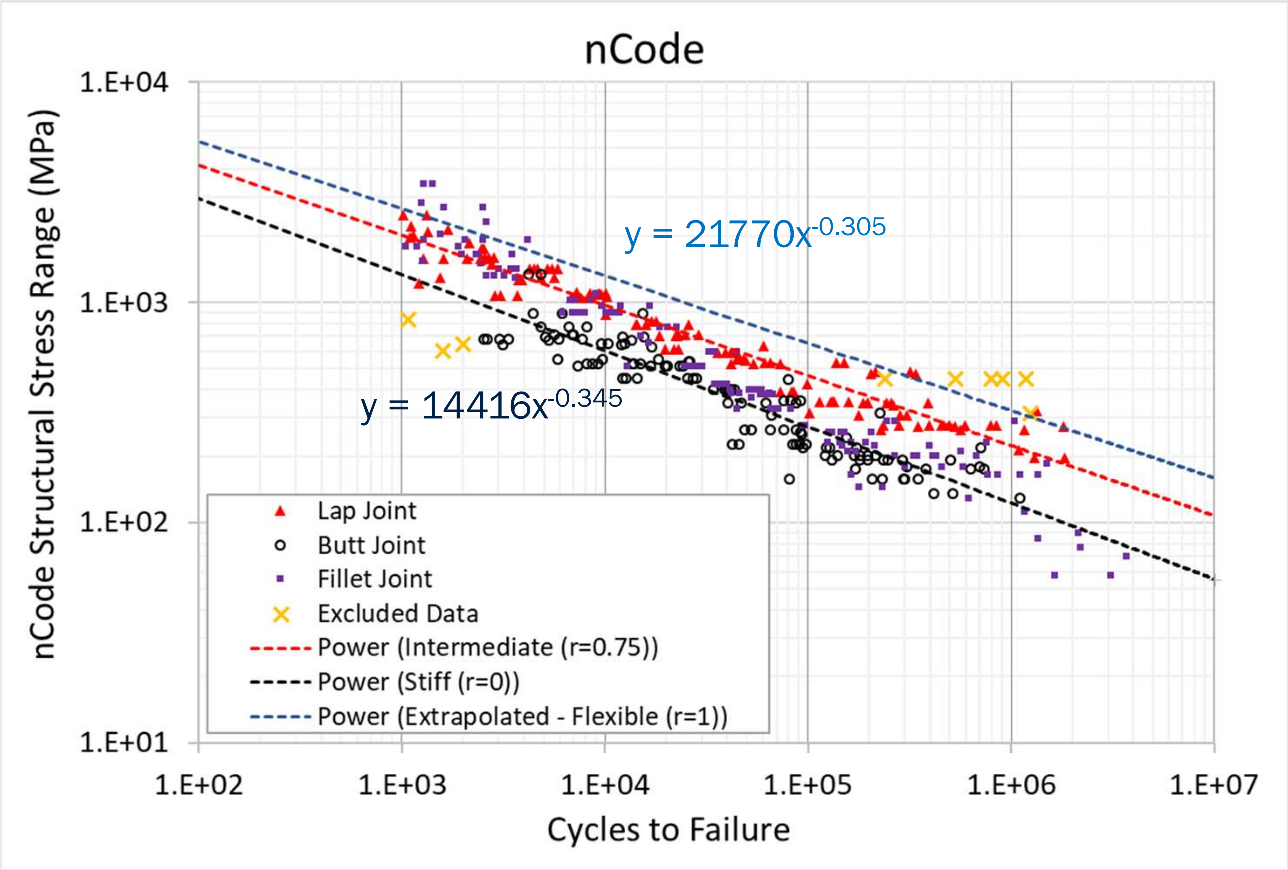


Cross-section photo of the lap joint with 1 mm thickness.

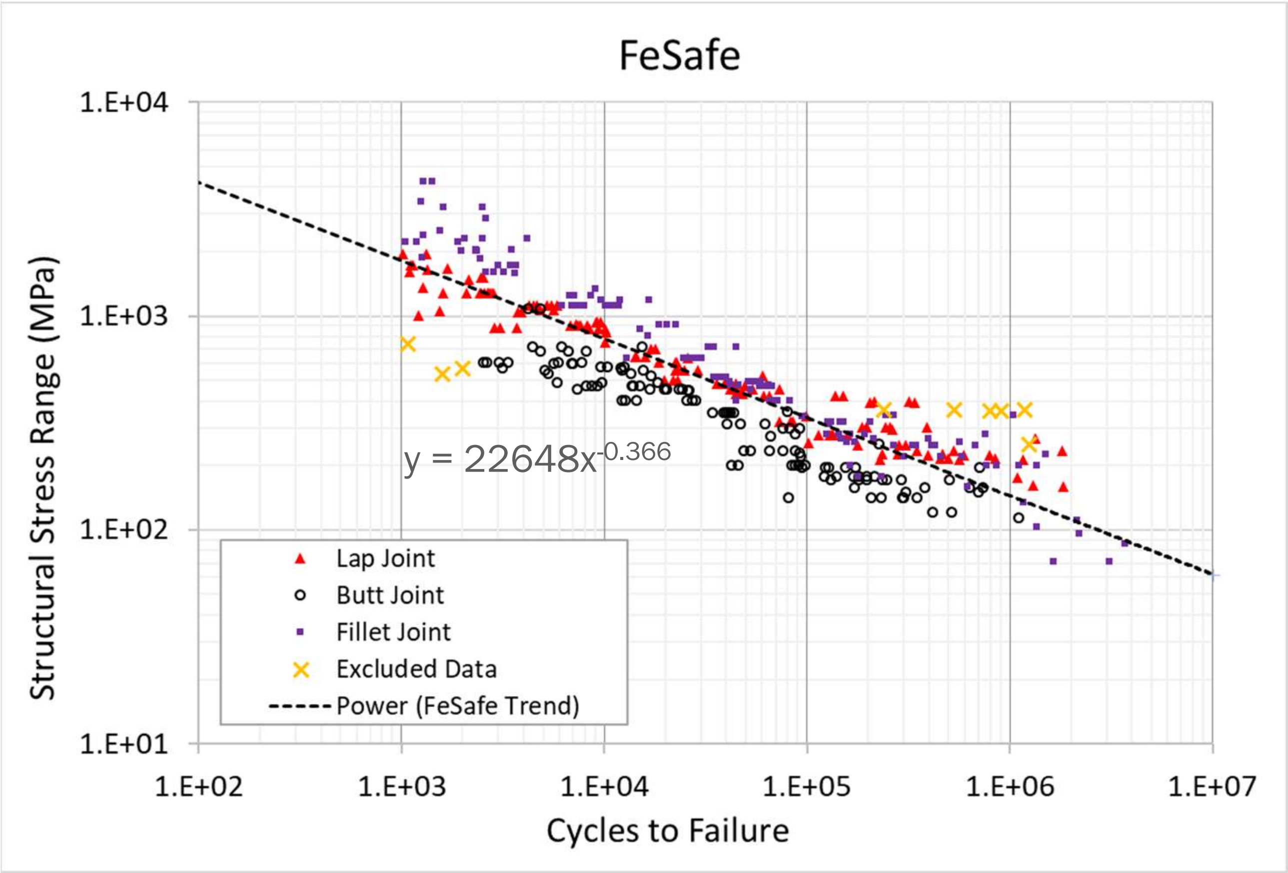
With local dimensions measured, (GSP) can be calculated as

$$\Delta S = \frac{t^{\frac{m-2}{2m}}}{I\left(r_b, \alpha, \frac{\rho}{t}\right)^{\frac{1}{m}}} \Delta\sigma_s$$

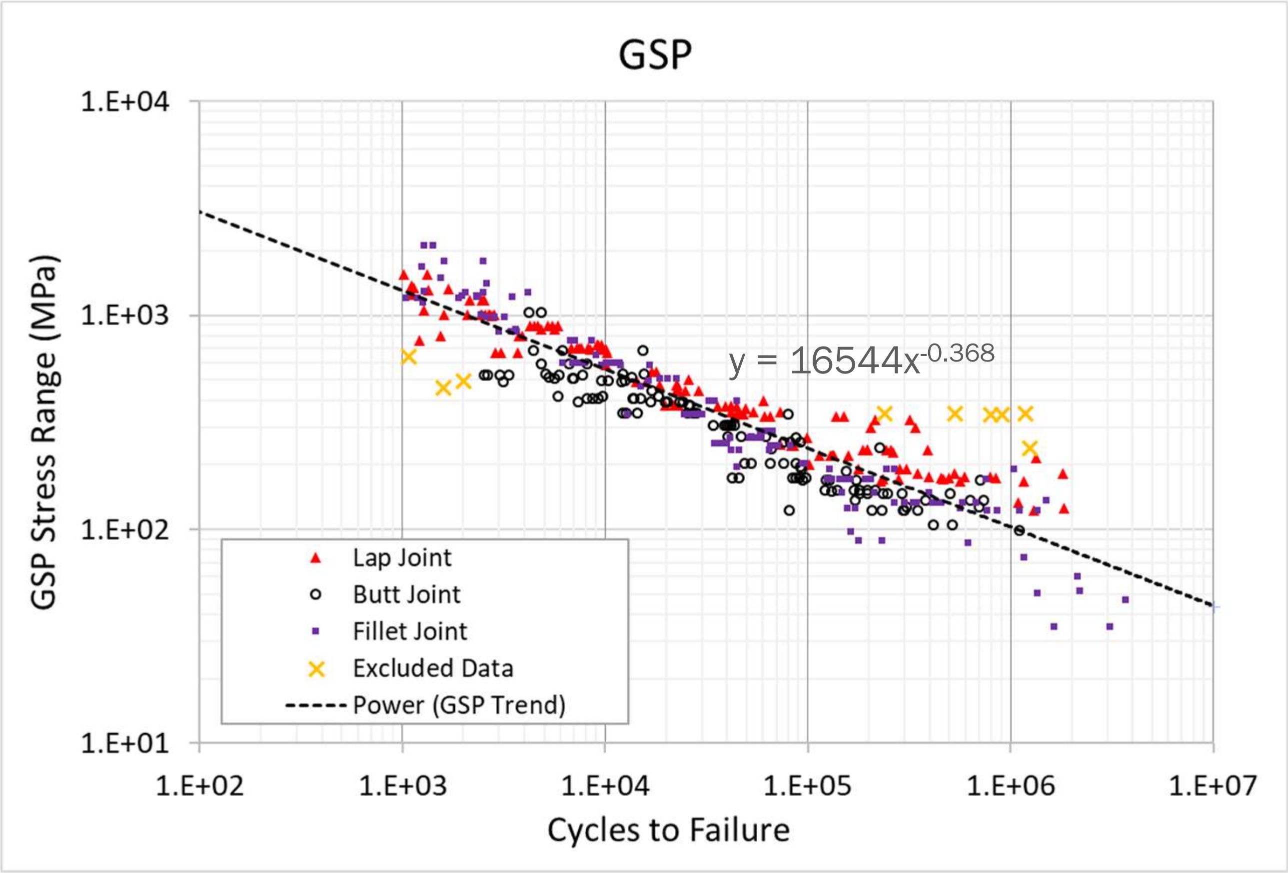
S-N Curves for nCode DesignLife



S-N Curve for Fe-Safe

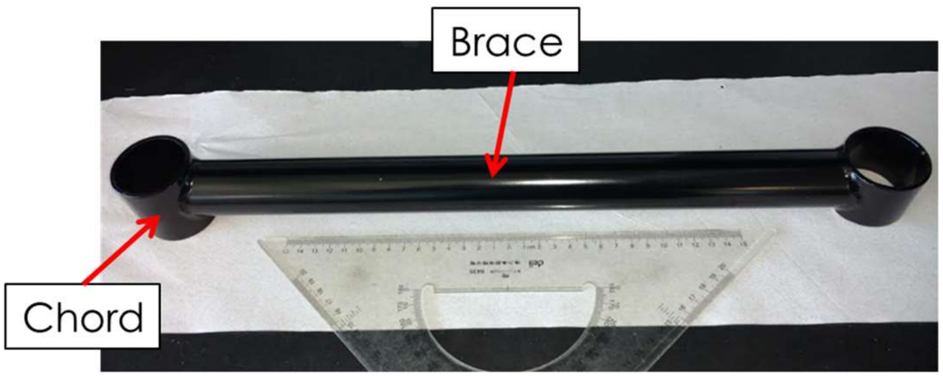


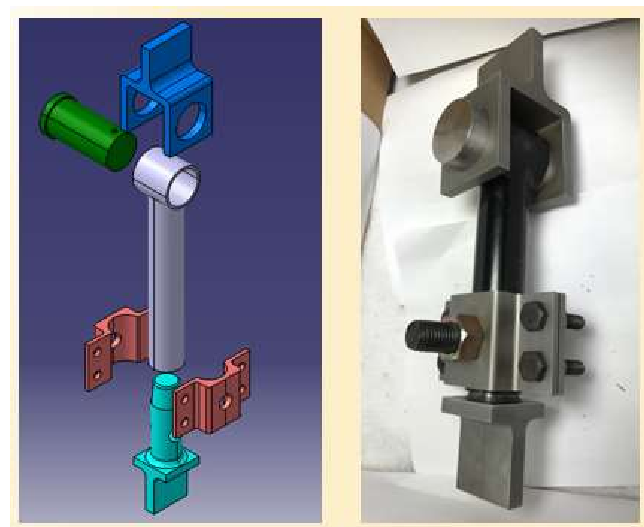
S-N Curve for GSP



Life Prediction of Welded Component

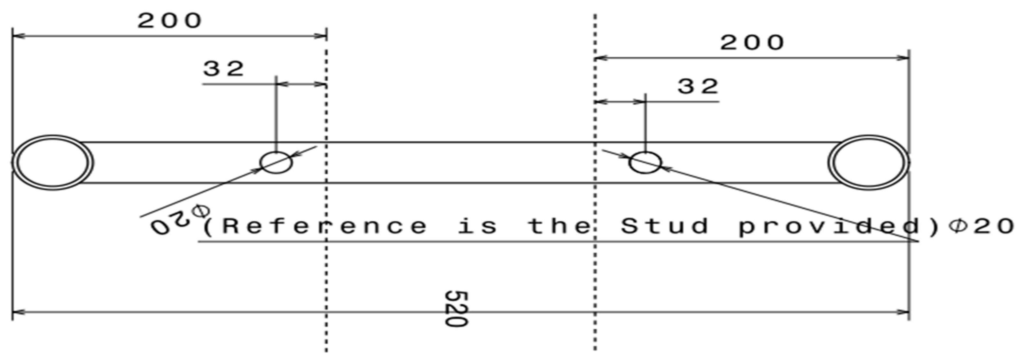
Production control arm which has a tubular construction was chosen for testing and validation

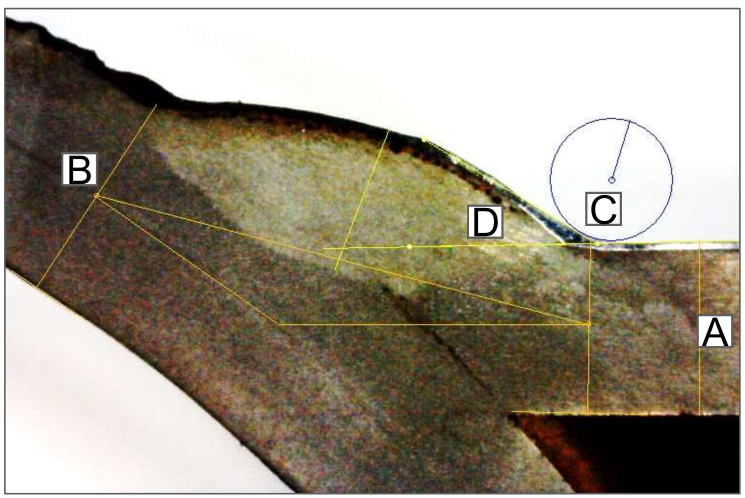




Life Prediction of Welded Component

Cross sections are cut and polished to measure the weld profile dimensions for GSP calculation

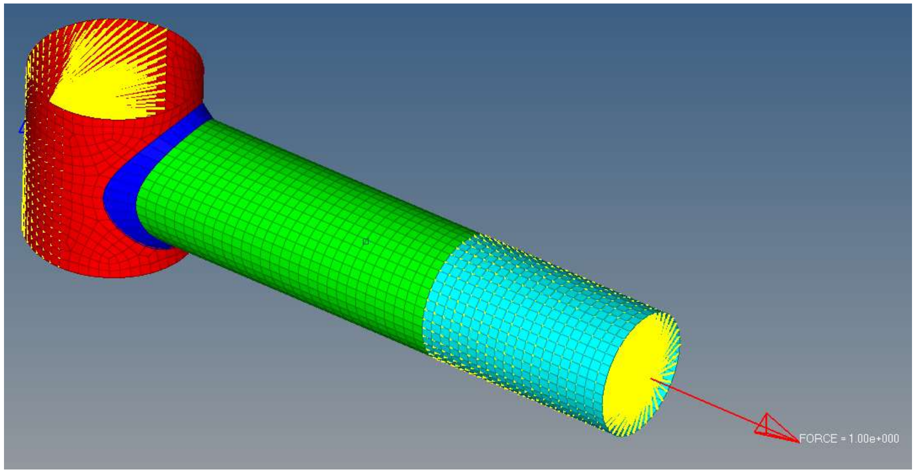


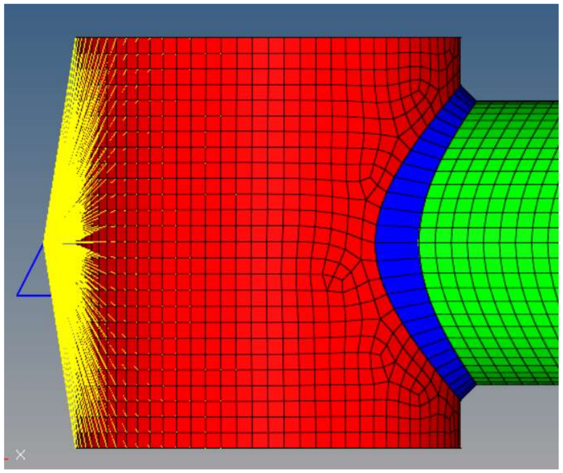


	Measurement	Value
A	Brace thickness	2.58 mm
B	Chord thickness	3.25 mm
C	Toe radius	0.92 mm
D	Weld Angle	31.94 degree

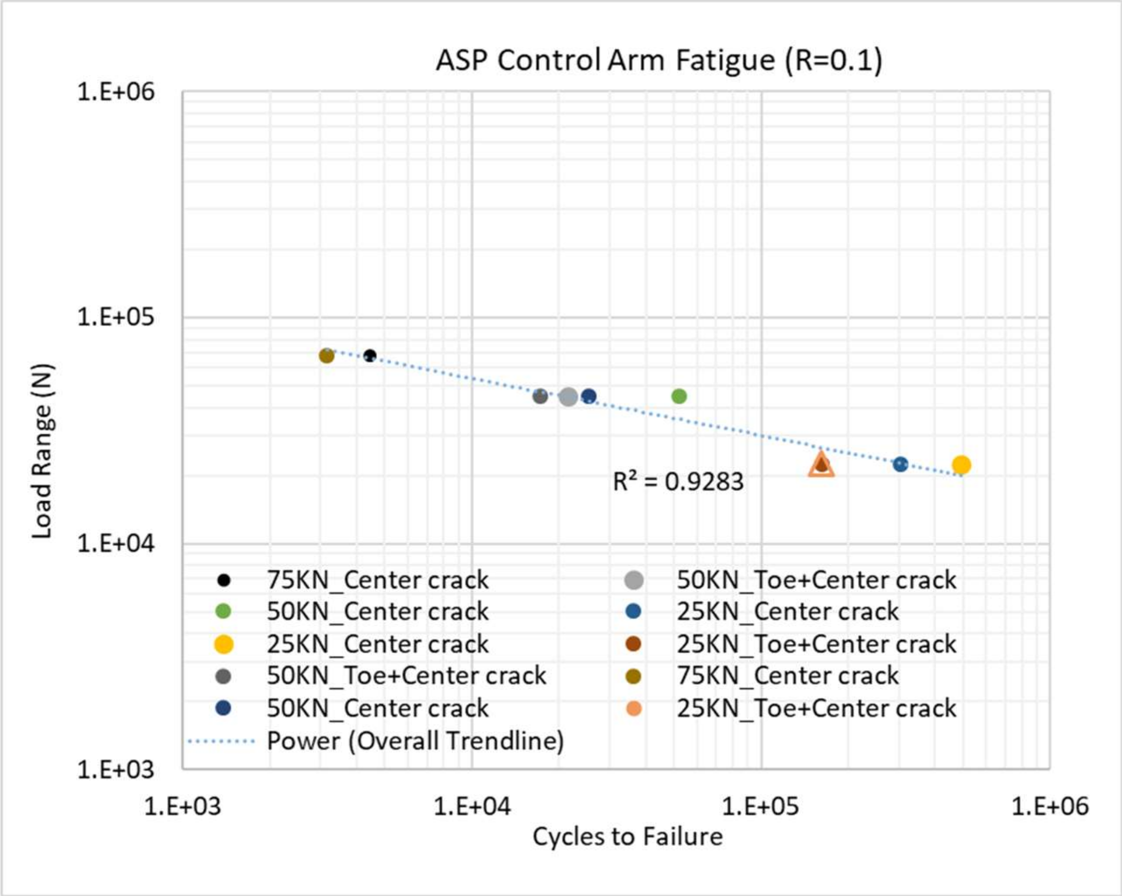
Life Prediction of Welded Component

- FEA model is built according to the measured average dimensions and nCode modeling guildelines
- The mesh size for chord and brace is around 2 mm
- Life prediction was made before testing

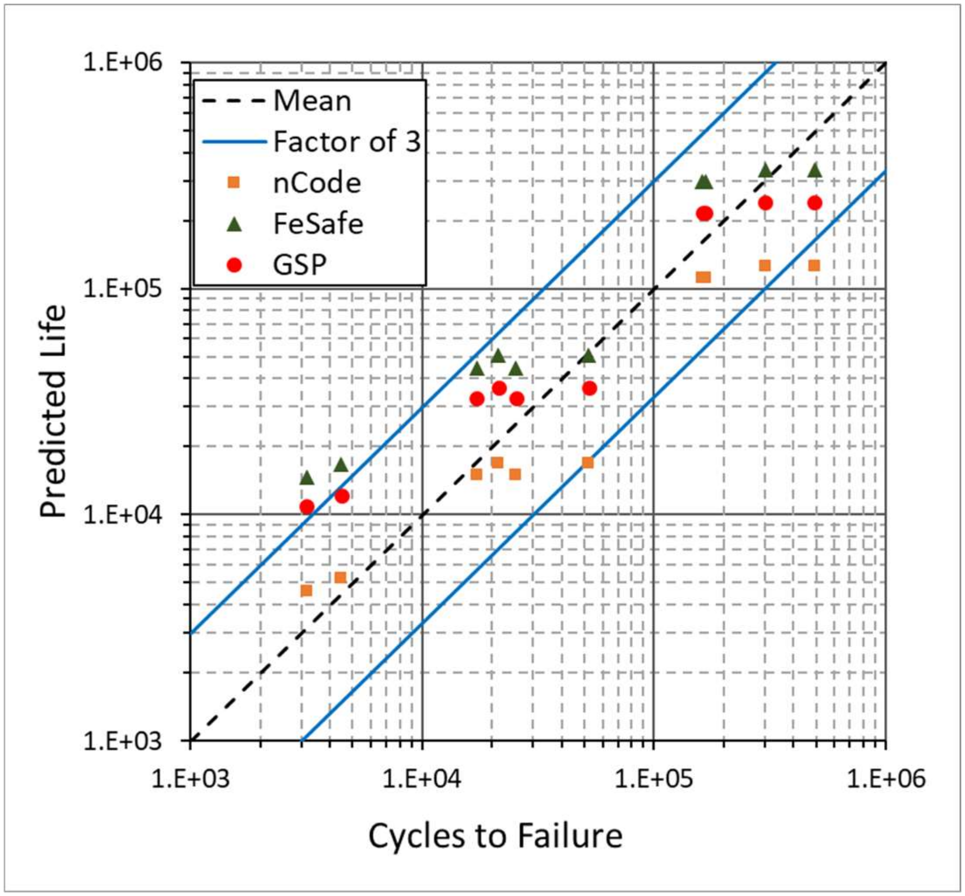




Life Prediction of Welded Component



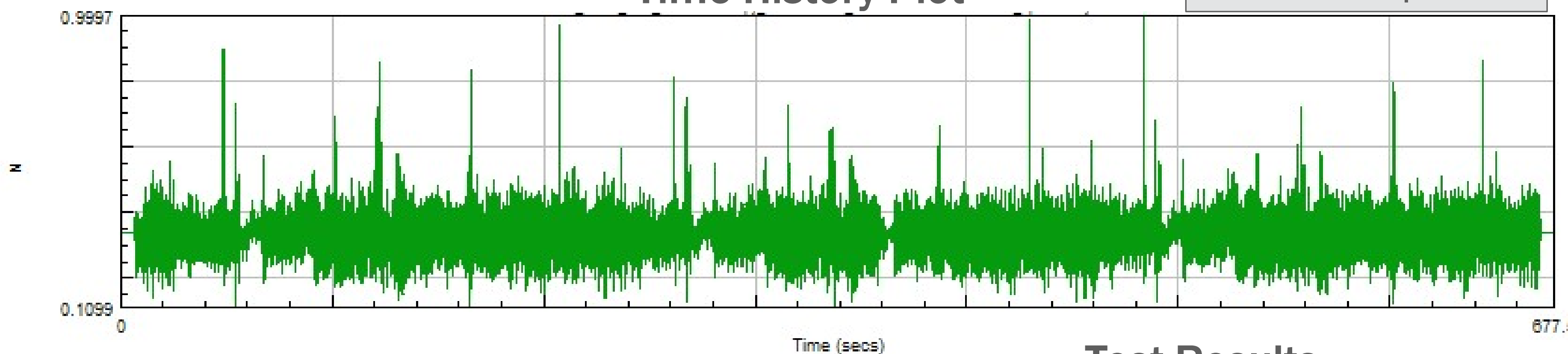
Life Prediction of Constant-Amplitude Testing



Life Prediction of Variable-Amplitude Testing

Time History Plot

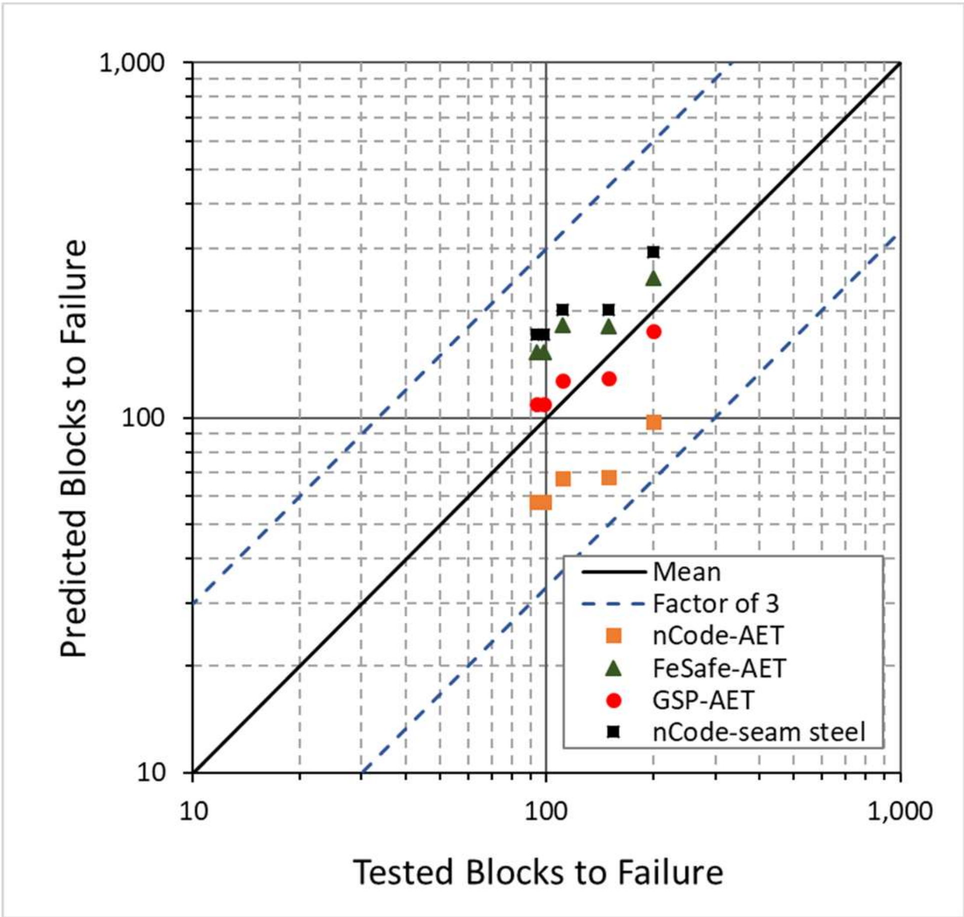
~680 seconds per block



Test Results

Variable Amplitude Test	Specimen	Scaling Factor	Tested Blocks to Failure
1	Control Arm_1	75200X	150
2	Control Arm_3	75200X	111
3	Control Arm_4	78000X	94
4	Control Arm_5	78000X	98
5	Control Arm_2	68400X	200

Life Prediction of Variable-Amplitude Testing



CONCLUSIONS

- A new fatigue life prediction model was successfully developed using generalized stress parameter (GSP), based on fracture mechanics consideration
- The method was validated with fatigue test results of a control arm component subjected to constant amplitude and variable amplitude loadings
- In this investigation, compared to the structural stress methods, a better correlation is established using the GSP method, which considers the global and local geometric effect at the same time.
- It may need further study for more complicated structural components (fatigue data are welcomed to test this method)

ACKNOWLEDGEMENTS

- Financial support from Auto/Steel Partnership is recognized
- Thanks to AET Integration Inc. for providing coupon fatigue testing data

Thank you !

GREAT DESIGNS IN STEEL

Presentations will be available for download on SMDI's website on Wednesday, May 22