MODEL DEVELOPMENT AND VALIDATION FOR FATIGUE LIFE PREDICTION OF WELDED JOINTS

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College of Engineering & Computer Science

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Education

- **University of Michigan - Rackham Graduate School (**GPA: 3.94/4.00**)** 2015 - 2017
  Master's Degree, Mechanical Engineering
- **Chongqing University**, China 2009 - 2016
  BS, MS, Major: Engineering Mechanics (BS); Automotive Engineering (MS)

Advisor

Hong-Tae Kang, Ph.D.

Professor, Mechanical Engineering

Current Position

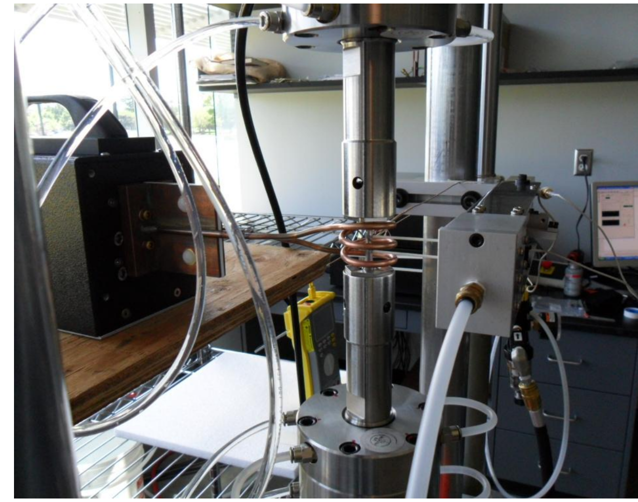
FEA Engineer at Caterpillar, Inc. (Agency) December 2017-Current

Mossville, IL

tigue Analysis and Testing Lab in UM-Dearborn

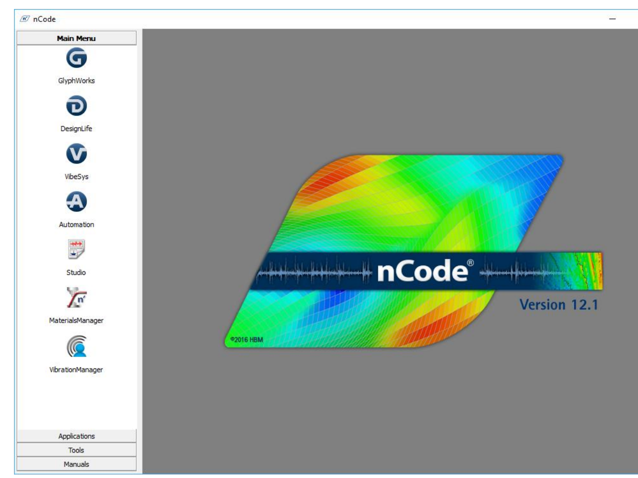
Fatigue testing

- Various joints: Spot weld, SPR, FSLW, GMAW, Adhesive joints, etc.
- Strain-controlled fatigue, four-point bending fatigue, etc.
- Round bar specimen, sheet specimen
- Thermo-mechanical fatigue (TMF)



FEA based fatigue life analysis

- Stress-life approach (S-N)
- Strain-life approach (E-N)
- Structural stress method



ntents

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

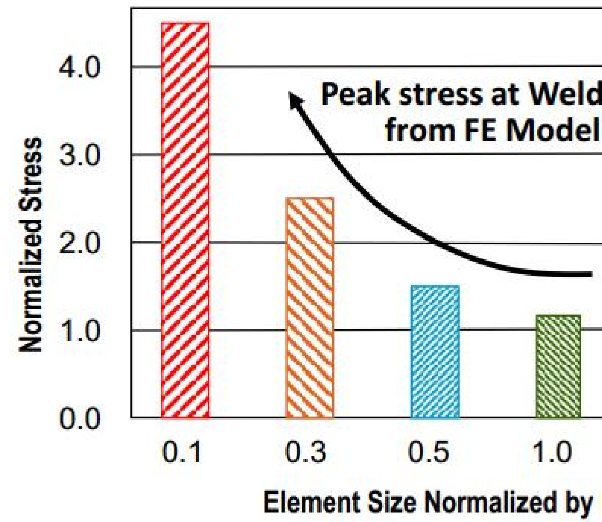
- Consolidation of coupon fatigue test results
- Life prediction of welded component

Conclusions

jective

Background:

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



Current methods:

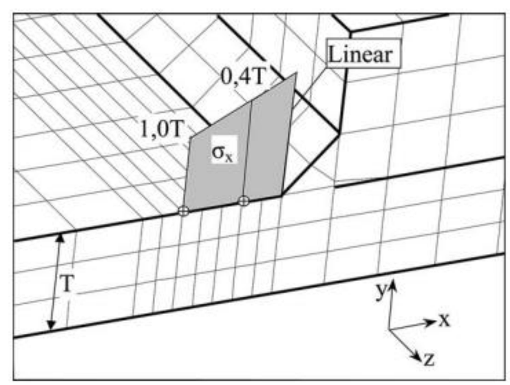
FEA stress output (mesh-sensitive)

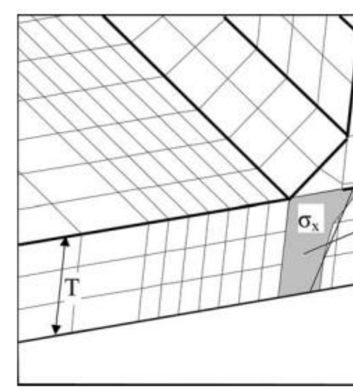
Stress intensity factor (time-consuming)

Structural stress

1. Linear surface extrapolation
2. Linearization through thickness
3. Nodal force-based structural stress

only considers global geometry effect





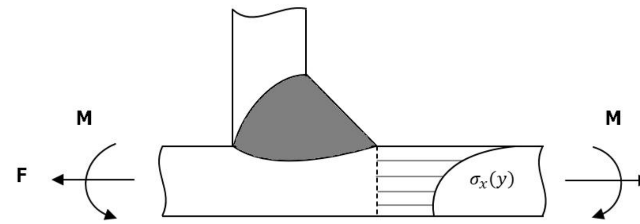
attelle structural stress training, 2016

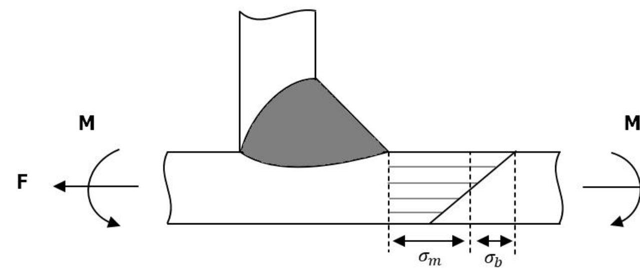
nite element methods for structural hot spot stress determination—a comparison of procedures

jective

Structural stress definition (nCode, Fe-Safe, etc.)

$$\sigma_s = \sigma_m + \sigma_b$$



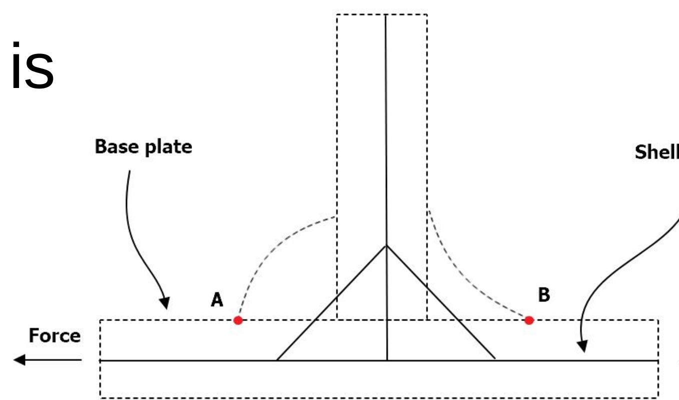


Observation:
Structural stress tells us:

$$\sigma^A = \sigma^B$$

n fact, $\sigma^A_{Local} > \sigma^B_{Local}$ (Larger stress concentration at Point A)

Stress concentration caused by the weld profile is considered (local geometric effect)



esignLife Theory Manuals, HBM-nCode, 2016

jective

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

orkflow

ructural stress σ

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

SIF K

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

Fatigue life N

2. Weight function

ress Intensity Factors

ations between SIF and structural stress:

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

and Y_b are geometric correction factors under pure tension and pure bendi
pectively

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

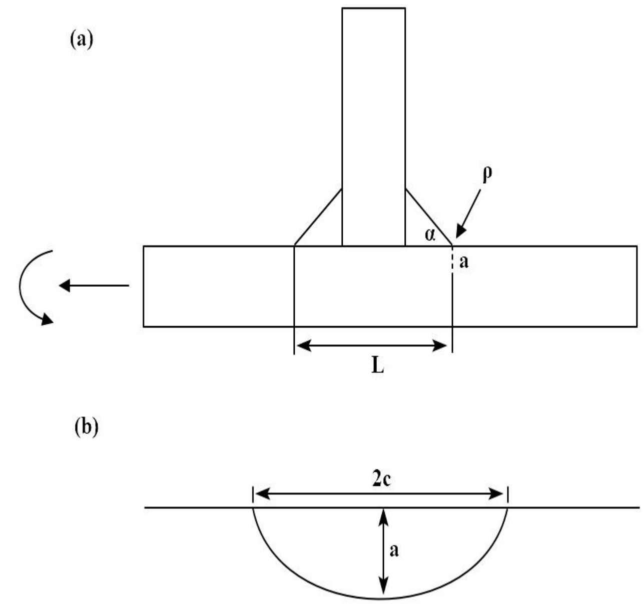
$$\sigma_b = r_b \sigma_s$$

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

structural stress
bending ratio (=σ_b/σ_s)

. Radaj, C.M. Sonsino, W. Fricke, *Fatigue assessment of welded joints by local approaches*, Woodhead publishing, 2006.

ress Intensity Factors

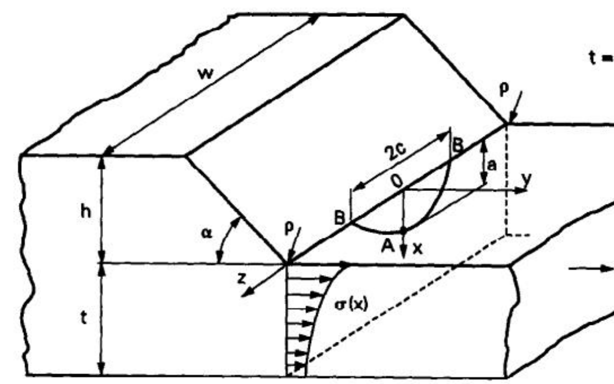


s are calculated using weight function method

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

$x, \frac{a}{t}, \frac{a}{c}, \alpha\big)$ is the weight function provided by Niu
Glinka

) is the normal stress distribution on the un-
cked cross-section at the critical point of the
ded plate. Mode I failure is assumed



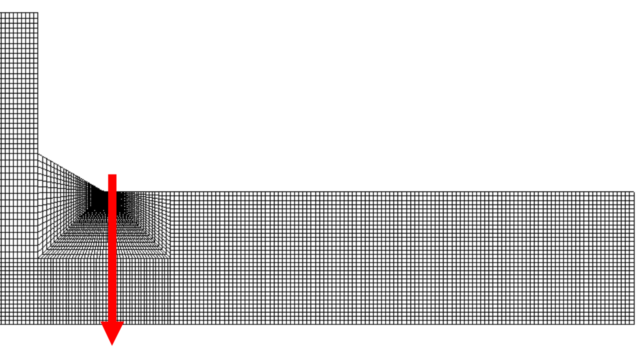
Niu, G. Glinka, Theoretical and experimental analyses of surface fatigue cracks in weldments, in: Surface-Crack Growth: Models, Experiments, and tures, ASTM International, 1990.

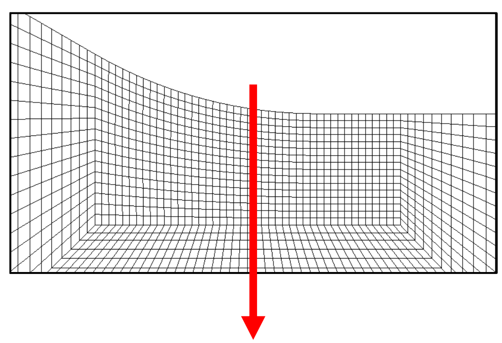
ress Intensity Factors

A stress analysis

ld angle α = 30°, 45°, and 60° and weld radius ρ/t = 0.1, 0.3, and 0.5

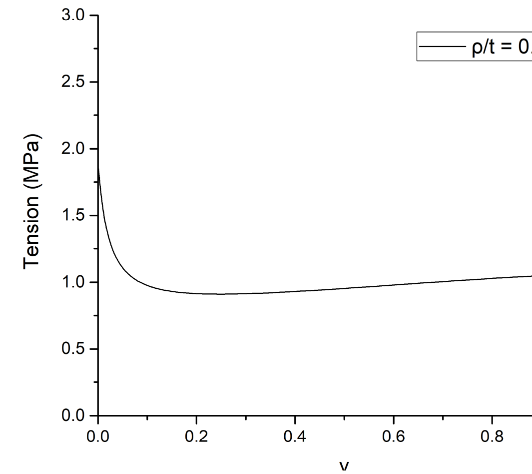
$$K = \int_0^a \sigma(x) m\left(x, \frac{a}{t}, \frac{a}{c}, \alpha\right) dx$$



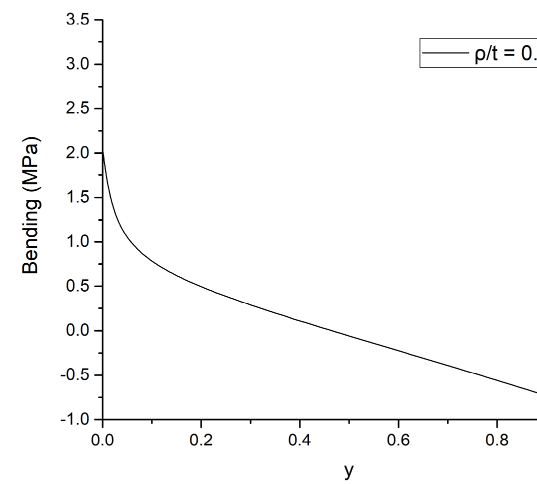


Stress distribution at weld

Tension



Bending



ress Intensity Factors

nsider two cases:

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

Bending only

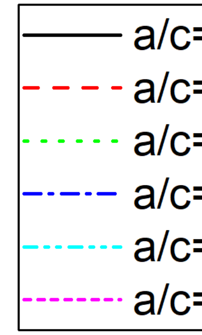
$$K = \int_0^a \sigma(x) m\left(x, \frac{a}{t}, \frac{a}{c}, \alpha\right) dx$$

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

Y_b is obtained

ress Intensity Factors

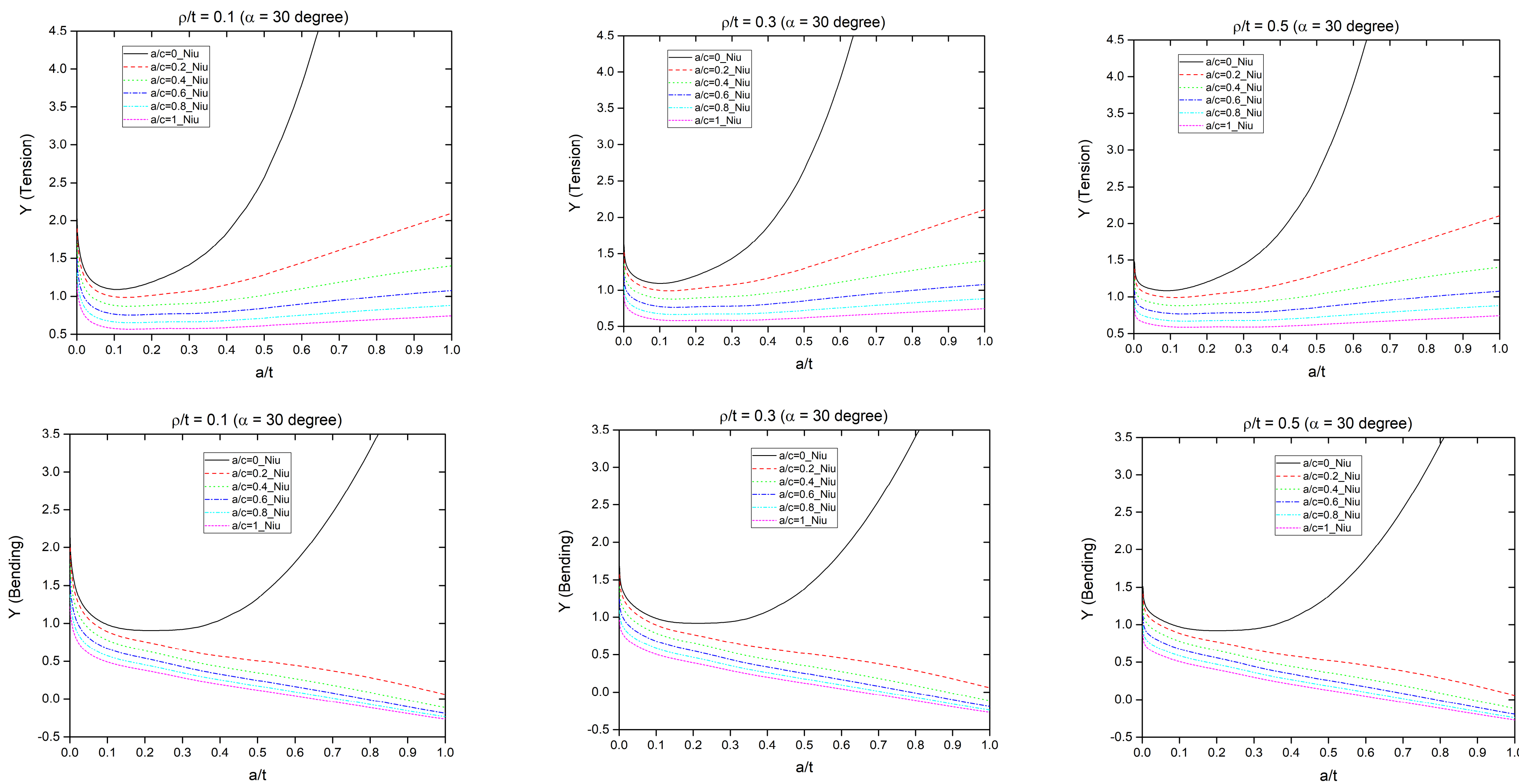
tribution of Y_m and Y_b (α = 30°)



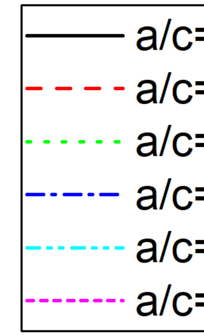
(a) ρ/t = 0.1 (b) ρ/t = 0.3 (c) ρ/t = 0.5

Y_m

Y_b



ress Intensity Factors



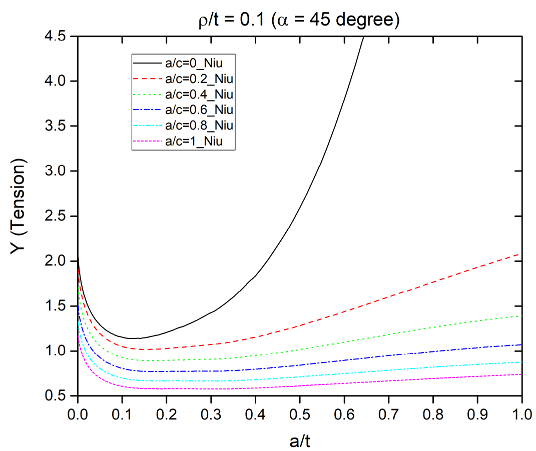
tribution of Y_m and Y_b (α = 45°)

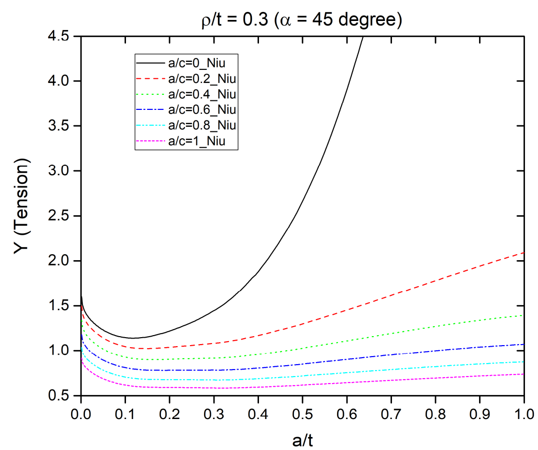
(a) ρ/t = 0.1

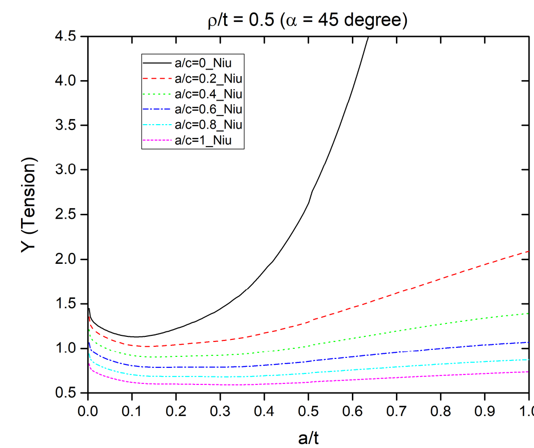
(b) ρ/t = 0.3

(c) ρ/t = 0.5

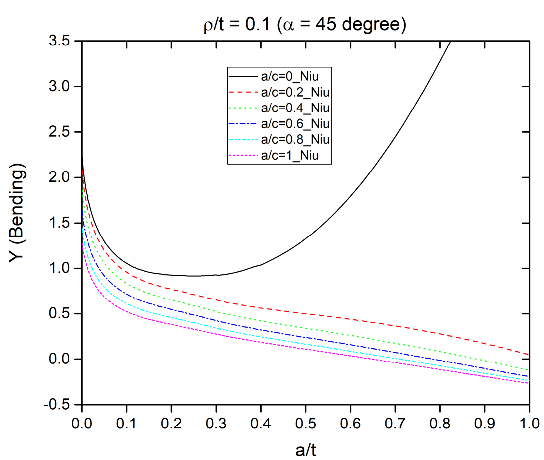
Y_m

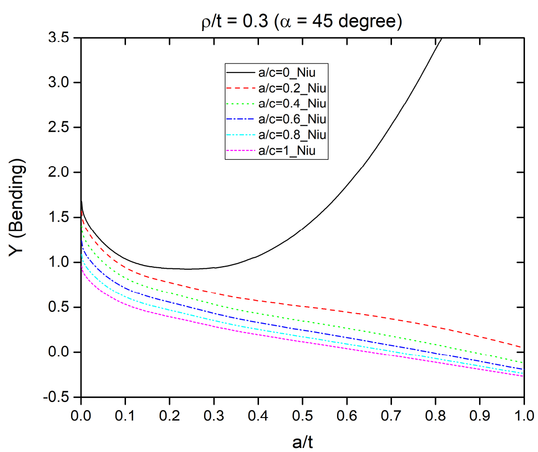


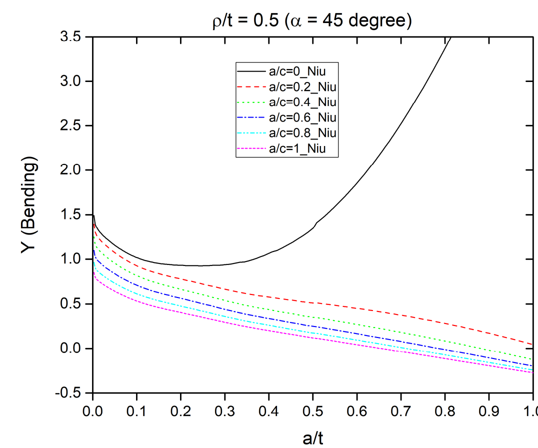




Y_b

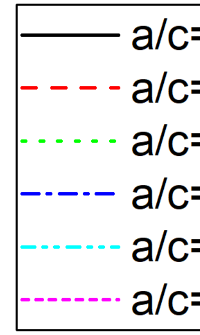






ress Intensity Factors

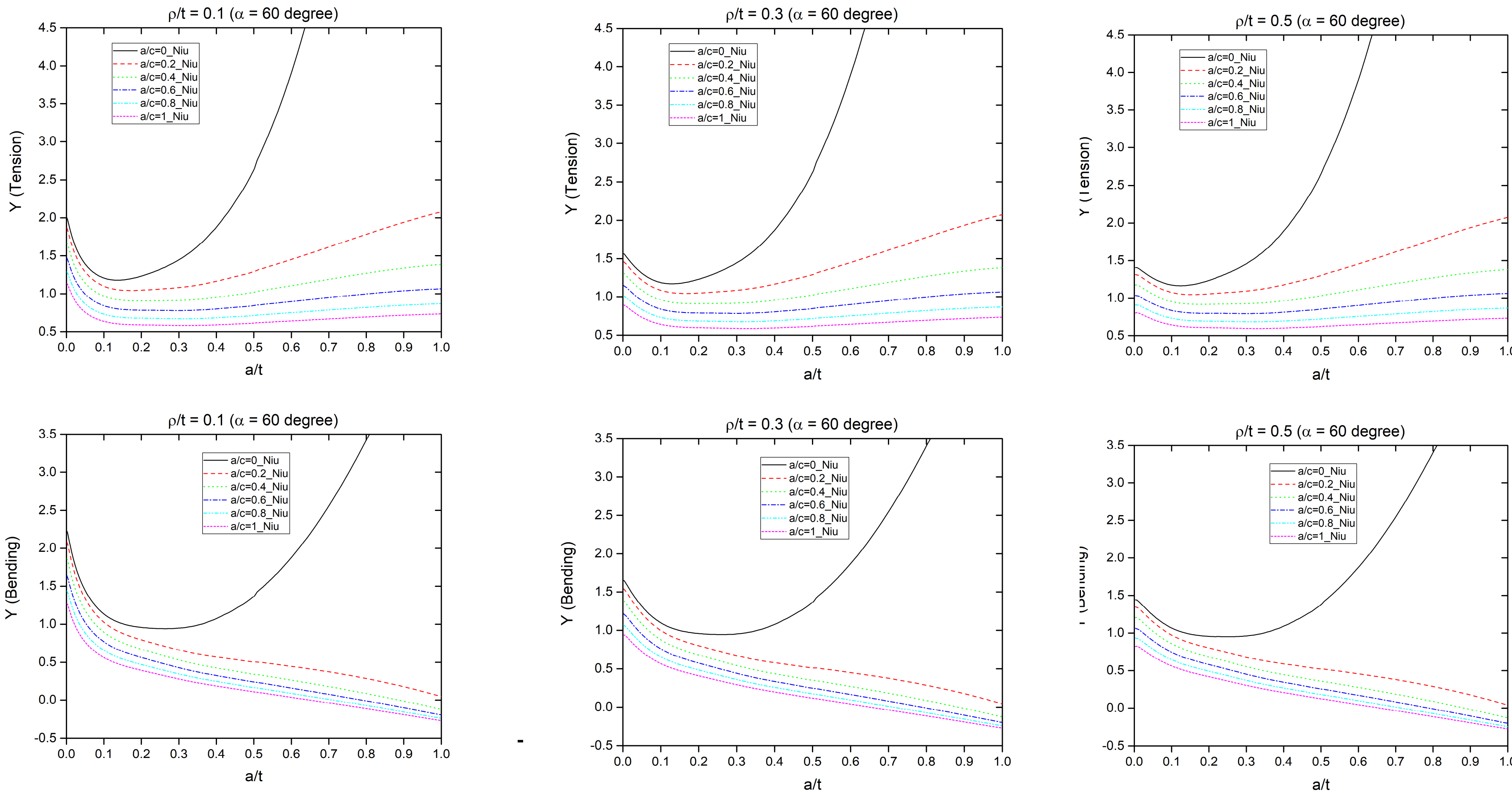
tribution of Y_m and Y_b (α = 60°)



(a) ρ/t = 0.1 (b) ρ/t = 0.3 (c) ρ/t = 0.5

Y_m

Y_b



ress Intensity Factors

cussion:

- Geometric correction factors Y_m and Y_b change along the crack depth a/t
- Weld angle α, weld toe radius ρ/t, and crack aspect ratio a/c will affect the distributions Y_m and Y_b
- Edge crack cases ($\frac{a}{c}$ = 0) have higher Y_m and Y_b compared to semi-elliptical crack cas ($\frac{a}{c}$ > 0)
- Smaller weld toe radius corresponds to higher Y (or equivalently, SIF), which means it w have a shorter fatigue life and makes sense in reality. Similarly, larger weld angle induc higher Y, and will have shorter life compared to smaller weld angle cases, which can understood since the stress concentration effect is enhanced with larger angles.

Y_m and Y_b are functions of weld angle α, weld toe radius ρ/t, and crack aspect ratio a/c

eneralized Stress Parameter Approach

igue life can be estimated by integrating the Paris' Law

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

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

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

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

eneralized Stress Parameter Approach

ganizing the stress term to the left hand side, we have

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

ddox defined a so-called “generalized stress parameter” (GSP) as

$$\Delta S = \frac{t^{\frac{m-2}{2m}}}{I^{\frac{1}{m}}} \Delta\sigma_s$$

m $t^{\frac{m-2}{2m}}$ can be seen as a thickness correction for the cases of $t \neq 1$, in order to compensate for the ct induced by different thicknesses of welded structures

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

neralized Stress Parameter Approach

te:

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

Y_m and Y_b are in terms of weld angle α, weld toe radius $\frac{t}{\rho}$ and crack aspect r

have

Thickness effect

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

Global geometric effect

Loading mode effect

Local geometric effect

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

neralized Stress Parameter Approach

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

rrying 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 =

a/c assumed to be 0.25, and the fatigue crack growth factor m is taken as for steel, a simple parametric expression is obtained by multivariate ression

Weld angle effect

$$_b, \alpha, \frac{\rho}{t}\right)^{\frac{1}{m}} = e^{6.939 r_b - 8.174} + 0.097 r_b - 0.415\alpha + 0.066\frac{\rho}{t} + 0.496 * \alpha * \frac{\rho}{t} + 1.58$$

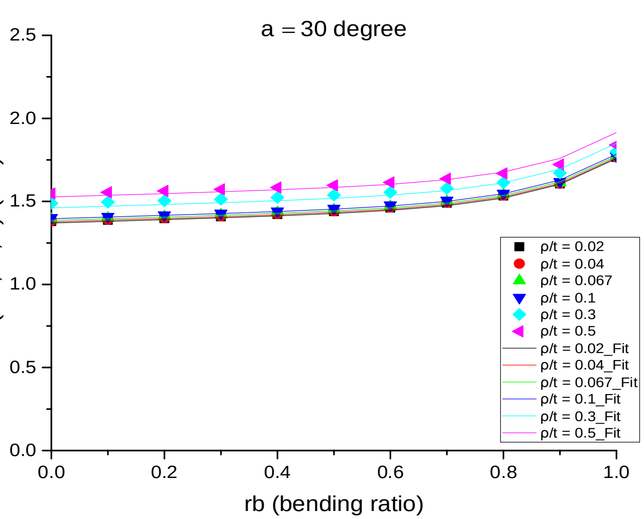
Bending ratio effect

Weld toe radius effect

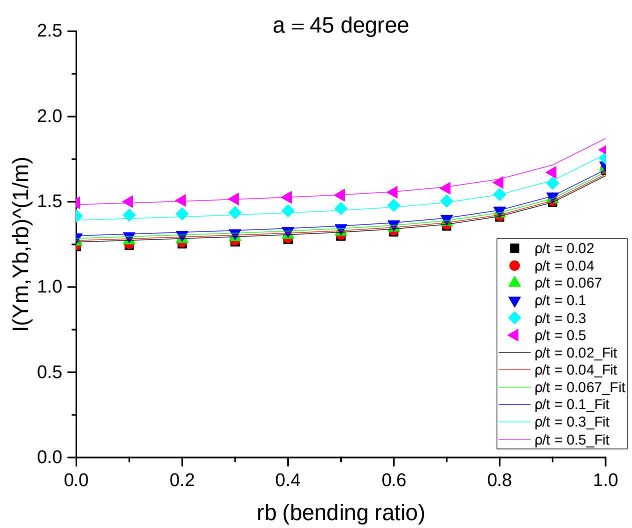
eneralized Stress Parameter Approach

mparison between regression equation and numerical data of $I\left(r_b, \alpha, \frac{\rho}{t}\right)^{\frac{1}{m}}$

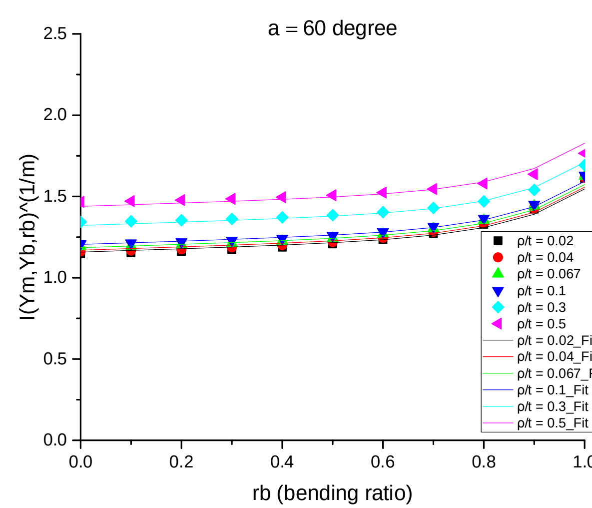
(a) α = 30°



(b) α = 45°

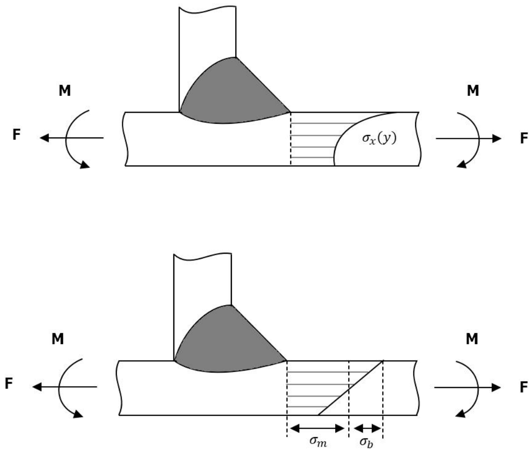


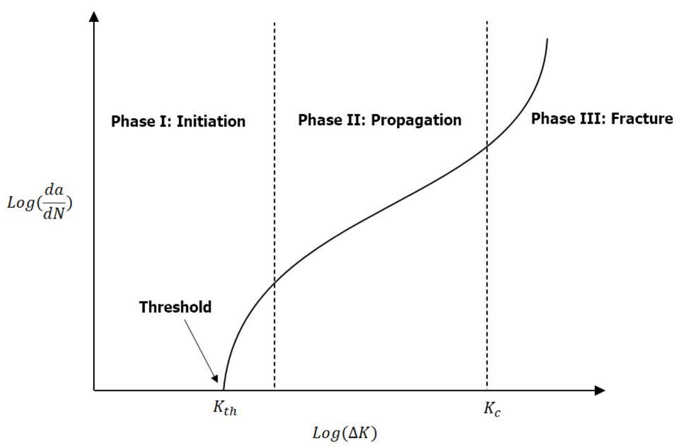
(c) α = 60°

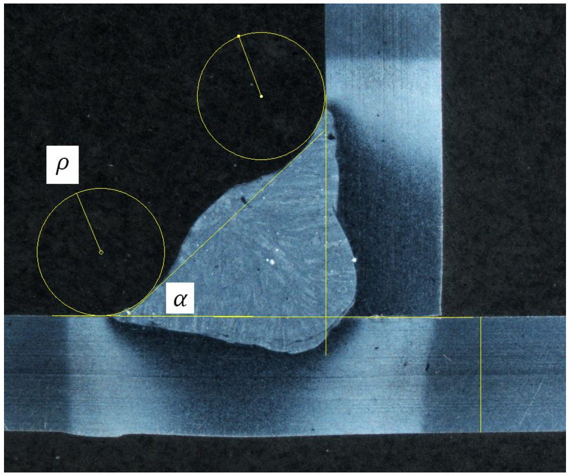


The distribution and trend of $I\left(r_b, \alpha, \frac{\rho}{t}\right)^{\frac{1}{m}}$ are well captured by the proposed equation

eneralized Stress Parameter Approach







Global (Structural) geometric effect

Crack Propagation

Local geometric effect

GSP

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

ean Stress Correction

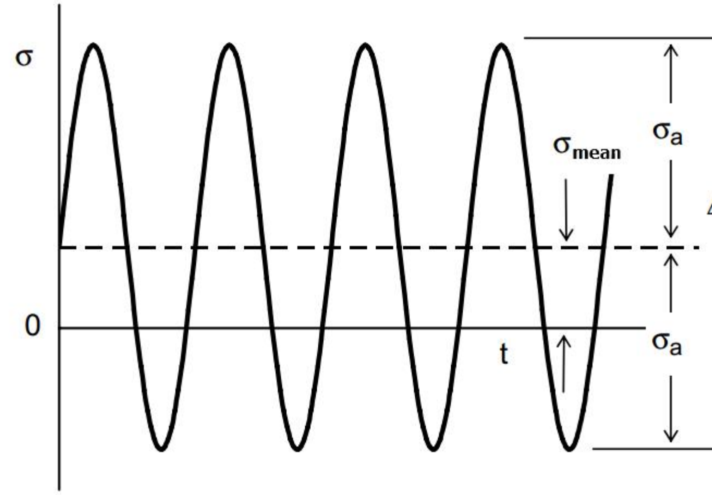
ith, Watson, and Topper (SWT) equation

$$\sigma_{ar} = \sqrt{\sigma_{max} * \sigma_a}$$

ernatively,

$$\Delta\sigma_r = \sqrt{\frac{2}{1-R}}\Delta\sigma_s$$

ere $\Delta\sigma_r$ is the fully reversed structural stress ge



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

mparison with Equivalent Structural Stress Method

ilarity:

$$\Delta\sigma^{*} = \Delta\sigma\left(\frac{B^{(m/2)-1}}{I}\right)^{1/m}$$

(Maddox, 1974)

erence:

GSP

Thickness effect

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

Global geometric effect

Loading mode effect

Local geometric effect

Weld angle effect

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

Bending ratio effect

Weld toe radius effect

ESS

Equivalent Structural Stress Range Equation

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

Structural Stress Range

Loading Mode effects

thickness

(Displacement control, a/c=0.6; Load control, a/c=0.2)

$$I(r)^{1/m} = 2.1549r^6 - 5.0422r^5 + 4.8002r^4 - 2.0694r^3 + 0.561r^2 + 0.0097r + 1.5426$$

$$I(r)^{1/m} = 0.0011r^6 + 0.0767r^5 - 0.0988r^4 + 0.0946r^3 + 0.0221r^2 + 0.014r + 1.2223,$$

Bending ratio effect only

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

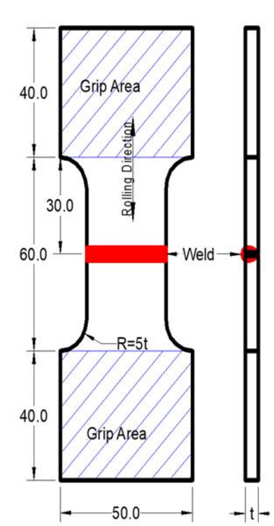
mparison with Equivalent Structural Stress Method

Differences	GSP	ESS
Paris' Law	Original form ($\frac{da}{dN} = C(\Delta K)^m$)	Two-stage model ($\frac{da}{dN} = C(M_{kn})^n(\Delta K)^m$)
SIF calculation	Glinka's weight function	Magnification factor M_{kn}
Crack shape assumption	Semi-elliptical (a/c=0.25)	Semi-elliptical (a/c=0.6 for displacement control; a/c=0.2 for load control)
Weld local geometric effect	Explicitly considered (parameters α and $\frac{\rho}{t}$ are presented in $I\left(r_b, \alpha, \frac{\rho}{t}\right)$)	Implicitly considered (But no dimension parameter is presented in $I(r)$)

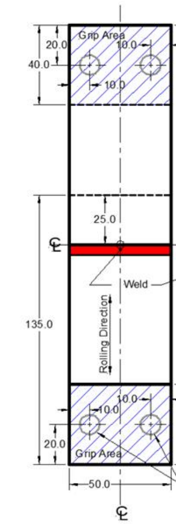
Part II. Validation and Application

upon Fatigue Test Results

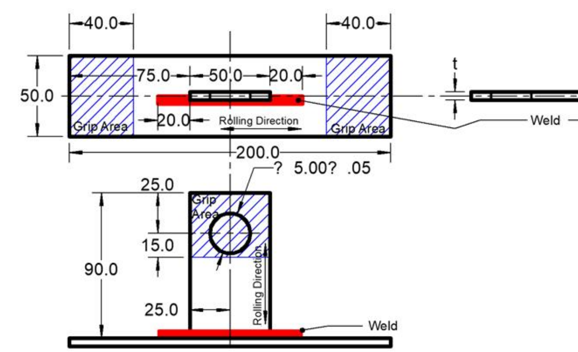
- Gas metal arc welding (GMAW)
- Advanced high strength steel (AHSS)
  - 4 different steel grades (DP780, DP980, CP800, HRPO)
  - 3 different specimen types
  - 5 equal thickness combinations
  - 2 unequal thickness combinations
  - 2 loading ratios (R=0.1 and R=0.3)



(a)



(b

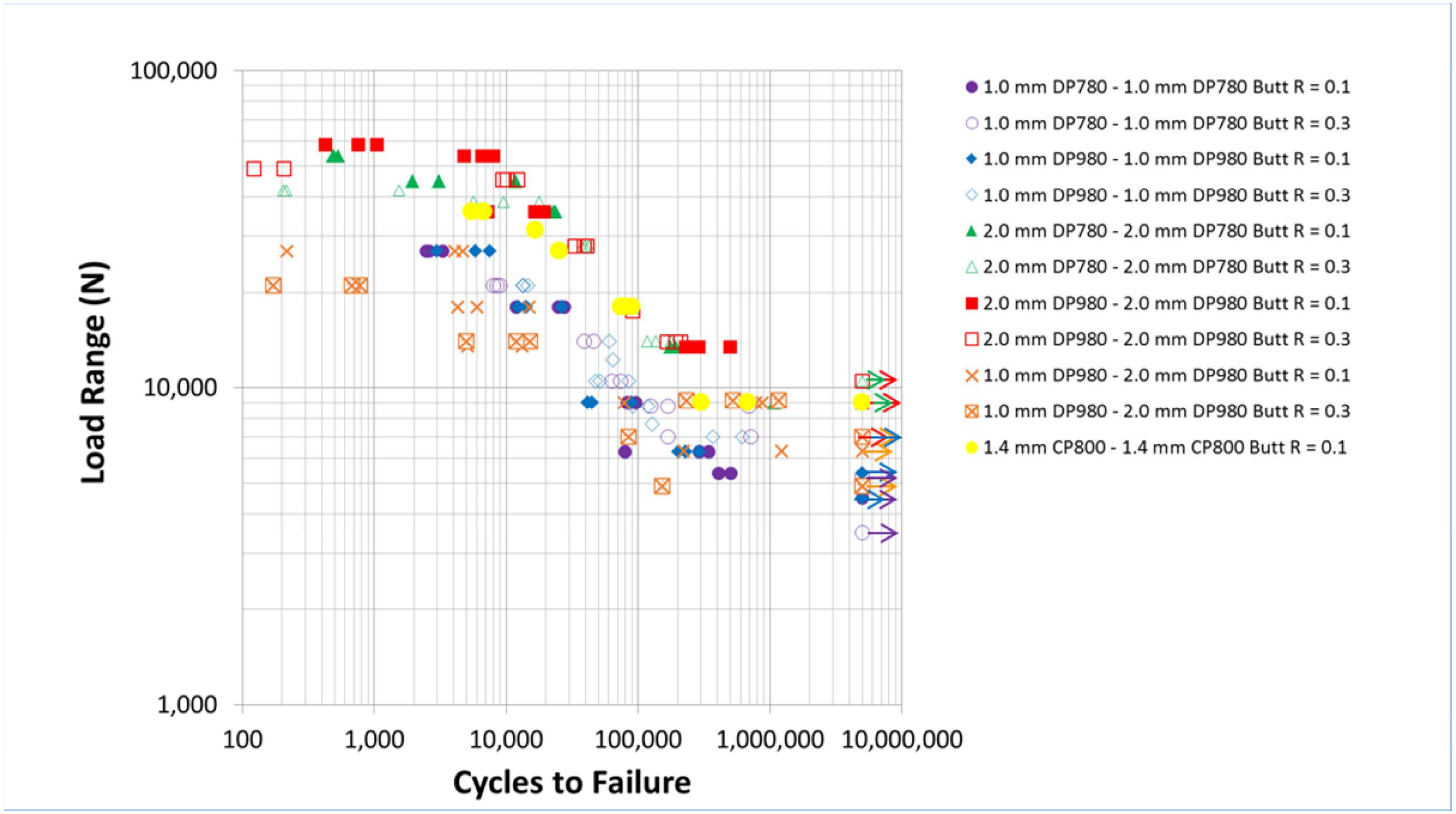


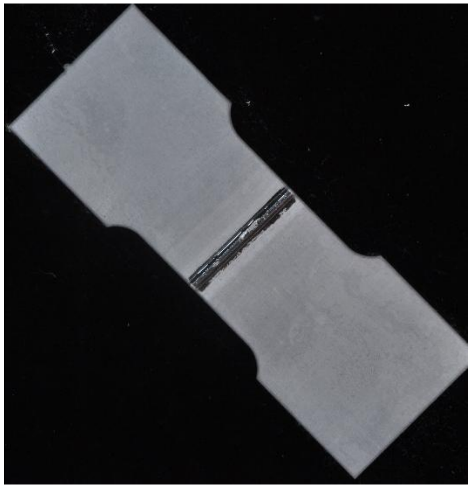
Thickness combinations						
1mm-1mm	2mm-2mm	1mm-2mm	1.4mm-1.4mm	-	-	-
1mm-1mm	2mm-2mm	1mm-2mm	1.4mm-1.4mm	2.5mm-2.5mm	1.4mm-2.5mm	4.9mm-4.9mm
1mm-1mm	2mm-2mm	1mm-2mm	1.4mm-1.4mm	2.5mm-2.5mm	-	4.9mm-4.9mm

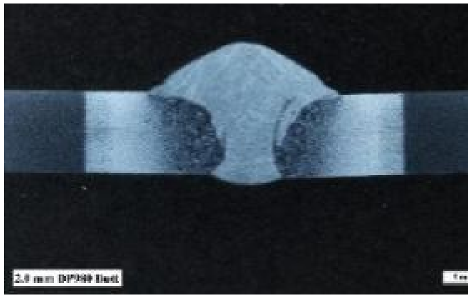
(c)

upon Fatigue Test Results

Butt Joint



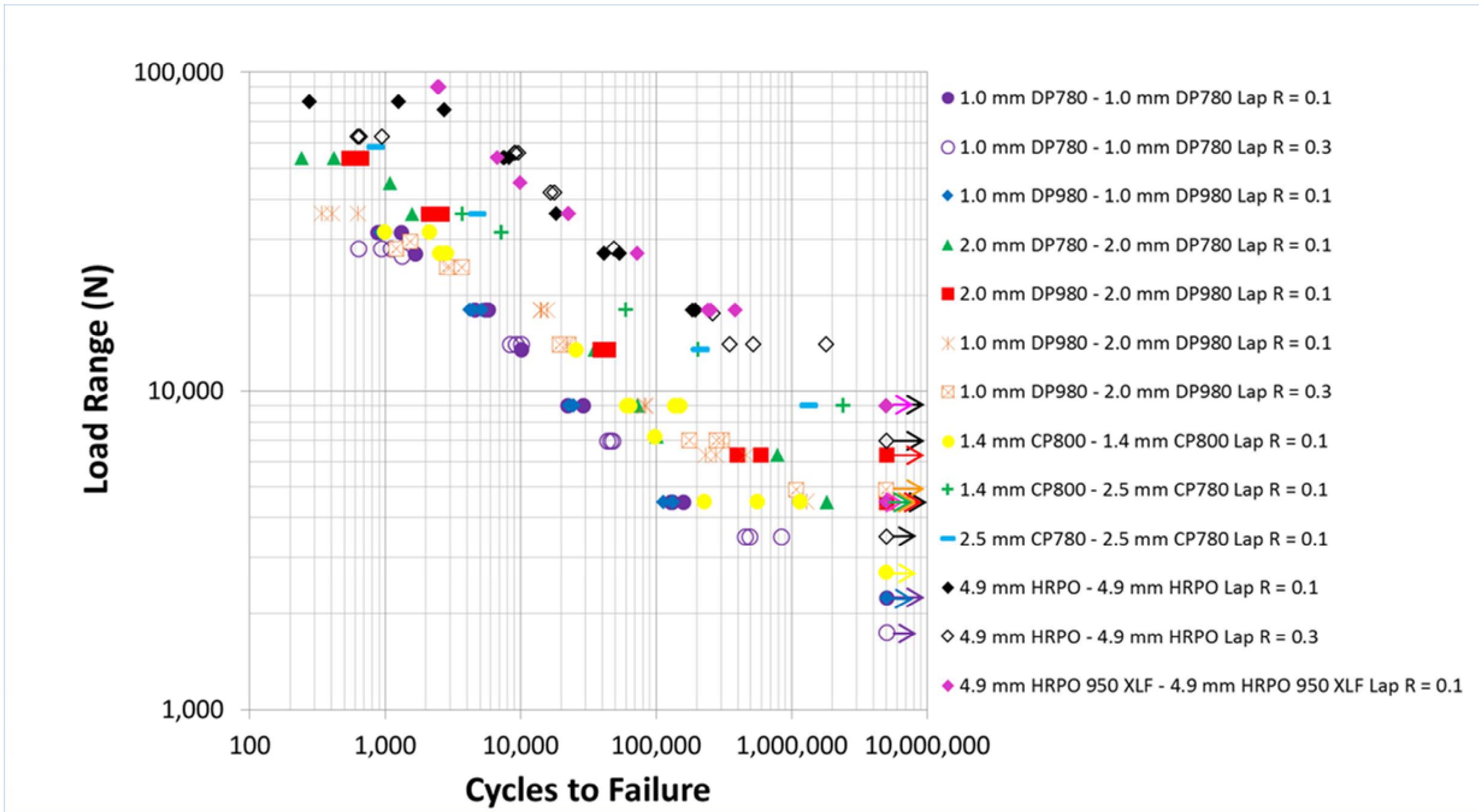


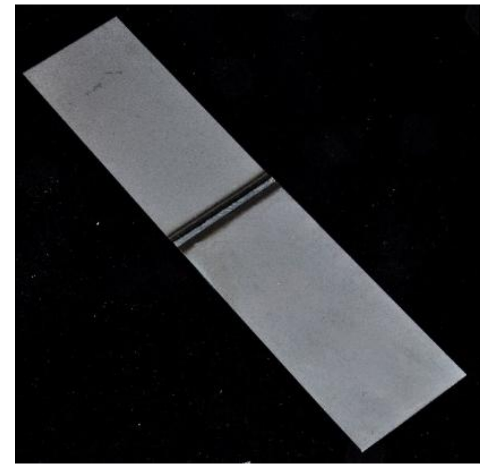


2.0 mm DP980
2.0 mm DP980

upon Fatigue Test Results

Lap-Shear Joint

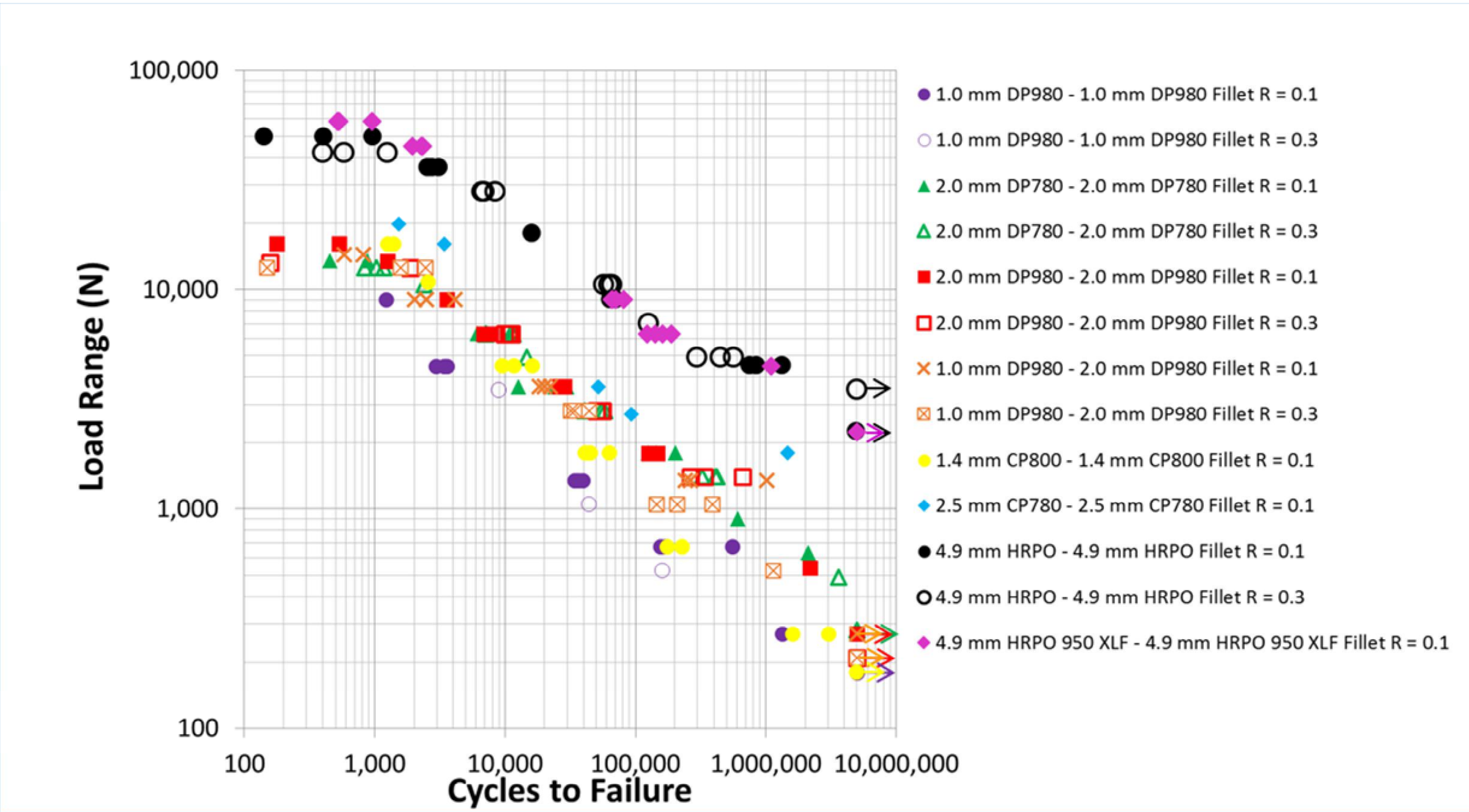


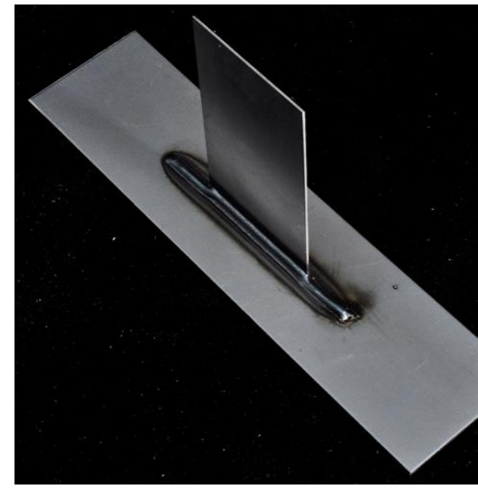


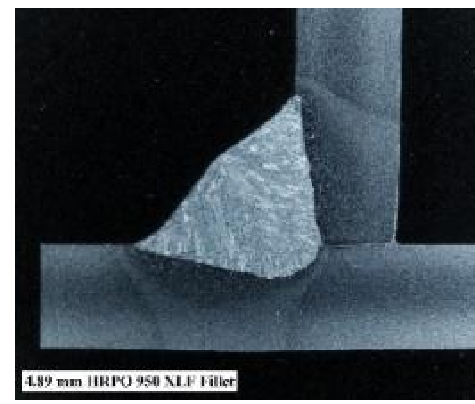
2.5 mm CP780
2.5 mm CP780

upon Fatigue Test Results

Fillet Joint

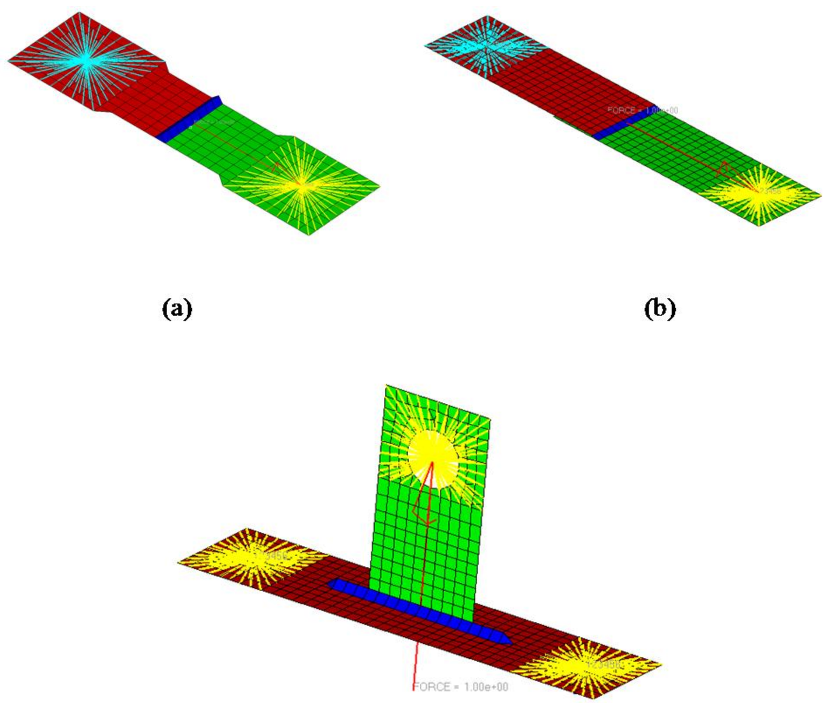






4.9 mm HRPO 950 XLF
4.9 mm HRPO 950 XLF

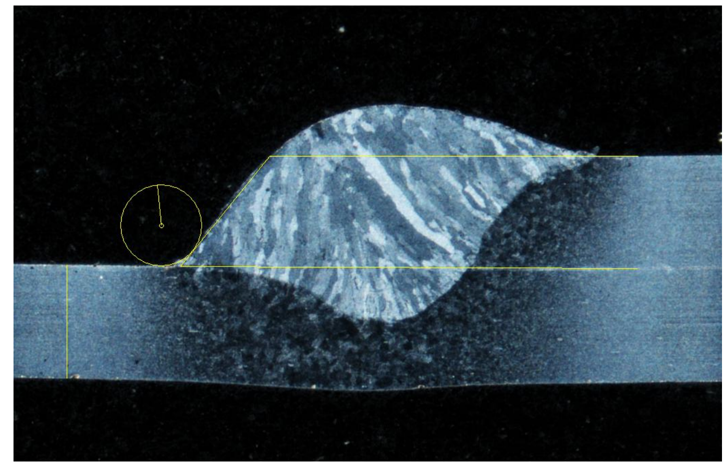
upon Fatigue Test Results



(a) (b)

(c)

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

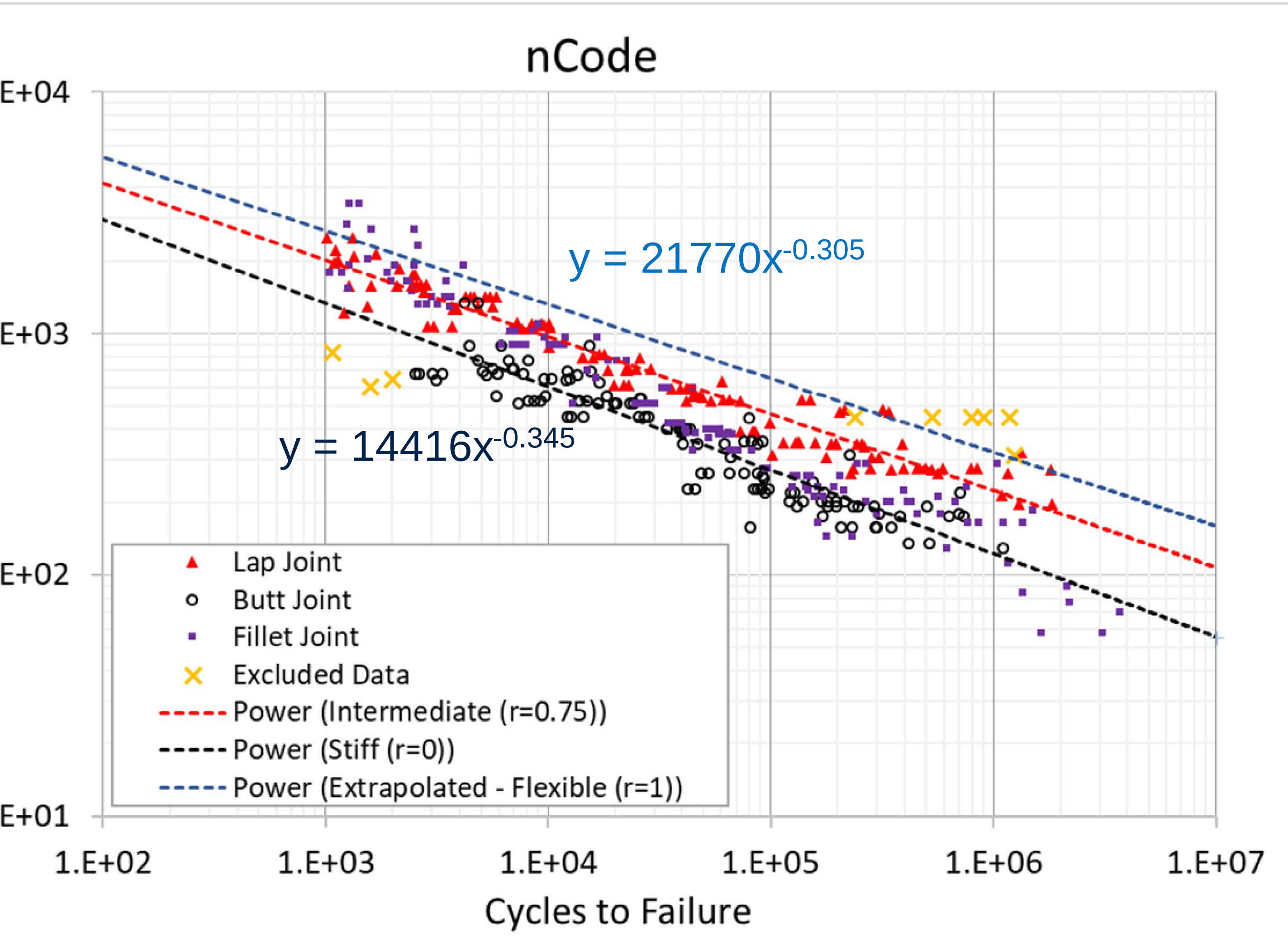


Cross-section photo of the lap joint wit 1mm thickness.

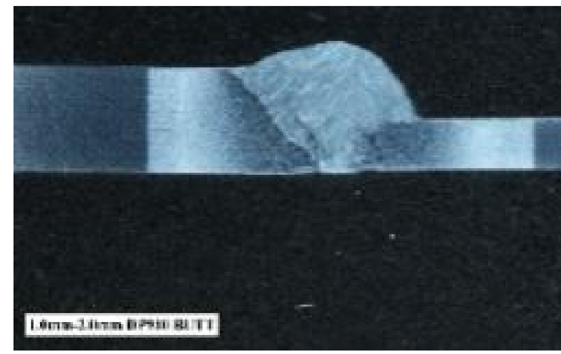
With local dimensions measure (GSP) can be calculated as

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

N Curves for nCode DesignLife

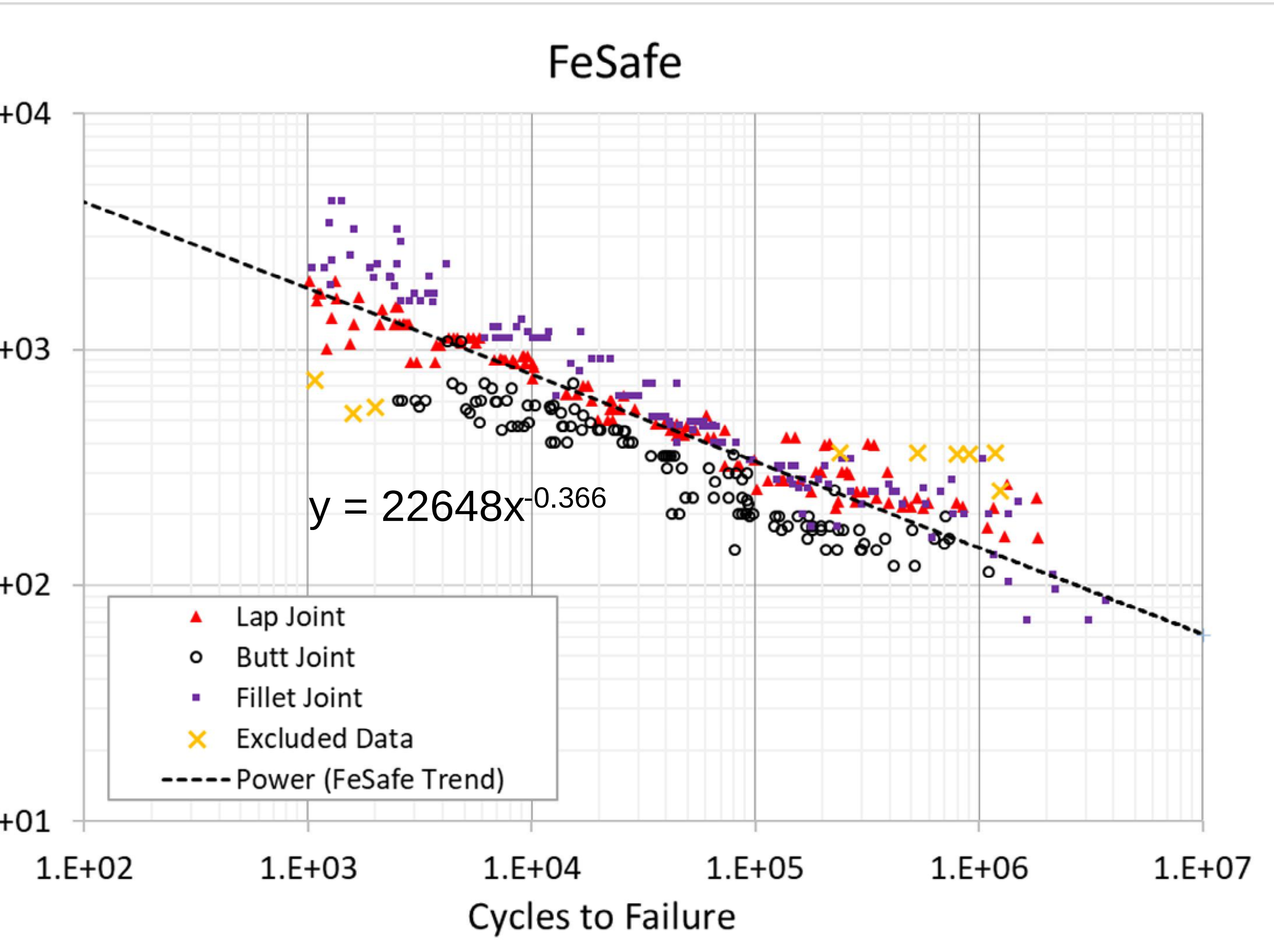


Butt joint 1mm-2mm data excluded, as showing flat in S-N curves, which ma caused by large misalignm

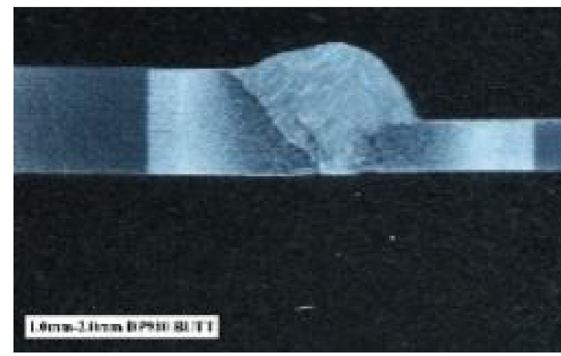


1.0 mm DP980
2.0 mm DP980

N Curve for Fe-Safe

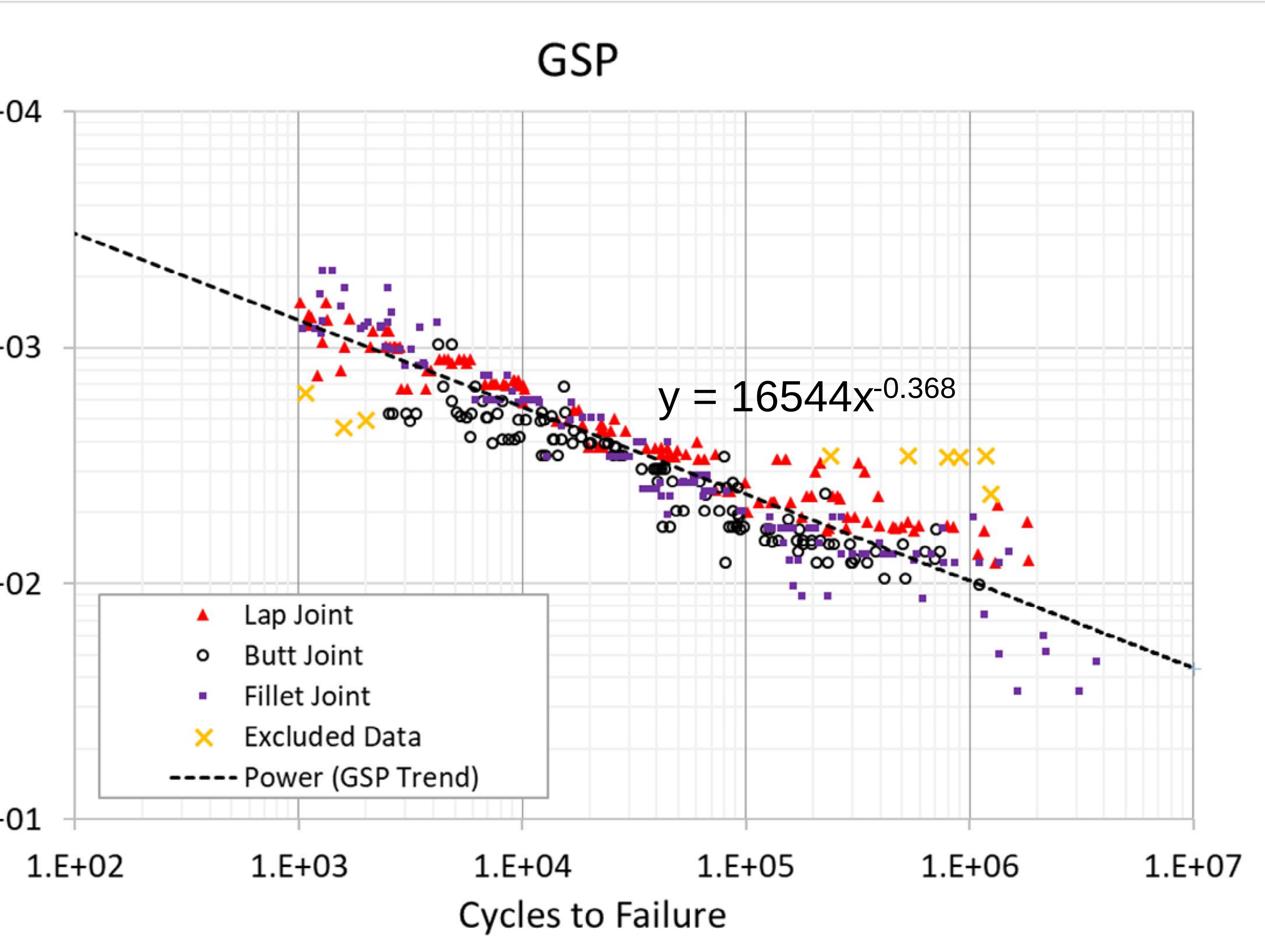


Butt joint 1mm-2mm data excluded, as showing flat in S-N curves, which ma caused by large misalignm

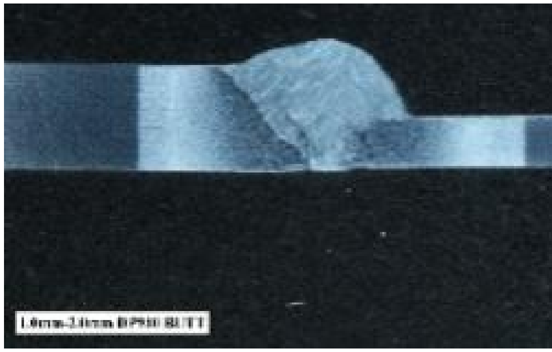


1.0 mm DP980
2.0 mm DP980

N Curve for GSP



Butt joint 1mm-2mm data excluded, as showing flat in S-N curves, which ma caused by large misalignm

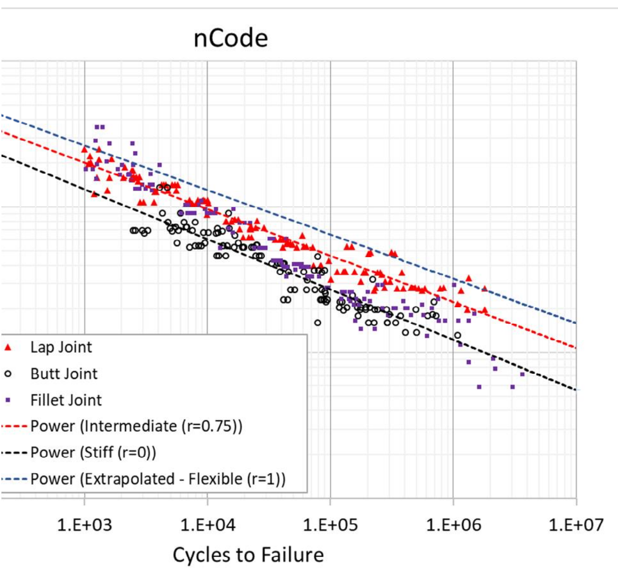


1.0 mm DP980
2.0 mm DP980

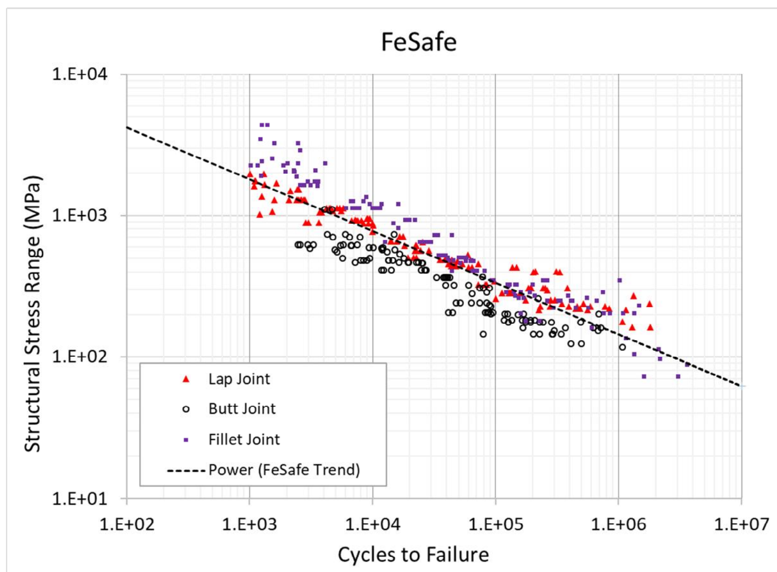
N Curve Comparison

- GSP has the best consolidation for coupon fatigue test data
- Generated S-N curves then will be used to predict the fatigue life of welded component

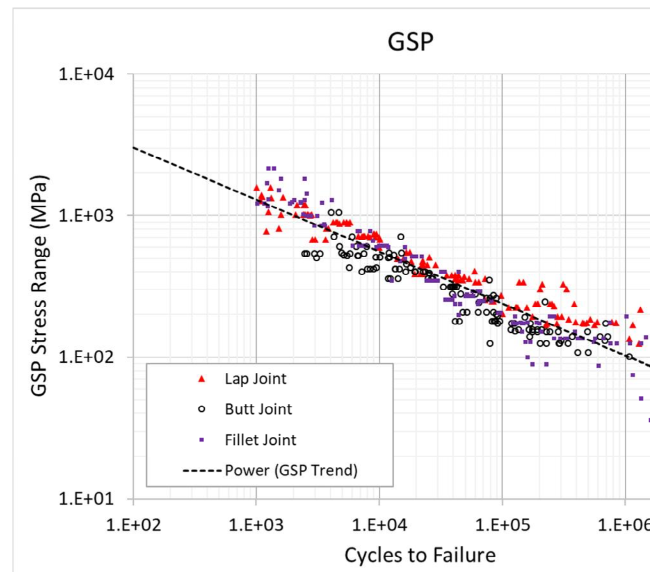
nCode



Fe-Safe

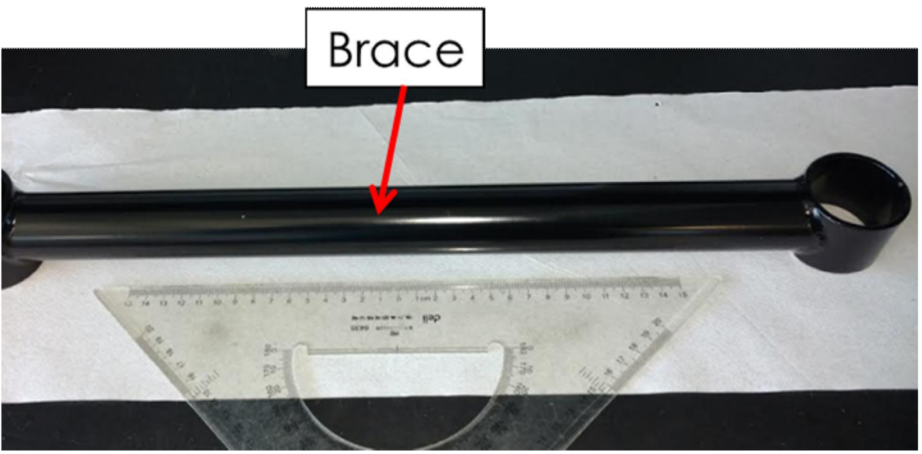


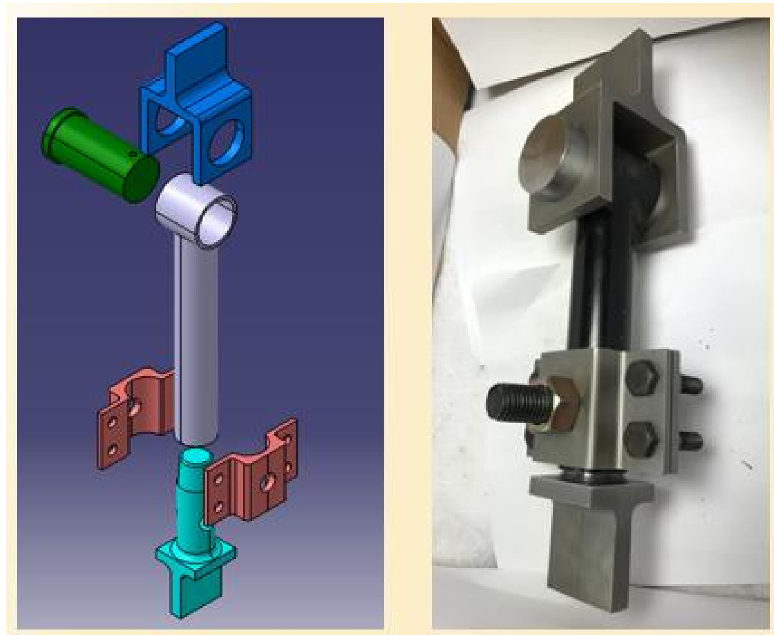
GSP



e Prediction of Welded Component

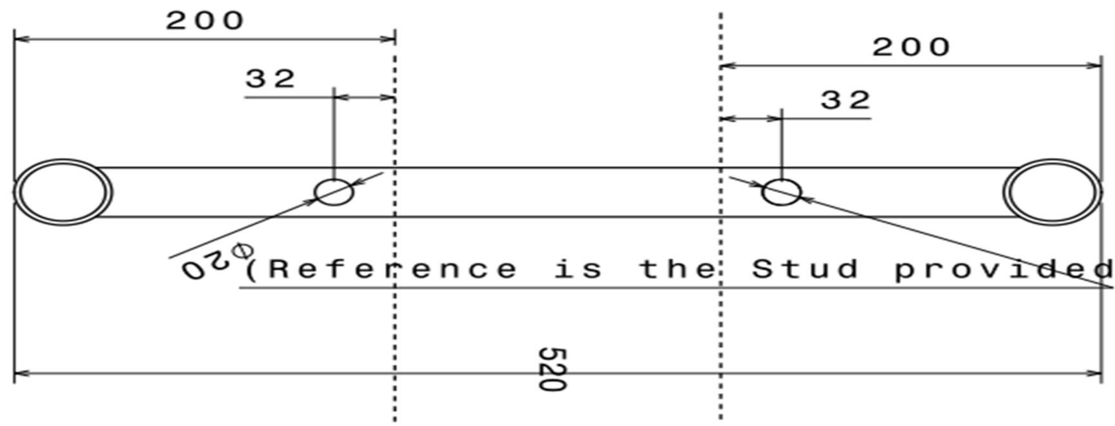
Ford Mustang control arm which has a tubular construction was chosen for testing and validation

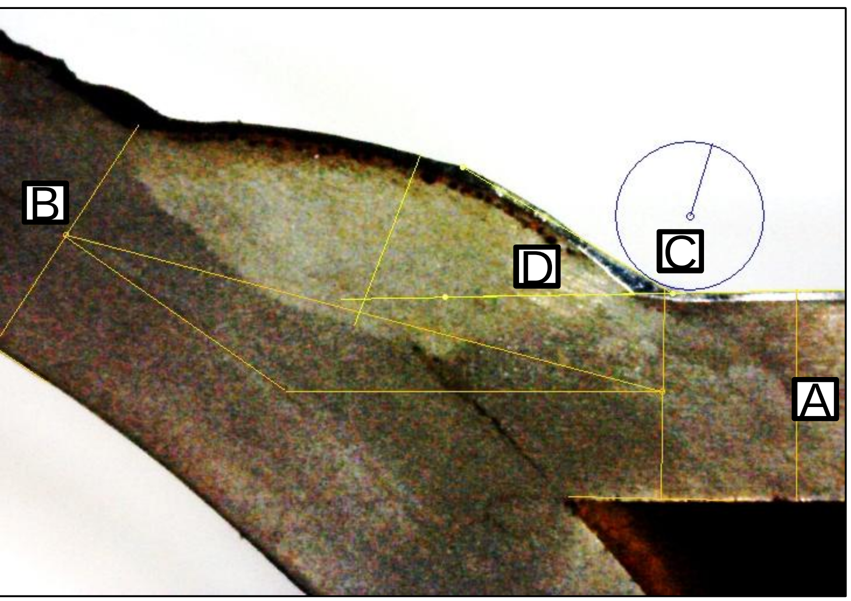




e Prediction of Welded Component

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





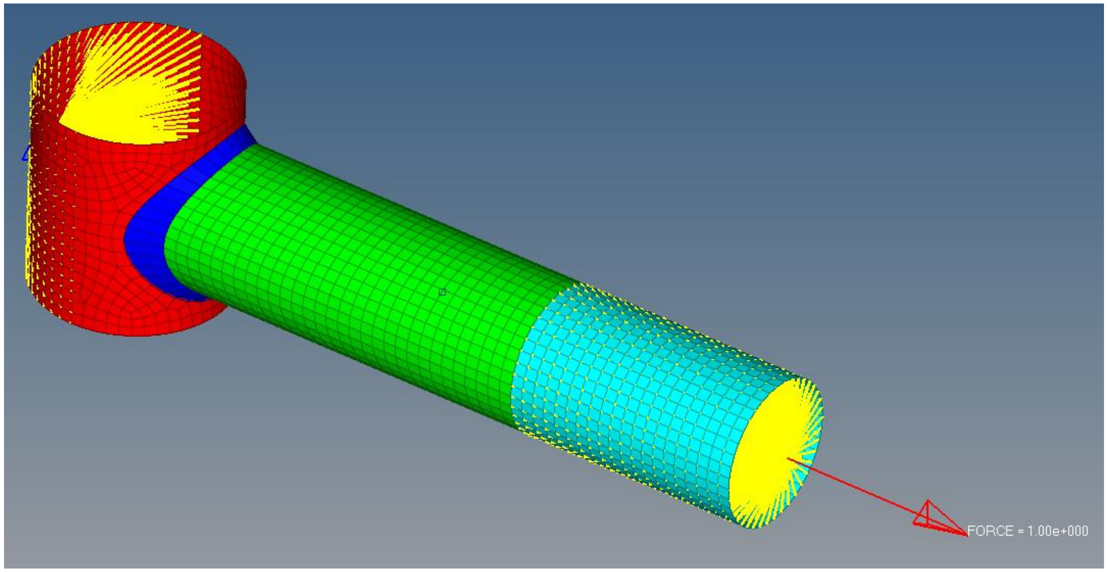
	Measurement	Value
A	Brace thickness	2.58 mm
B	Chord thickness	3.25 mm
C	Toe radius	0.92 mm
D	Weld Angle	31.94 degree

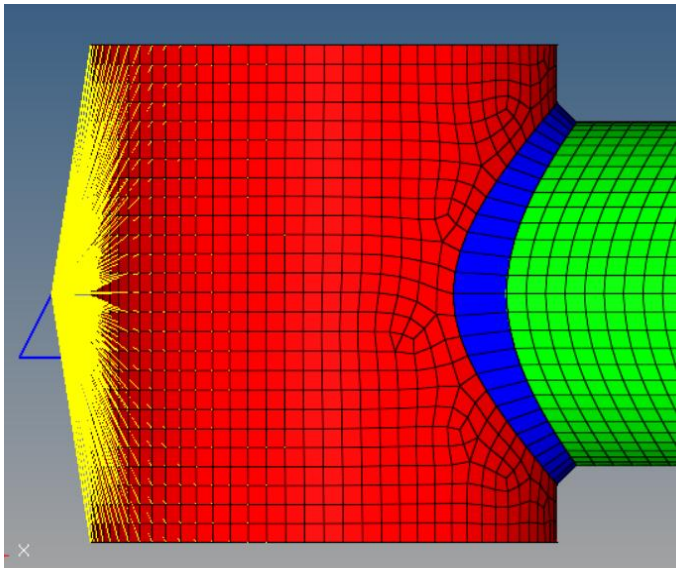
e Prediction of Welded Component

FEA model is built according to the measured average dimensions and nCode modeling guildeline

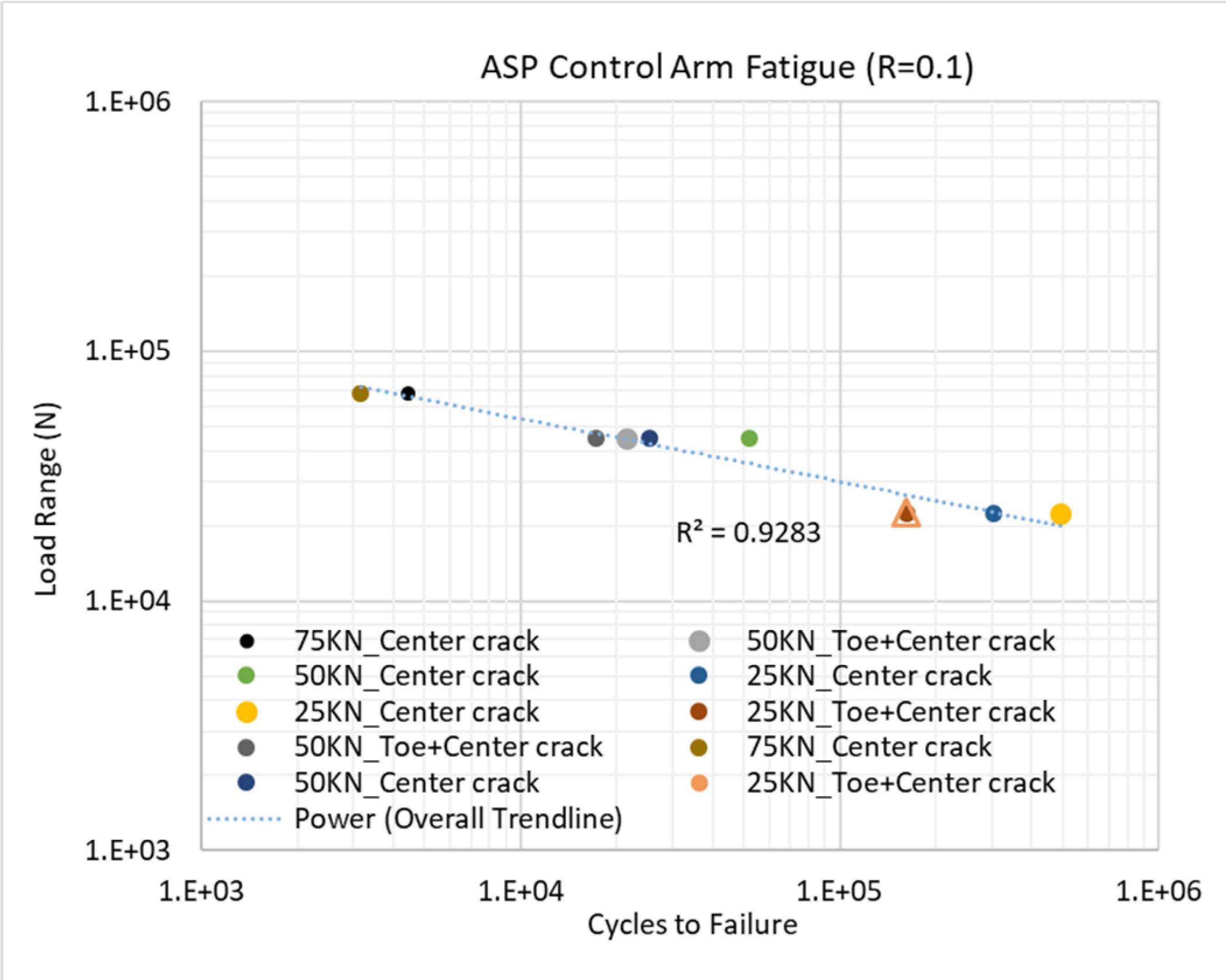
The mesh size for chord and brace is around 2 mm

Life prediction is made before testing





e Prediction of Welded Component



e Prediction of Welded Component

e below SN curves obtained from coupon fatigue data will be used for pred
e control arm

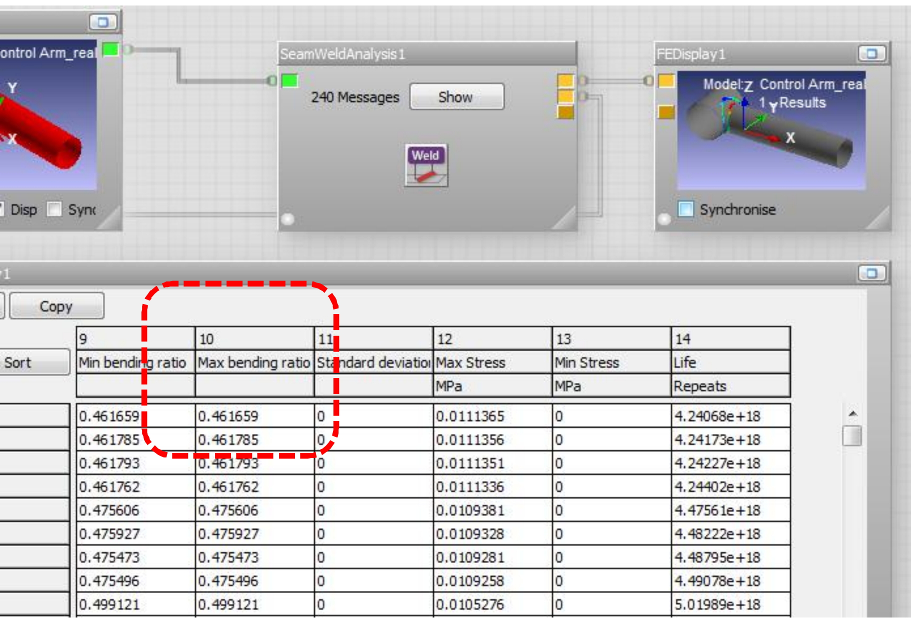
Approach	Bending Ratio	Trendline Equation
nCode	r=0 (stiff)	$y = 14416x^{-0.345}$
	r=1 (flex)	$y = 21770x^{-0.305}$
FeSafe	Any bending ratio	$y = 22648x^{-0.366}$
GSP	Any bending ratio	$y = 165444x^{-0.368}$

e Prediction Procedures – Constant Amplitude Testing

Coupon testing with different load ranges → Load Range vs. Life graph → FEA using load ranges as in testing → Establish S-N curve using different methods → Fatigue life prediction

e Prediction of Constant Amplitude Testing

imum Bending Ratio = 0.462, less than r_{th} = 0.5, the weld is considered
" and nCode S-N curve for r=0 will be used



9	10	11	12	13	14
Min bending ratio	Max bending ratio	Standard deviatio	Max Stress	Min Stress	Life
			MPa	MPa	Repeats
0.461659	0.461659	0	0.0111365	0	4.24068e+18
0.461785	0.461785	0	0.0111356	0	4.24173e+18
0.461793	0.461793	0	0.0111351	0	4.24227e+18
0.461762	0.461762	0	0.0111336	0	4.24402e+18
0.475606	0.475606	0	0.0109381	0	4.47561e+18
0.475927	0.475927	0	0.0109328	0	4.48222e+18
0.475473	0.475473	0	0.0109281	0	4.48795e+18
0.475496	0.475496	0	0.0109258	0	4.49078e+18
0.499121	0.499121	0	0.0105276	0	5.01989e+18

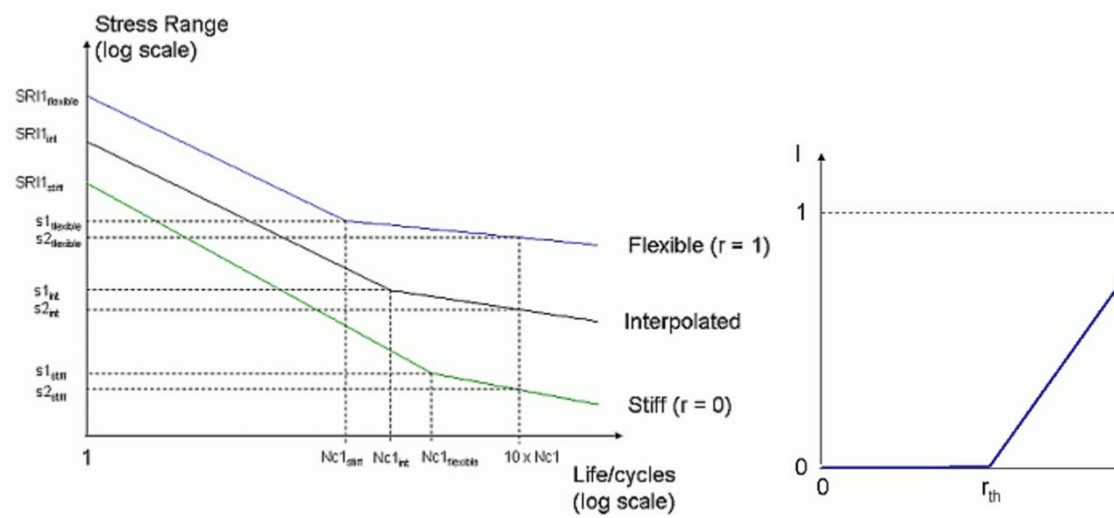
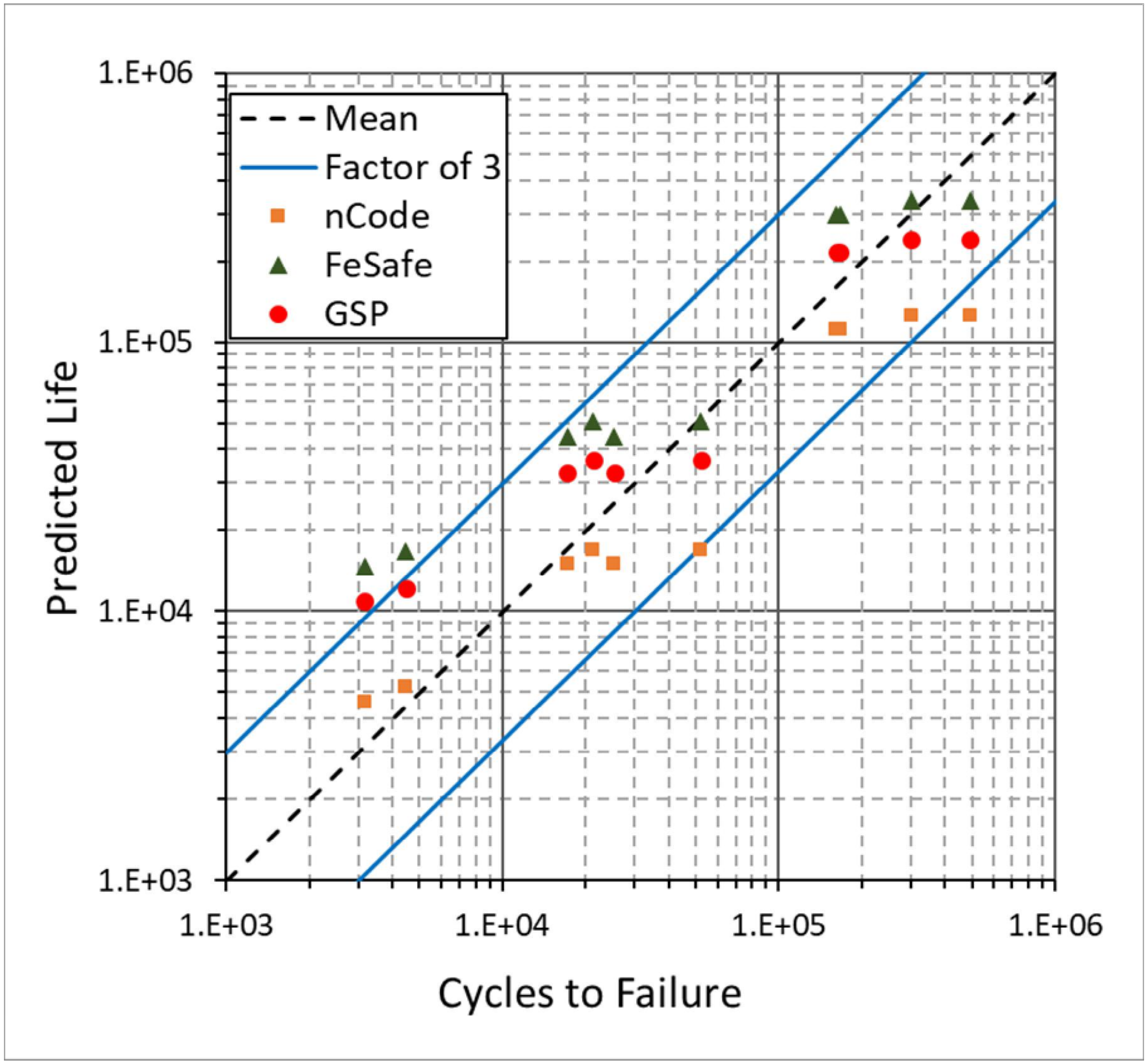


Fig. 5.5 (a) Interpolation between 'stiff' and 'bending' S-N curves (b) Interpolation

e Prediction of Constant Amplitude Testing



e Prediction Procedures – Variable Amplitude Testing

Input:
FEA results of control arm

Material:
Write S-N curves in material database

Loading:
Loading cycle input for each load scale factor.

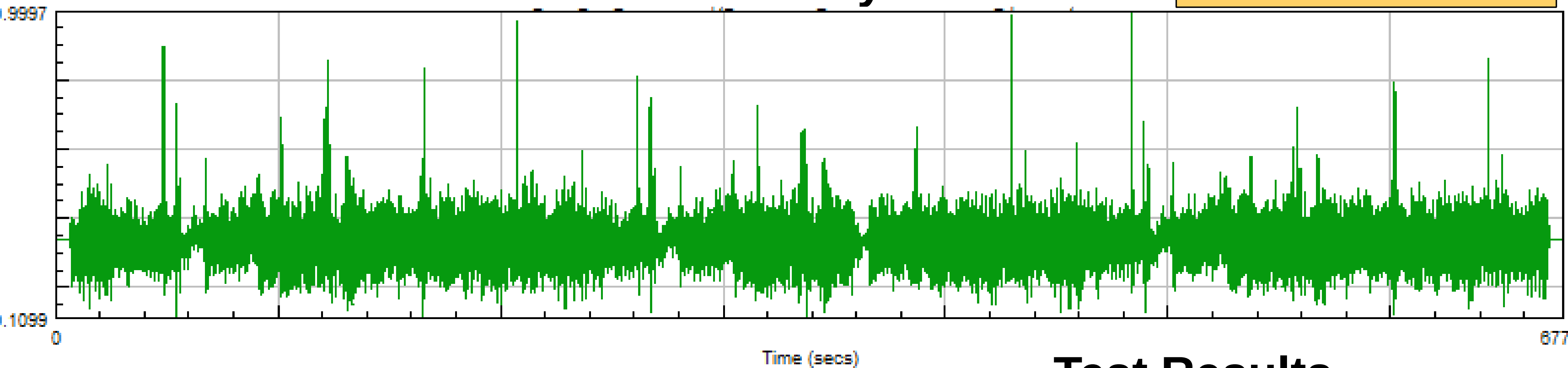
nCode Glyphworks: cycle counting and damage accumulation

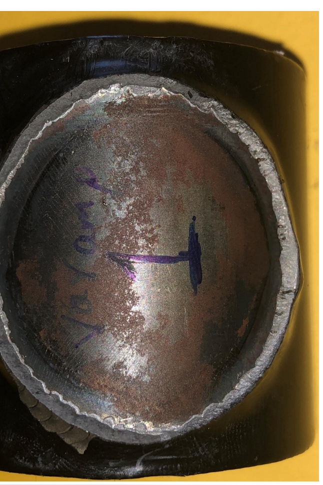
Life Prediction:
Blocks to failure is obtained

e Prediction of Variable Amplitude Testing

Time History Plot

~680 seconds per block

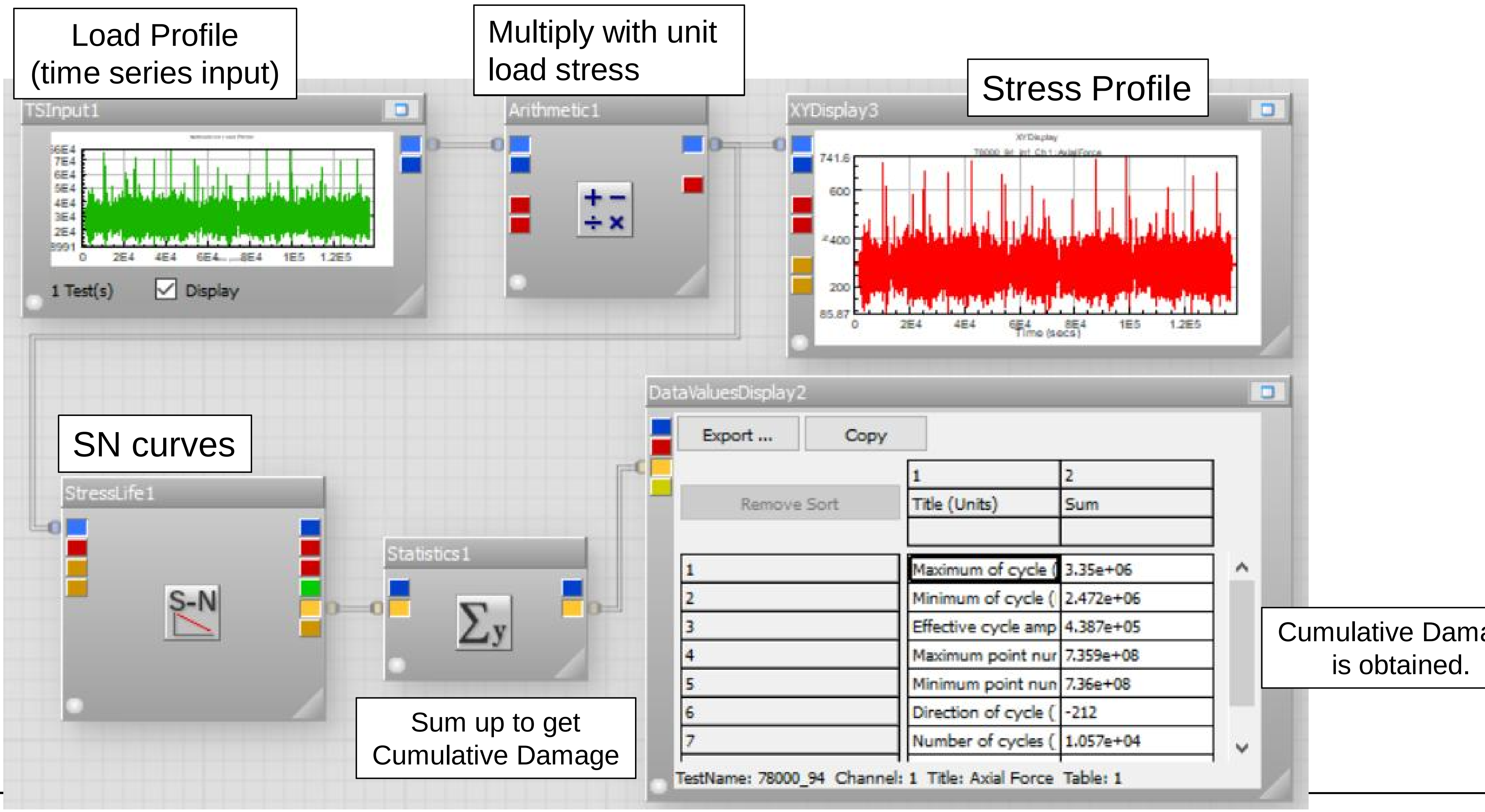




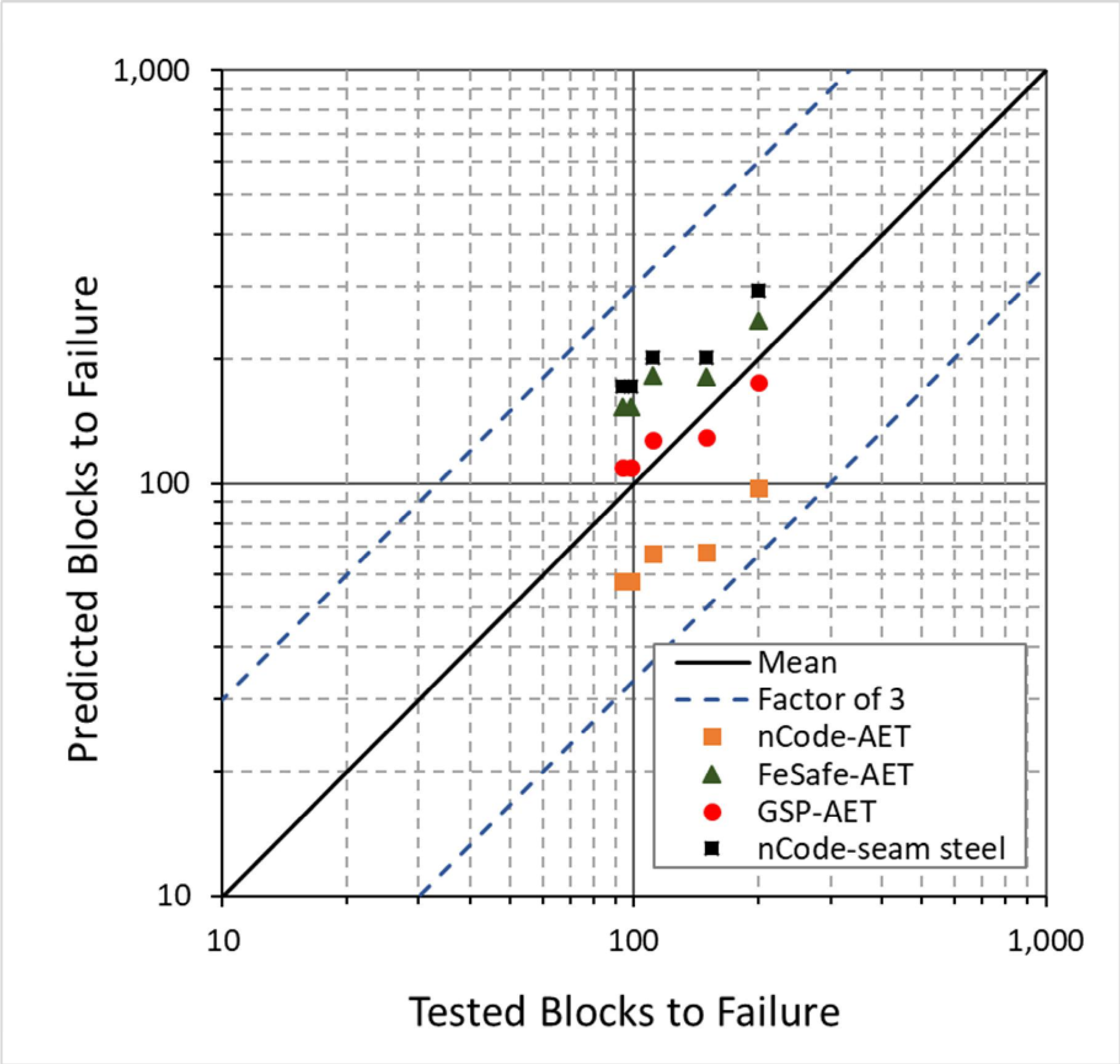
Test Results

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

e Prediction of Variable Amplitude Testing



e Prediction of Variable Amplitude Testing



nclusions

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)

knowledgements

Financial support from Auto/Steel Partnership is appreciated

Thank AET Integration Inc. for providing coupon fatigue testing data

Thank group member, Siva Vikranth Vayugundla, for fatigue testing on control arm and data processing on variable amplitude loading

THANK YOU !

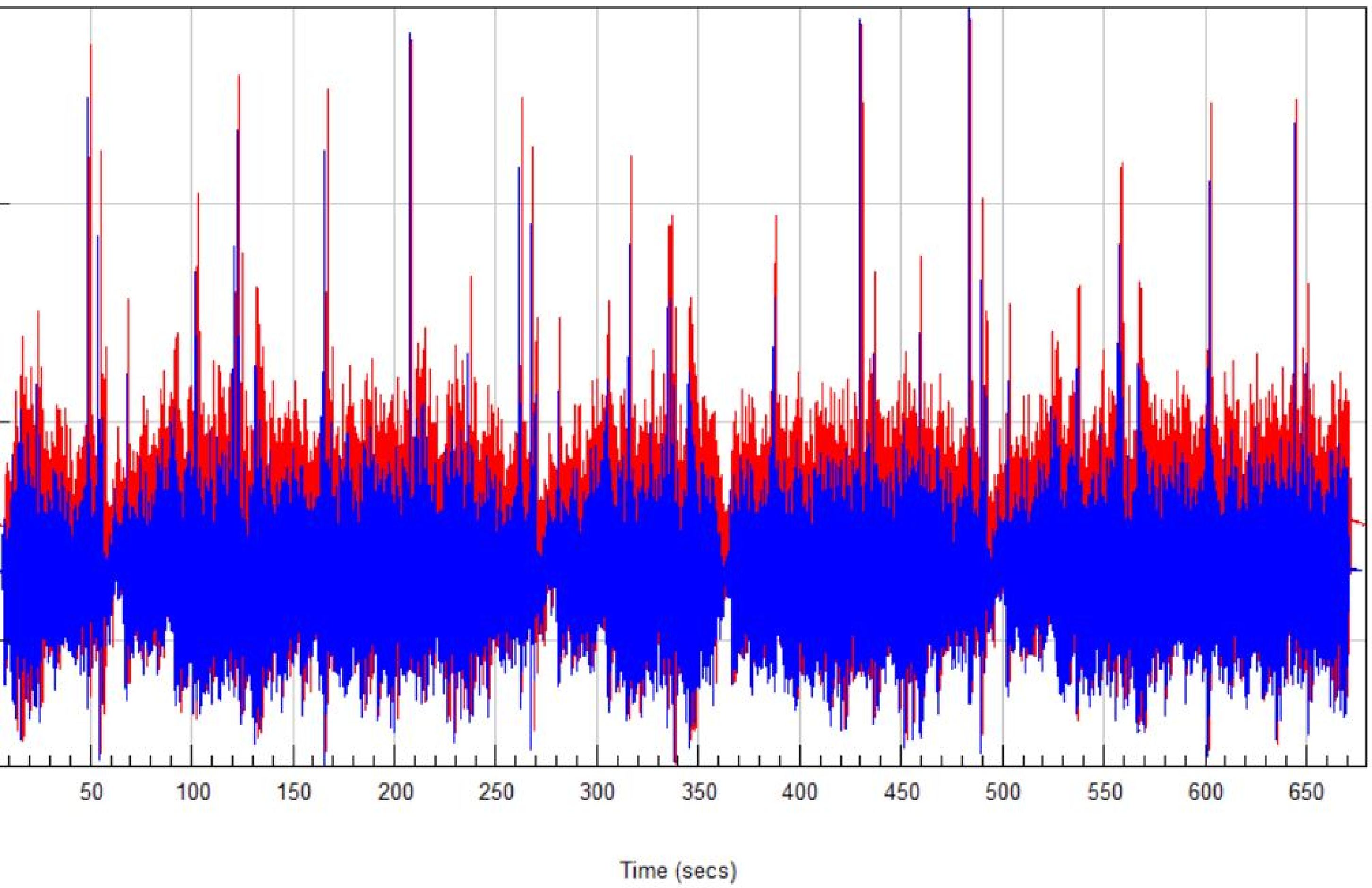
College of Engineering & Computer Science

UNIVERSITY OF MICHIGAN-DEARBORN

BACKUP

t Load Profile vs Machine Response

machine response has higher load values at peaks which causes higher damage than the input pro
diction was done using both profiles to show how the results differ.



---- Input Profile

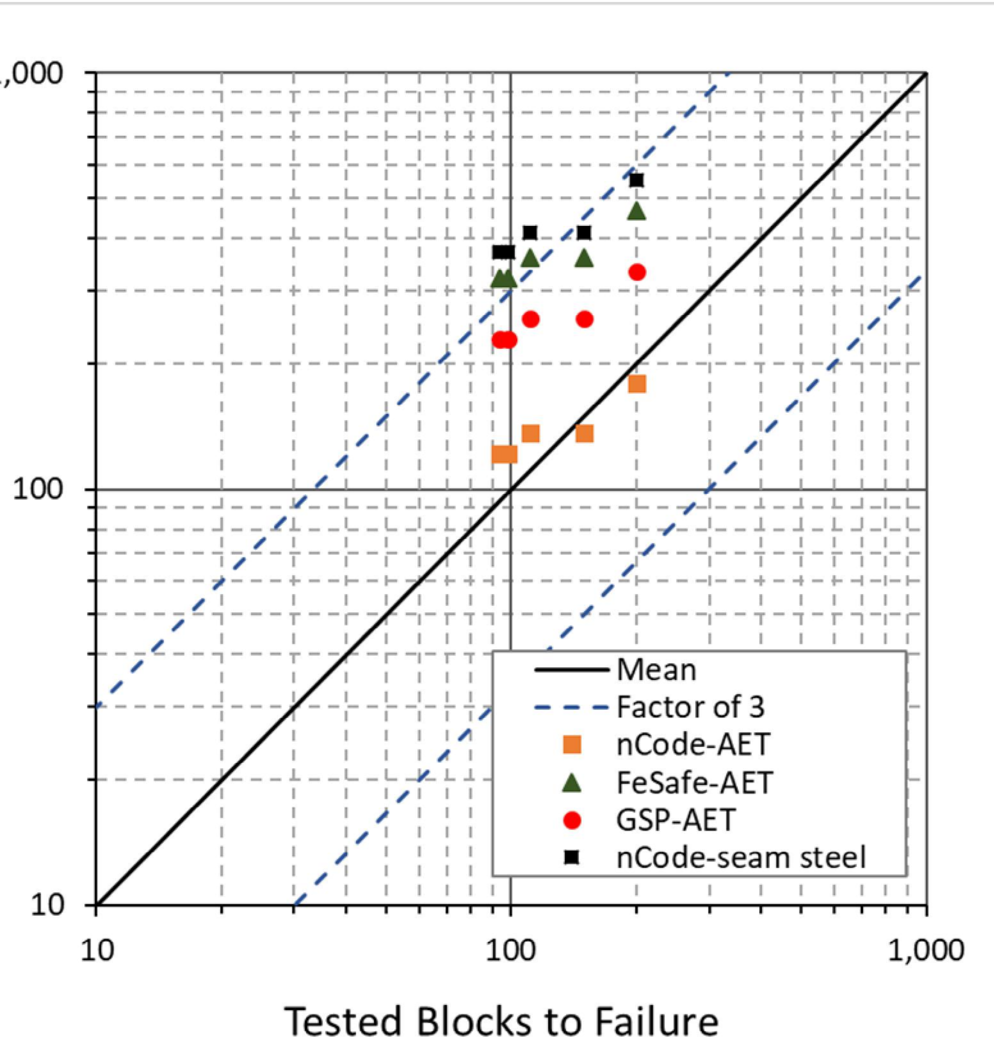
---- Machine Response

*Machine response is the actu
load experienced by the contr
arm during testing.

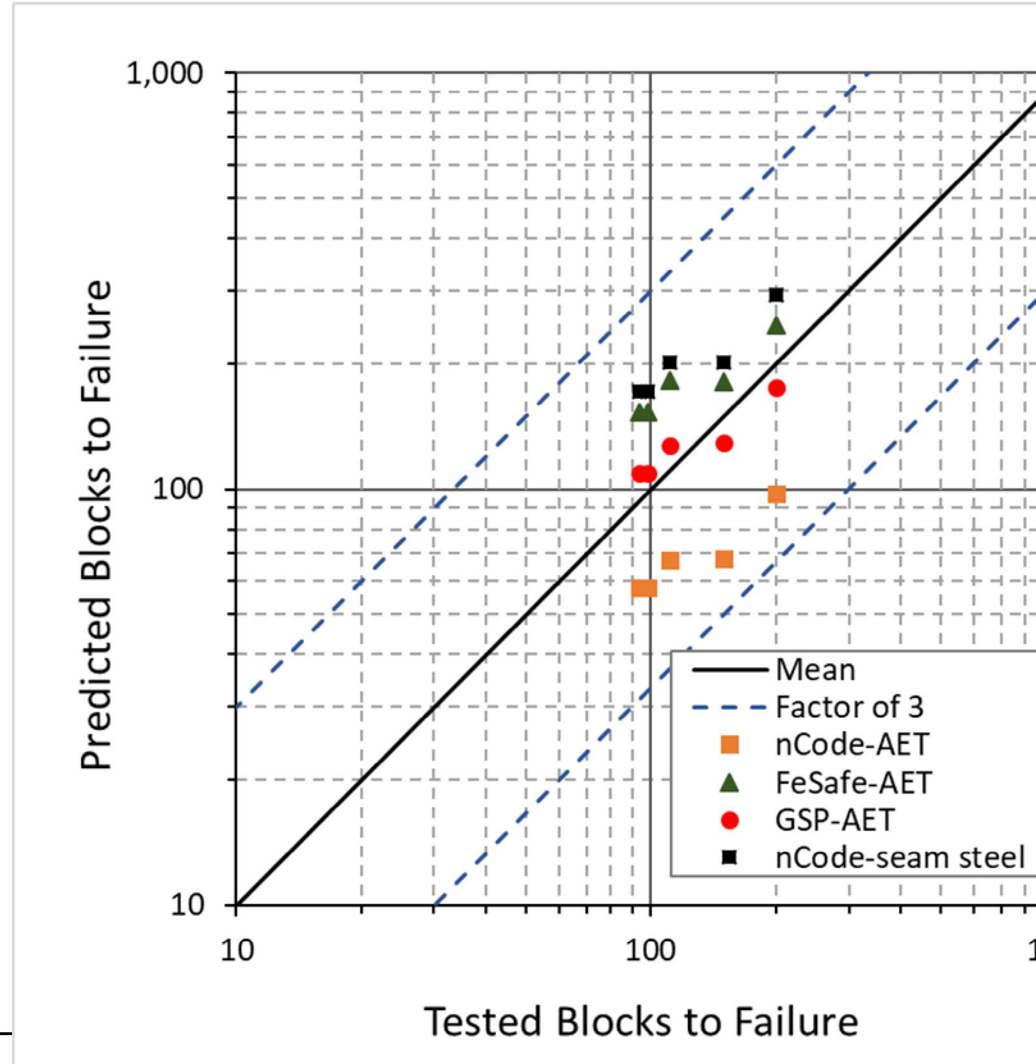
“Overshooting” happened a
variable amplitude loading

iction with Input Load Profile and Machine Response

Input Load Profile



Machine Response

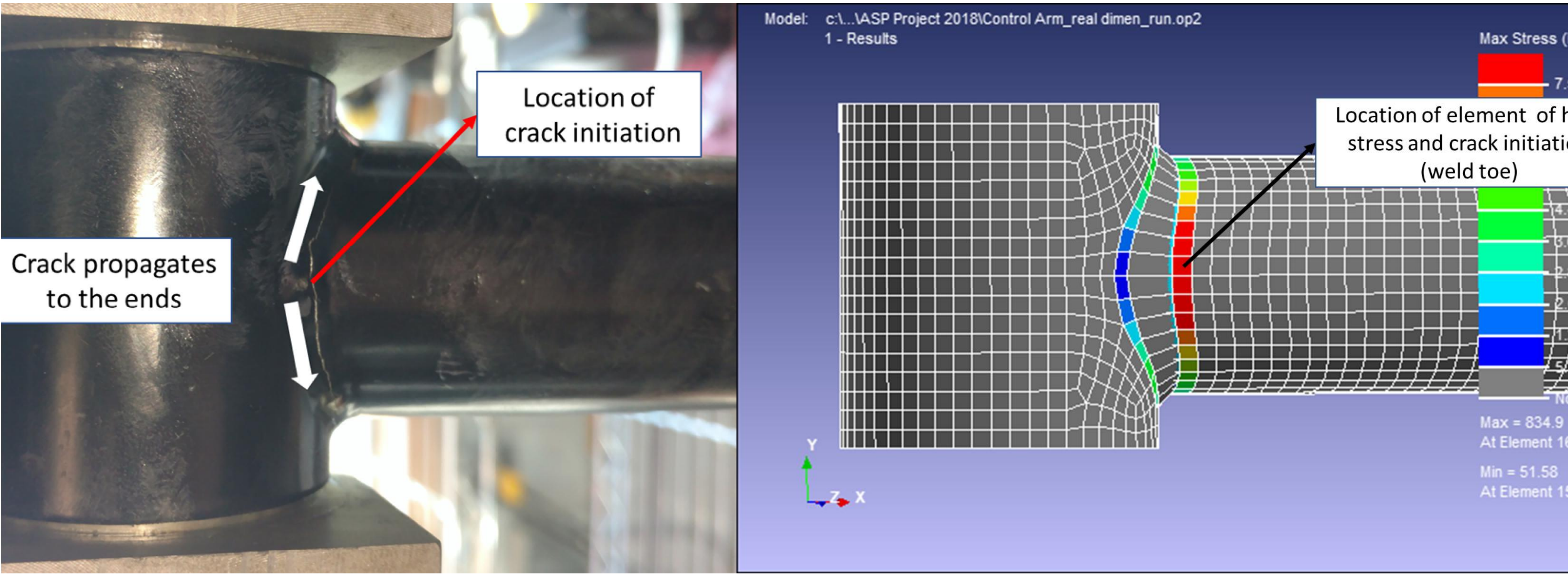


ness Testing of Control Arm Material

e control arm is constructed from heavy steel tubing. The hardness of the control arm material was und by testing polished samples with Rockwell hardness tester. The hardness of the brace and the ord were found to be 83 HRB and 74 HRB respectively. This proved that the control arm consisted o o different grades of heavy duty steel tubes with a seam-weld joint at the interface.

Control Arm is cut into small samples → Grinded and Polished to make them flat → Parameters set for Hardness Test (HRB) → Four measurements are taken and averaged.

re Location in Testing and FEA Analysis



ilure occurred in the weld close to the chord in majority of the control arms. It appears to be

failure.