Probabilistic 2D Fracture Mechanics Analysis of HFMI Treatment Effects on Structural Steel Welds

Rakesh Ranjan

Prof. Scott Walbridge

UNIVERSITY OF WATERLOO

Presentation Outline

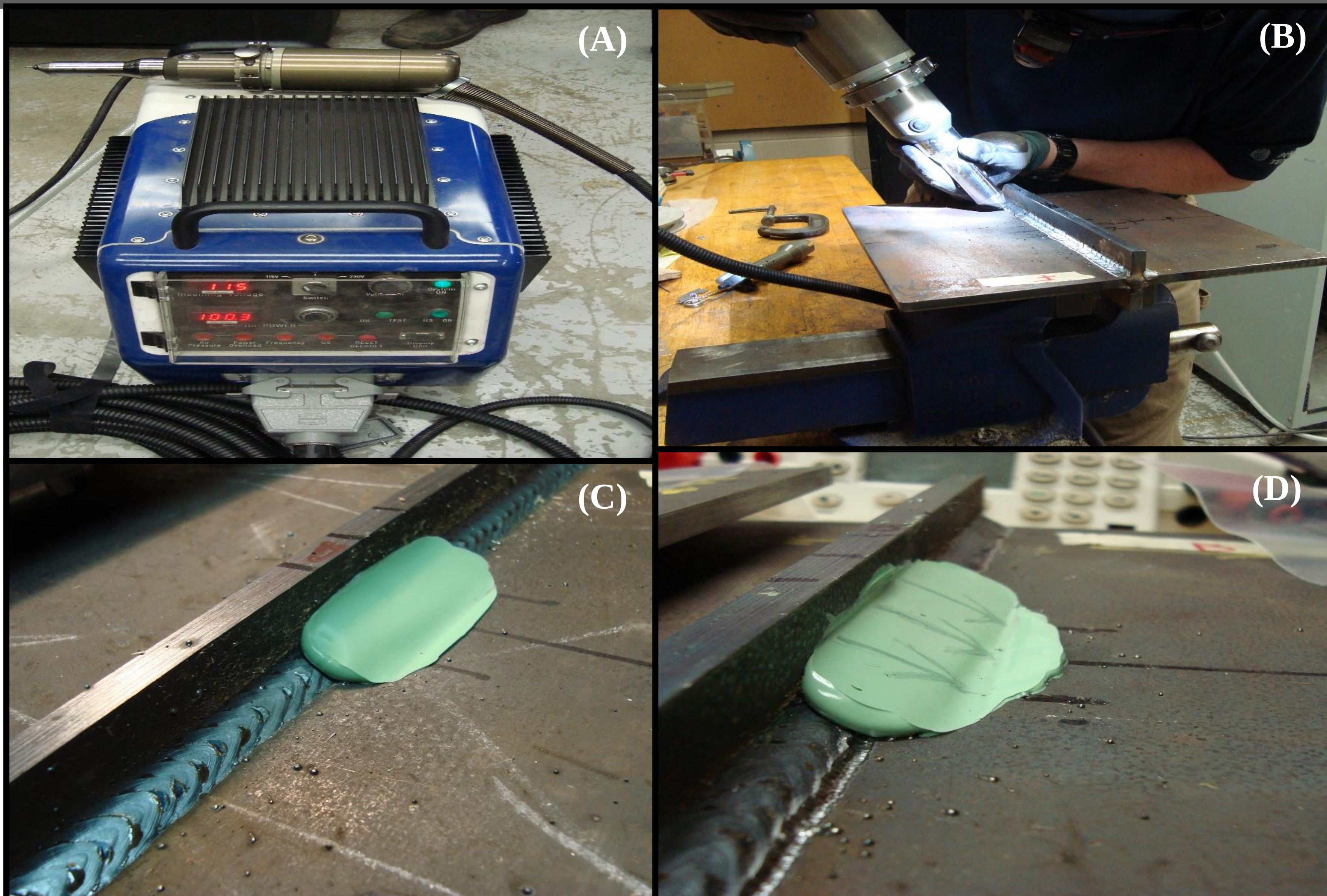
- Introduction & Background
- Objectives
- Methodology
- Results and Conclusions

Welded Joint

- **Stress Concentration**
- **Tensile Residual Stress**
- **Welding Defect**

[https://www.mig-welding.co.uk/arc-fillet-joints/fillet-root-large.jpg]

HFMI Treatment



Process to Obtain Design Curve

- Perform statistical analysis of fatigue test data
- Obtain design S-N curves corresponding to 95% survival probability

- Experimental testing is expensive and time consuming

- Models for fatigue analysis (SBFM, NASGROW, UNIGROW etc.) are needed
- This will reduce the required experimental fatigue test data to develop design provisions

Improvements Needed in 1D SBFM

- Existing 1D SBFM model did not allow parameters to be properly investigated that affect the crack shape and ultimately the fatigue life.

- The existing model has been shown to be systematically conservative in predicting the fatigue performance of impact treated welds under VA loading (Ghahremani 2015).

- Only superficial attempts (Rambault 2016; Walbridge et al. 2012) have been made to-date to implement the model in a probabilistic framework.

UNIVERSITY OF WATERLOO

Objectives

- **Improvement and extension of 1D SBFM model**

Improvement in failure criterion, implementation of weight function method, modelling of crack closure at the deepest and surface points of the crack

- **Validation of 2D SBFM model**

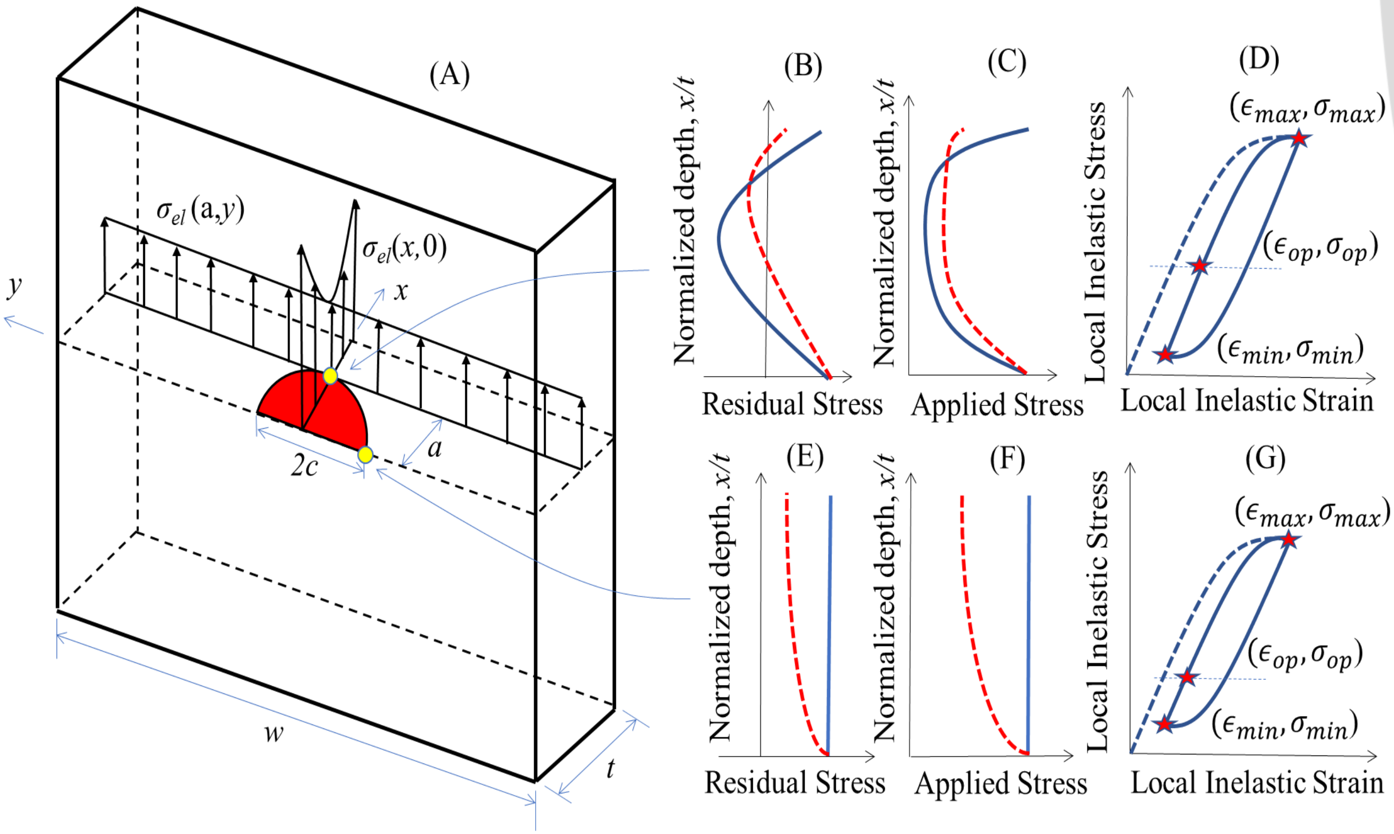
Validation of the model using experimental test results

- **Probabilistic analysis**

Sensitivity analysis, reliability based design S-N curves

UNIVERSITY OF WATERLOO

Conceptual Sketch of 2D SBFM

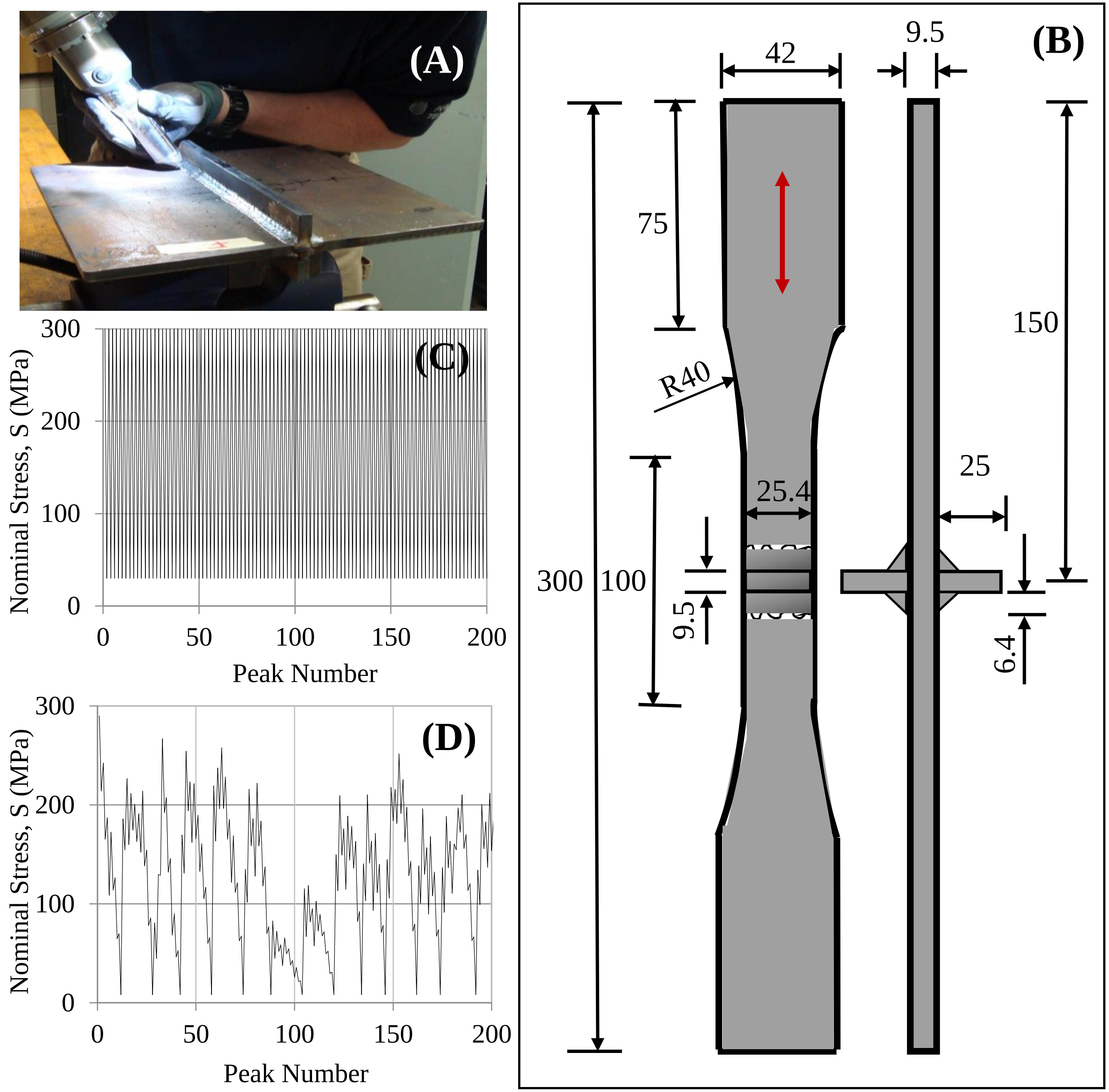


UNIVERSITY OF WATERLOO

Key Equations Involved in 2D SBFM

	Deepest Point (a)	Surface Point (c)
1	$\frac{da}{dN} = C \cdot \mathrm{MAX}\left(\left(\Delta K_{eff,a} - \Delta K_{th}\right)^m, 0\right)$	$\frac{dc}{dN} = C \cdot \mathrm{MAX}\left(\left(\Delta K_{eff,c} - \Delta K_{th}\right)^m, 0\right)$
2	$\Delta K_{eff,a} = K_{max,a} - \mathrm{MAX}\left(K_{op,a}, K_{min,a}\right)$	$\Delta K_{eff,c} = K_{max,c} - \mathrm{MAX}\left(K_{op,c}, K_{min,c}\right)$
3	$K_a = Y_a \cdot E \cdot \varepsilon_a \cdot \sqrt{\pi \cdot (a + a_0)}$	$K_c = Y_c \cdot E \cdot \varepsilon_c \cdot \sqrt{\pi \cdot (a + a_0)}$
4	$Y_a = \frac{\int_0^a m_a(x,a,c,t)\mathrm{d}x}{\sqrt{\pi \cdot a}}$	$Y_c = \frac{\int_0^a m_c(x,a,c,t)\mathrm{d}x}{\sqrt{\pi \cdot a}}$
5	$\alpha = 1.78 - 0.628 \cdot Y_a \cdot \mathrm{MIN}\left(\frac{\sigma_{\max,a}}{\sigma_0}, 1.0\right)$	$\alpha = 1.2$
6	$\sigma_{op,a} = \sigma_{cu,a} + \mu \cdot \left(\sigma_{ss,a} - \sigma_{cu,a}\right)$	$\sigma_{op,c} = \sigma_{cu,c} + \mu \cdot \left(\sigma_{ss,c} - \sigma_{cu,c}\right)$
7	$\sigma'_{el,app,a} = \frac{\int_0^a \sigma_{el,app}(x) \cdot m_a(x,a,c,t)\mathrm{d}x}{\sqrt{\pi \cdot a}}$	$\sigma'_{el,app,c} = \frac{\int_0^a \sigma_{el,app}(x) \cdot m_c(x,a,c,t)\mathrm{d}x}{\sqrt{\pi \cdot a}}$
8	$\sigma'_{el,r,a} = \frac{\int_0^a \sigma_{el,r}(x) \cdot m_a(x,a,c,t)\mathrm{d}x}{\sqrt{\pi \cdot a}}$	$\sigma'_{el,r,c} = \frac{\int_0^a \sigma_{el,r}(x) \cdot m_c(x,a,c,t)\mathrm{d}x}{\sqrt{\pi \cdot a}}$
9	$\sigma_{el,a} = \sigma'_{el,app,a} + \sigma'_{el,r,a}$	$\sigma_{el,c} = \sigma'_{el,app,a} + \sigma'_{el,r,c}$

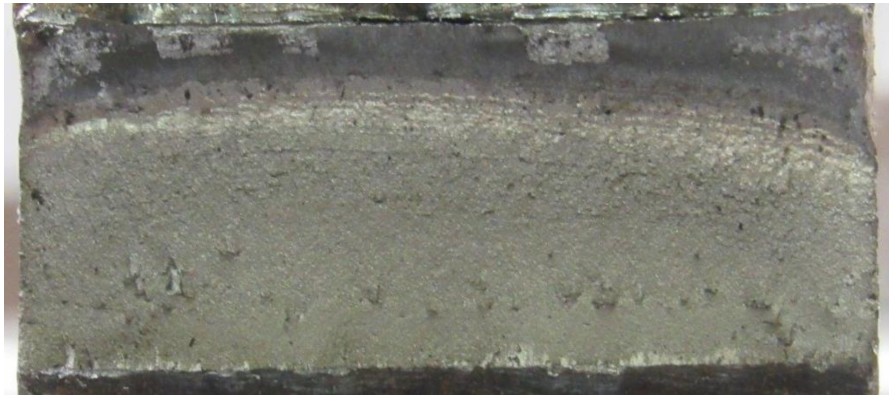
Experiment Details



Fracture Surface of As-Welded Specimens, VA Loading

ΔS_{eq} = 58 MPa, S_{max} = 167 MPa, N = 8203000

ΔS_{eq} = 78 MPa, S_{max} = 226 MPa, N = 1921000

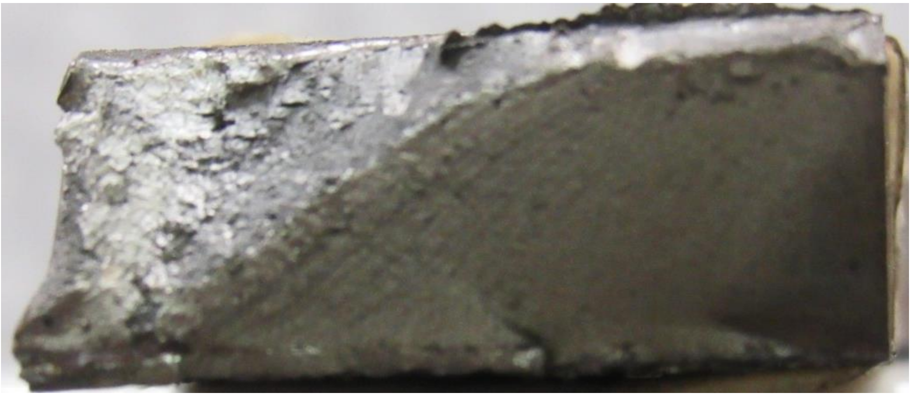


ΔS_{eq} = 111 MPa, S_{max} = 319 MPa, N = 1041000

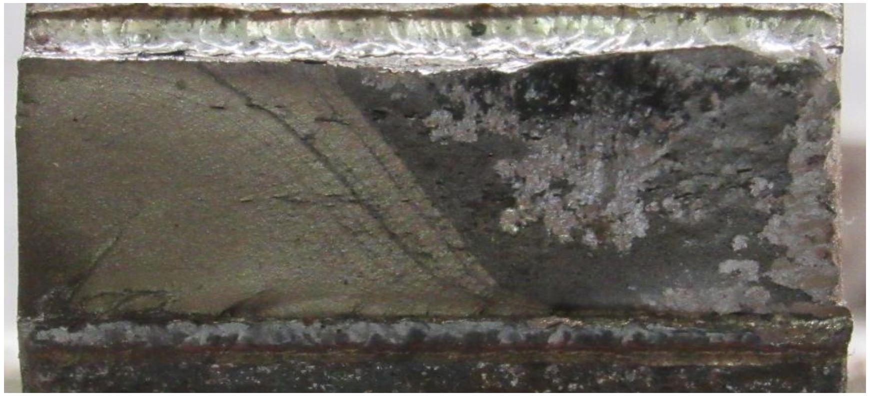
ΔS_{eq} = 134 MPa, S_{max} = 387 MPa, N = 627000

Fracture Surface of HFMI Treated Specimens, VA Loading

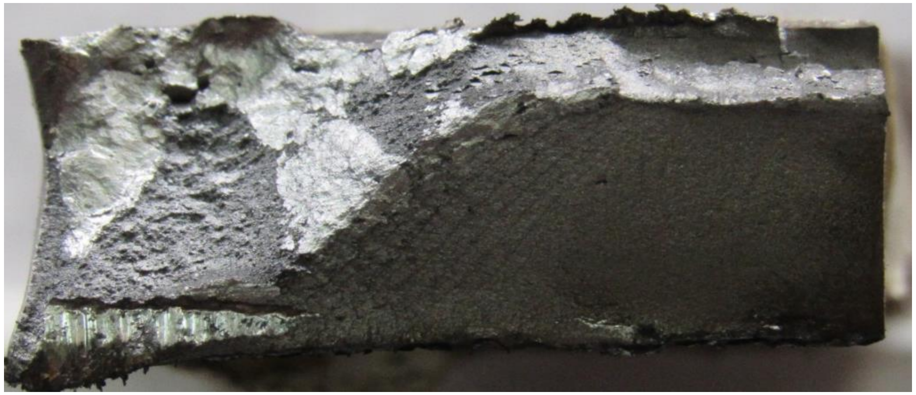
ΔS_{eq}= 133 MPa, S_{max}= 295 MPa, N = 13600000



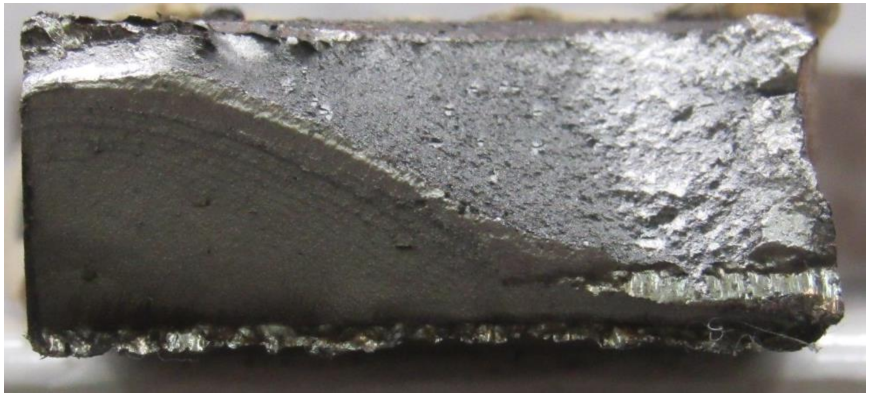
ΔS_{eq}= 143 MPa, S_{max}= 319 MPa, N = 27646000



ΔS_{eq}= 153 MPa, S_{max}= 341 MPa, N = 6593000



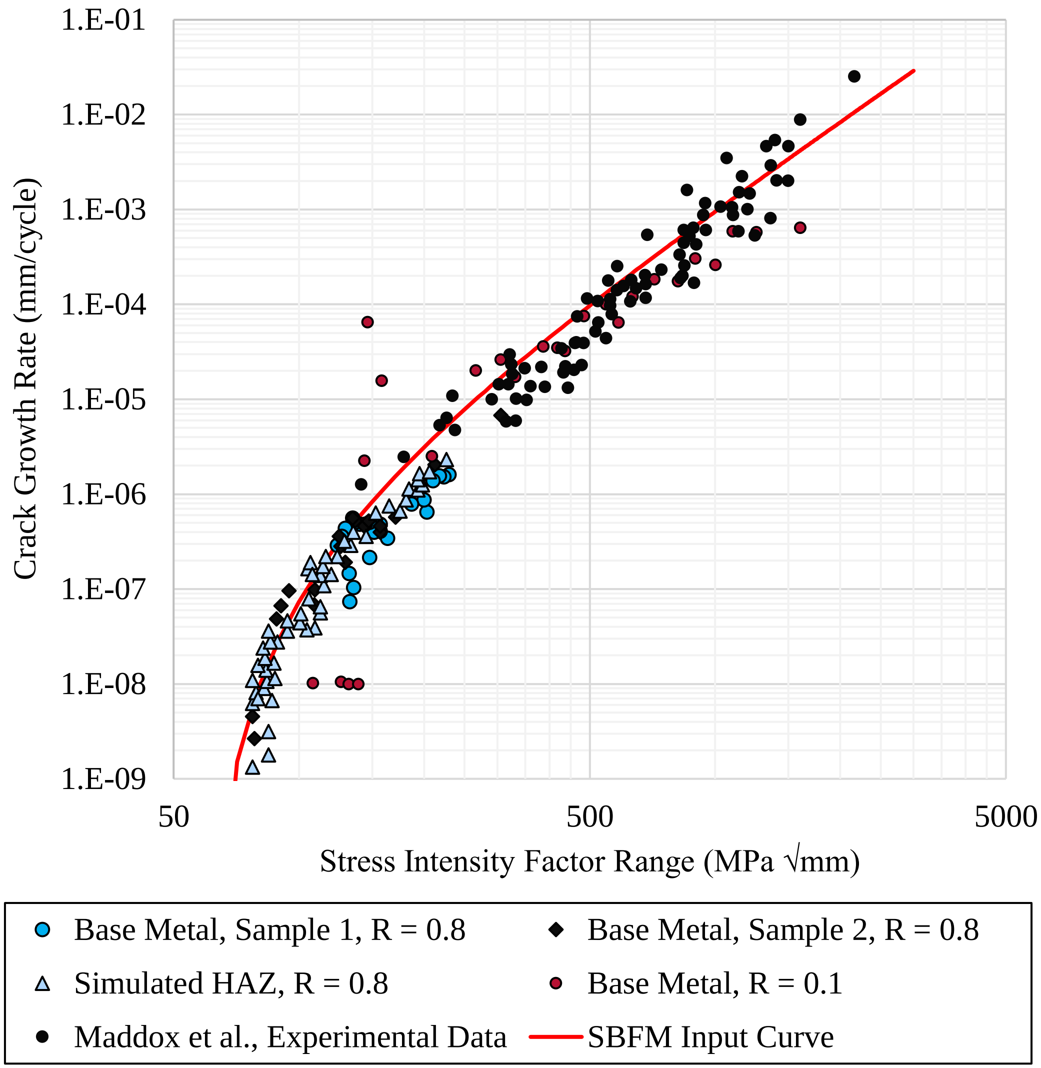
ΔS_{eq}= 174 MPa, S_{max}= 387 MPa, N = 1818000



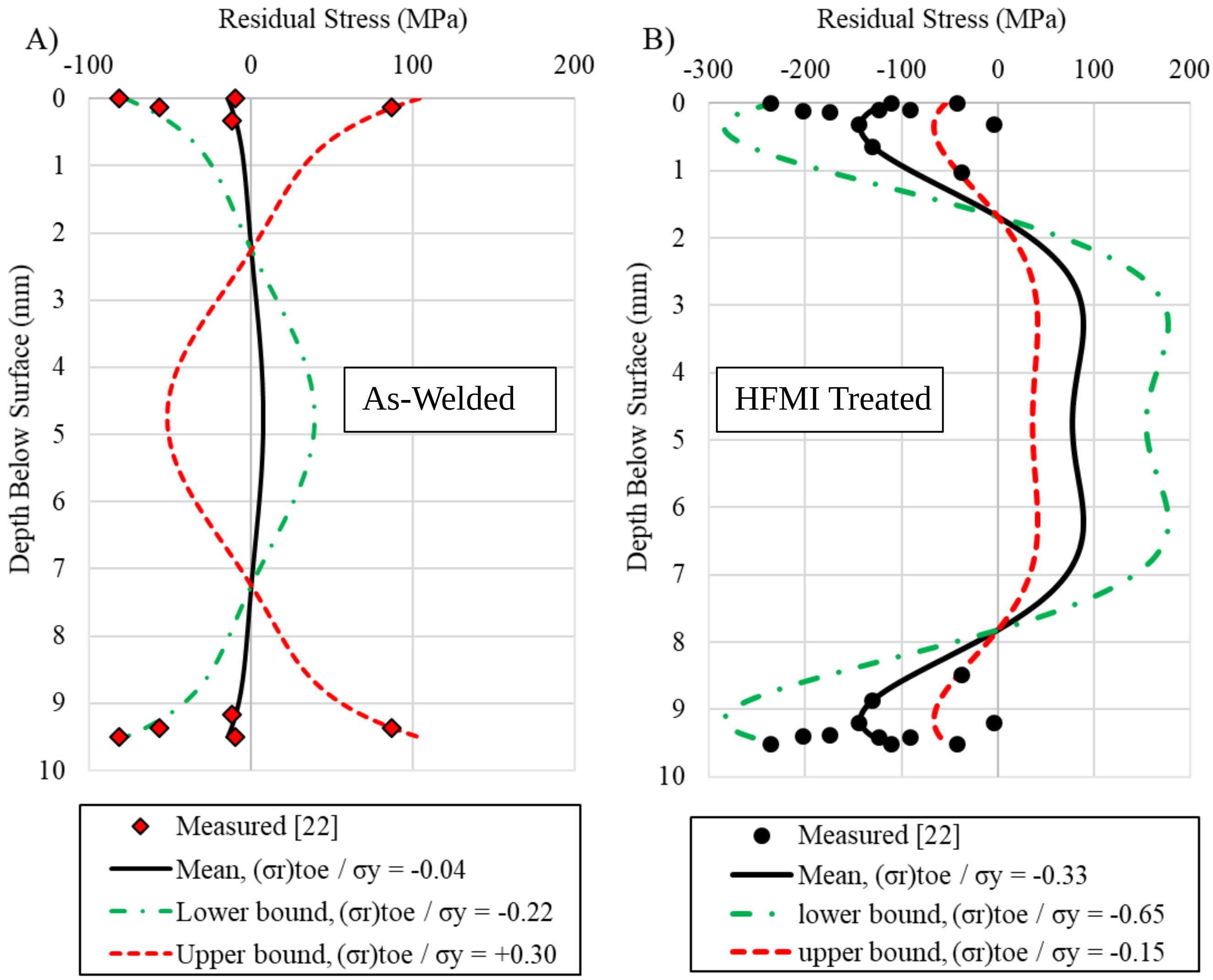
Input Data Used for 2D SBFM Analysis

Input Parameter	350W Steel	Units
t	9.5	mm
E	208083	MPa
σ_y	356	MPa
σ_u	616	MPa
LN(C)	-27.5	MPa, mm
m	3.0	MPa, mm
ΔK_{th}	60	MPa·√mm
K'	812.0	MPa
n'	0.108	-
a_i	0.15	mm
μ	0.018	-
$(a/c)_{initial}$	0.5	-

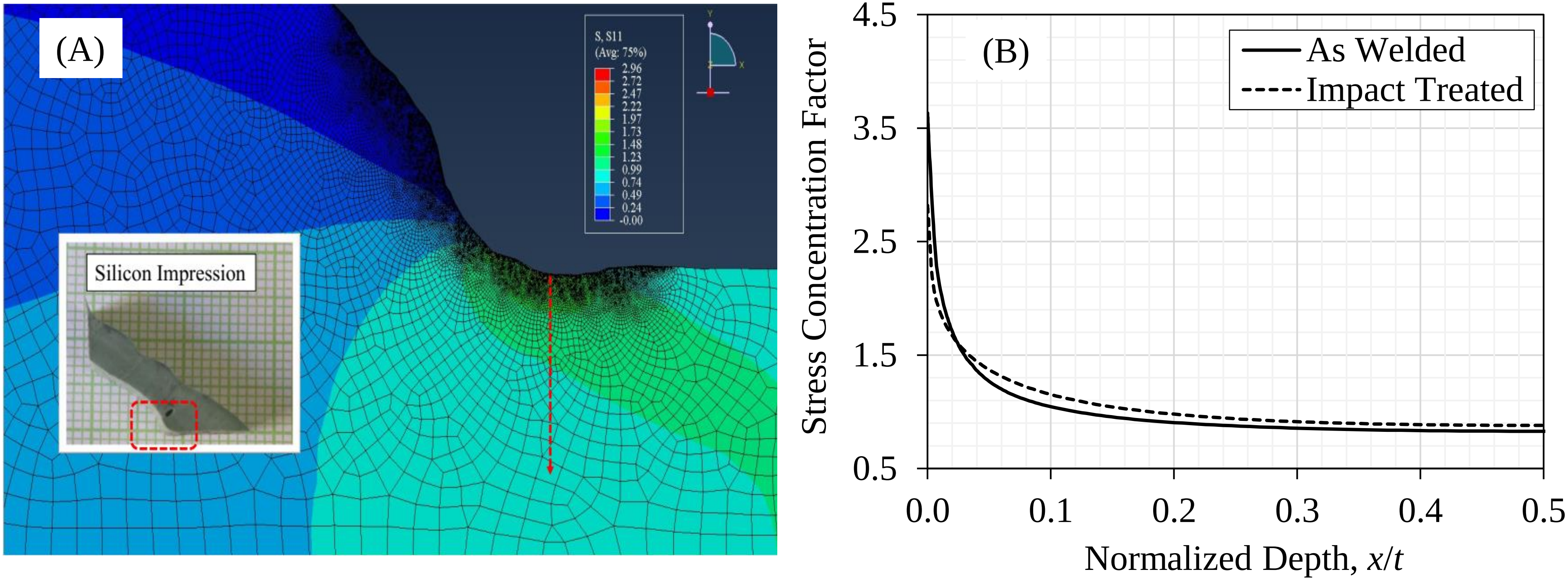
[Ghahremani 2015]



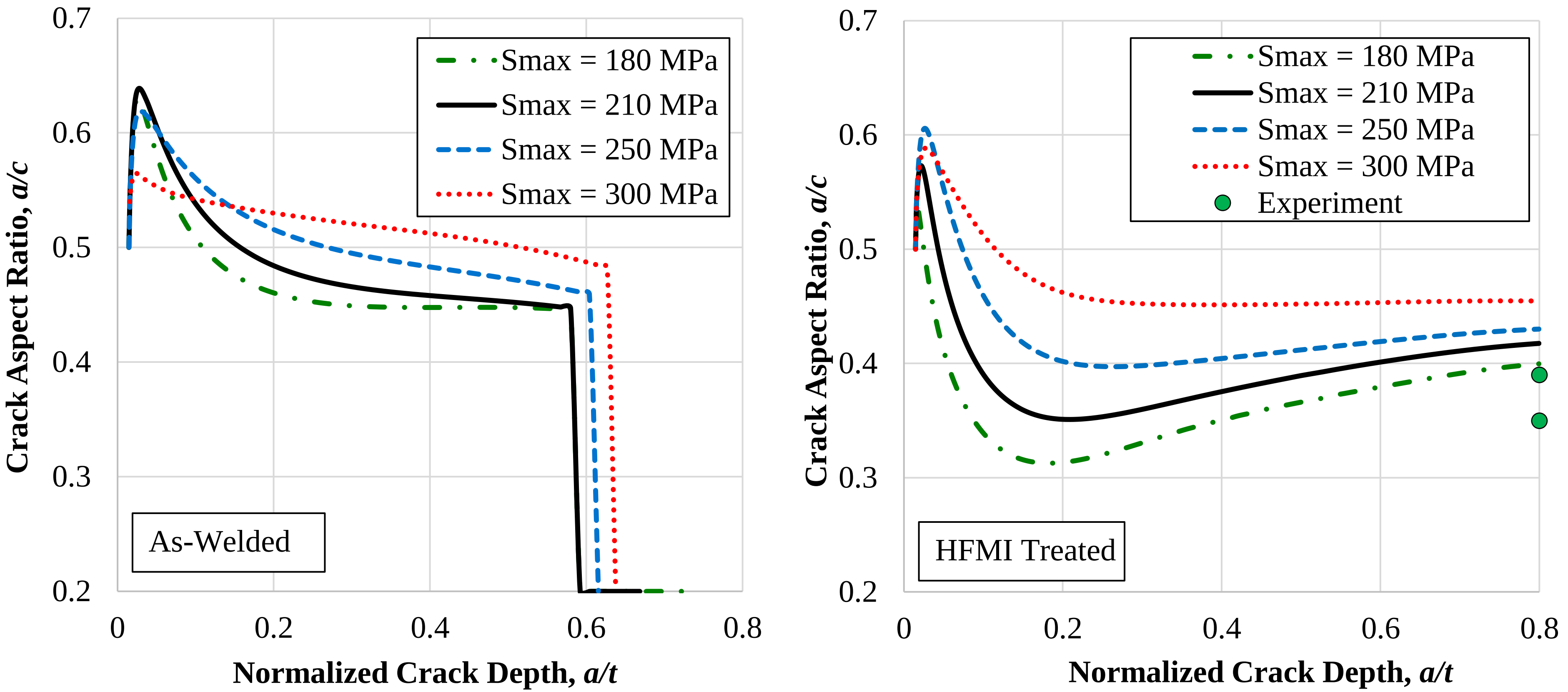
Residual Stress Distributions



FE Analysis Results



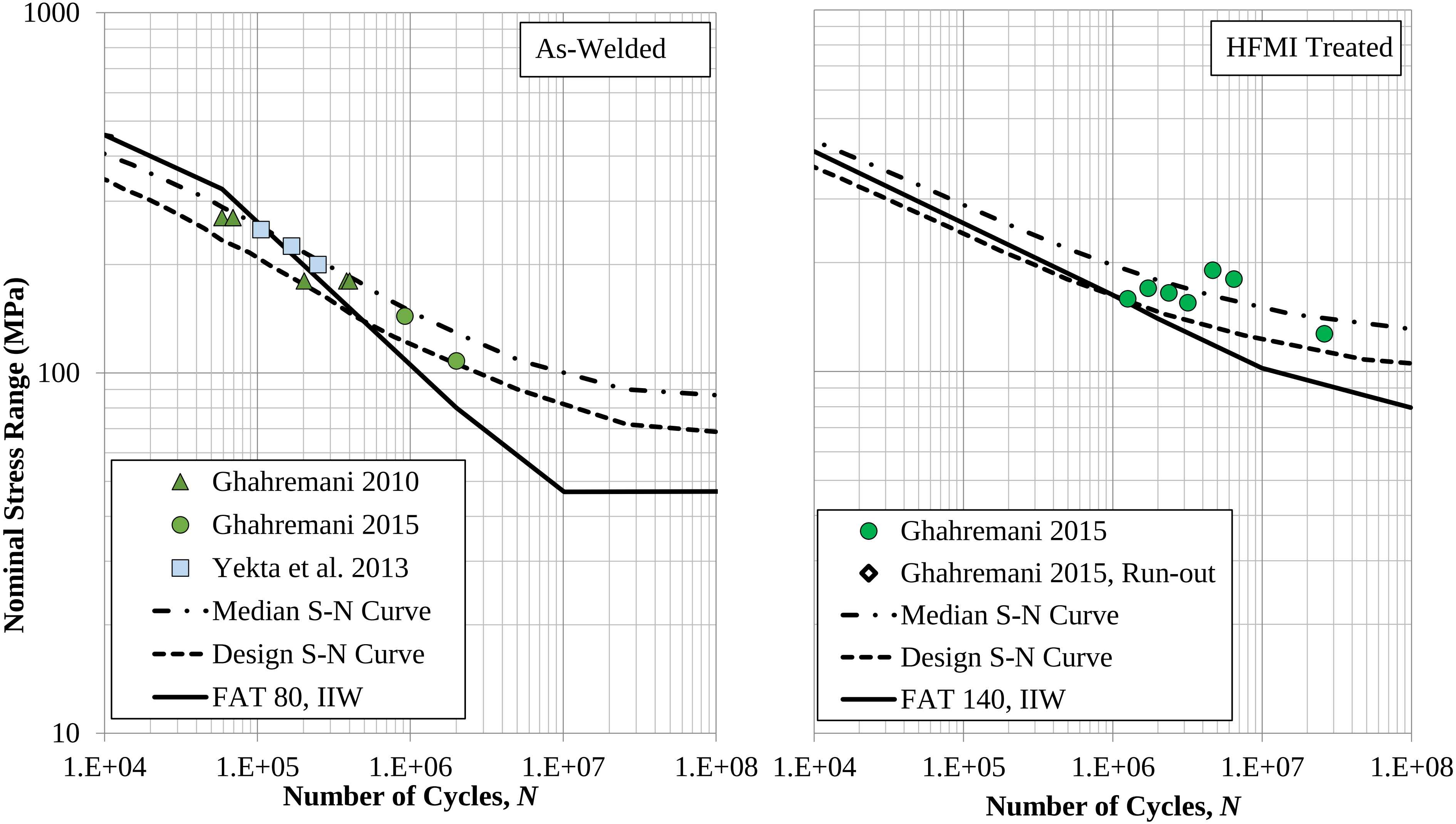
2D SBFM Analysis Results: CA Loading



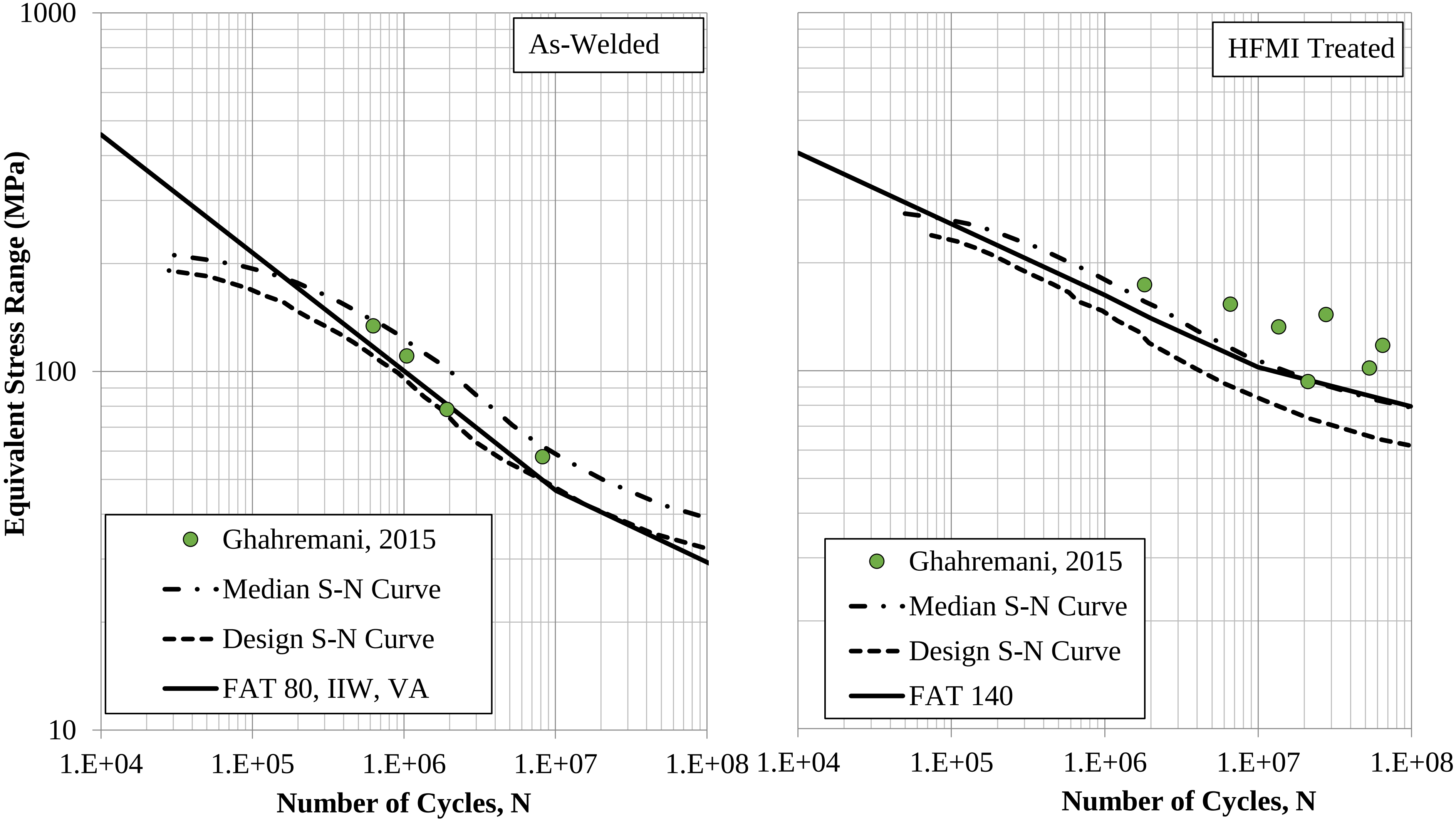
Input Data for Probabilistic Analysis

Symbol	Mean	COV	Distribution	References, Notes
LN(*C*)	-27.5	0.42	Lognormal	Lostberg et al. 2002
ΔK_{th}	60	0.07	Lognormal	BS 7910 - 2005
K'	812	0.05	Lognormal	Assumed
Var(σ_u)	1.0	0.07	Lognormal	BS 7910 - 2005
μ_{op}	0.018	0.5	Lognormal	Walbridge et al. 2012
a_i	0.15	0.3	Lognormal	Brückner et al. 1983
$(a/c)_{\mathrm{initial}}$	0.5	0.2	Lognormal	Righiniotis et al. 2003
Var (*SCF*)	1.0	0.07	Lognormal	JCSS (2011)
Var (σ_r)	1.0	1.25	Normal	As-Welded, Assumed
		0.3	Lognormal	Impact Treated, Assumed

Probabilistic Analysis Results: CA Loading



Probabilistic Analysis Results: VA Loading



Conclusions

- The model is capable of estimating the fatigue performance of HFMI treated welded joints under CA and VA loading conditions.
- The obtained design curves for the impact treated specimens under CA loading aligned well with the FAT 140 curve but fell below this curve under VA loading. This observation was made in previous 1D SBFM studies as well, suggesting that this is a feature of the SBFM modelling approach, which cannot be explained by the crack shape.
- Probabilistic analysis results show that the 2D SBFM model can be used as a tool to develop design S-N curves for HFMI treated welded joints.

Acknowledgements

- Financial Support: NSERC, CISC, MTO, GDLS Canada
- Pow Engineering, Applied Ultrasonics
- Waterloo Technicians: R. Morrison, D. Hirst, P. Volcic

UNIVERSITY OF WATERLOO