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THE MATERIALS JOINING EXPERTS

Strain-Based Design Final Presentation

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Disclaimers

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Introduction

Introductory Remarks

- Host
- Funding Agent - U.S. Government
- Funding Agent - PRCI
- EWI

Sponsorship

- 2(+) Year Project
- Sponsors
  - MMS of U.S. DOI
  - U.S. DOT
  - PRCI
- Meetings with General Industry
  - July 2004
  - June 2005
  - June 2006

Background (Phase 1)

- EWI Project for MMS and DOT on Strain-Based Design
  - Completed 2004
  - Survey of Information on Resistance to Failure
  - Guidance Document
  - Check Weld Effects
  - Both Compression and Tension

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Tasks for This Program (After Kick-Off Meeting)

- Review of Information on Soft Zones & Pressure
- More Realistic Models
- Tests for Materials and Welding Specs
- Materials and Welding Specifications
- Full Characterization of Stress-Strain Curves
- Reporting

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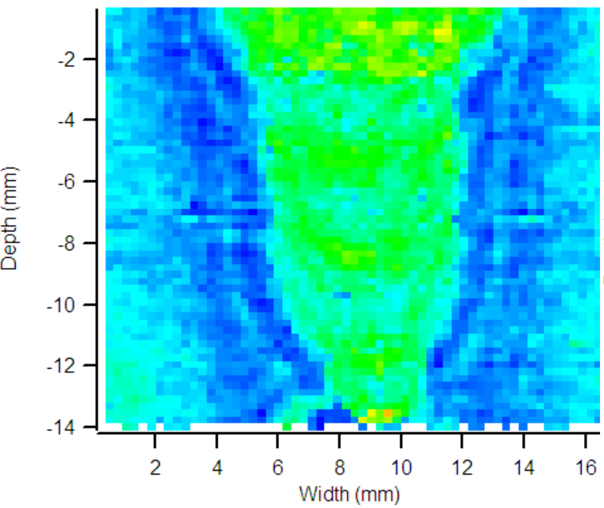
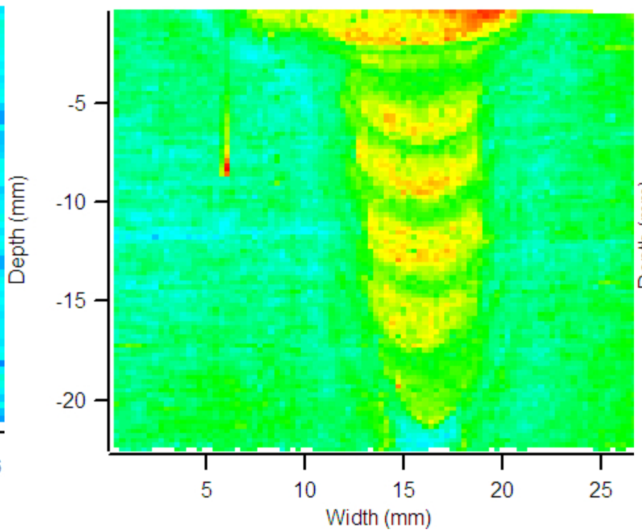
Testing

Hardness Map of X-100 Welds

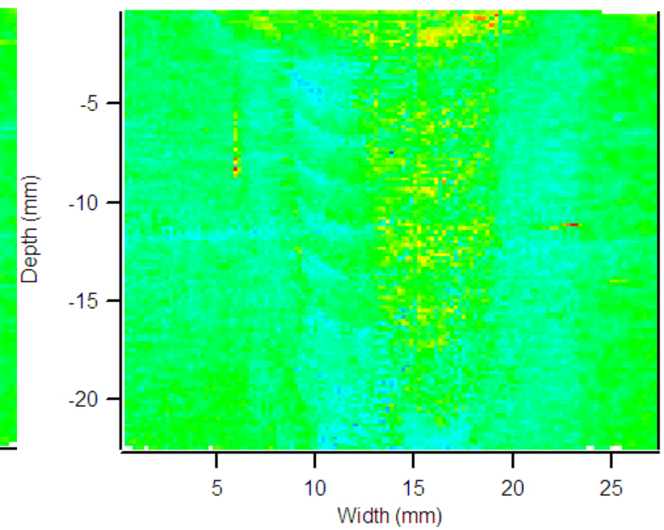
Weld 1

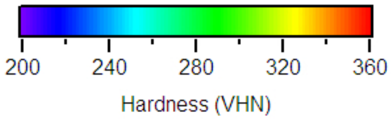


Weld 2a Dual Torch



Weld 2b Tandem





Stress-Strain Curve Tests

- Base Metal Longitudinal
- Base Metal Hoop
- All-Weld Metal
- Non-Standard Tests
  - Micro-Tensiles
  - Stub Tensiles

Micro-Tensiles

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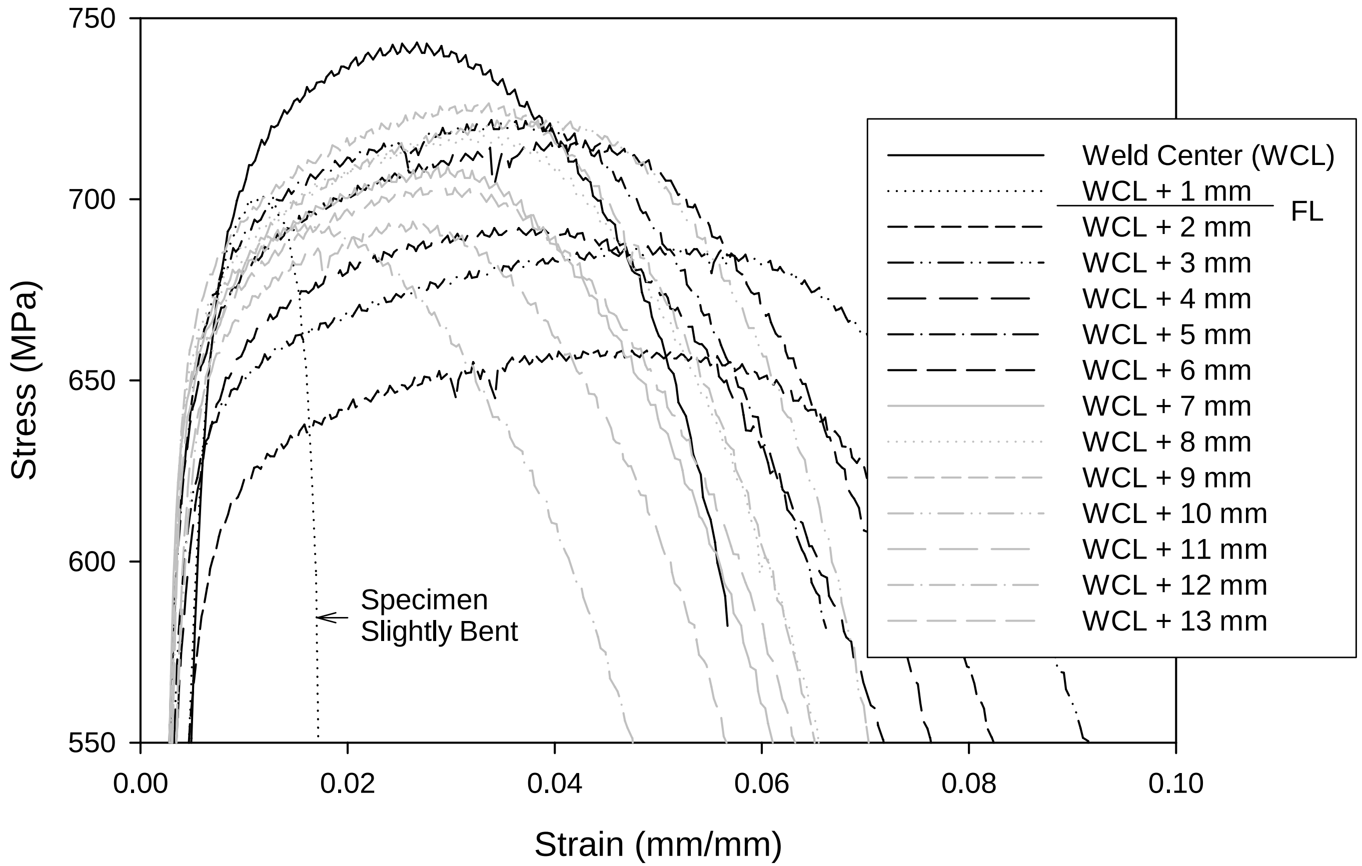
Weld 1 Softened HAZ



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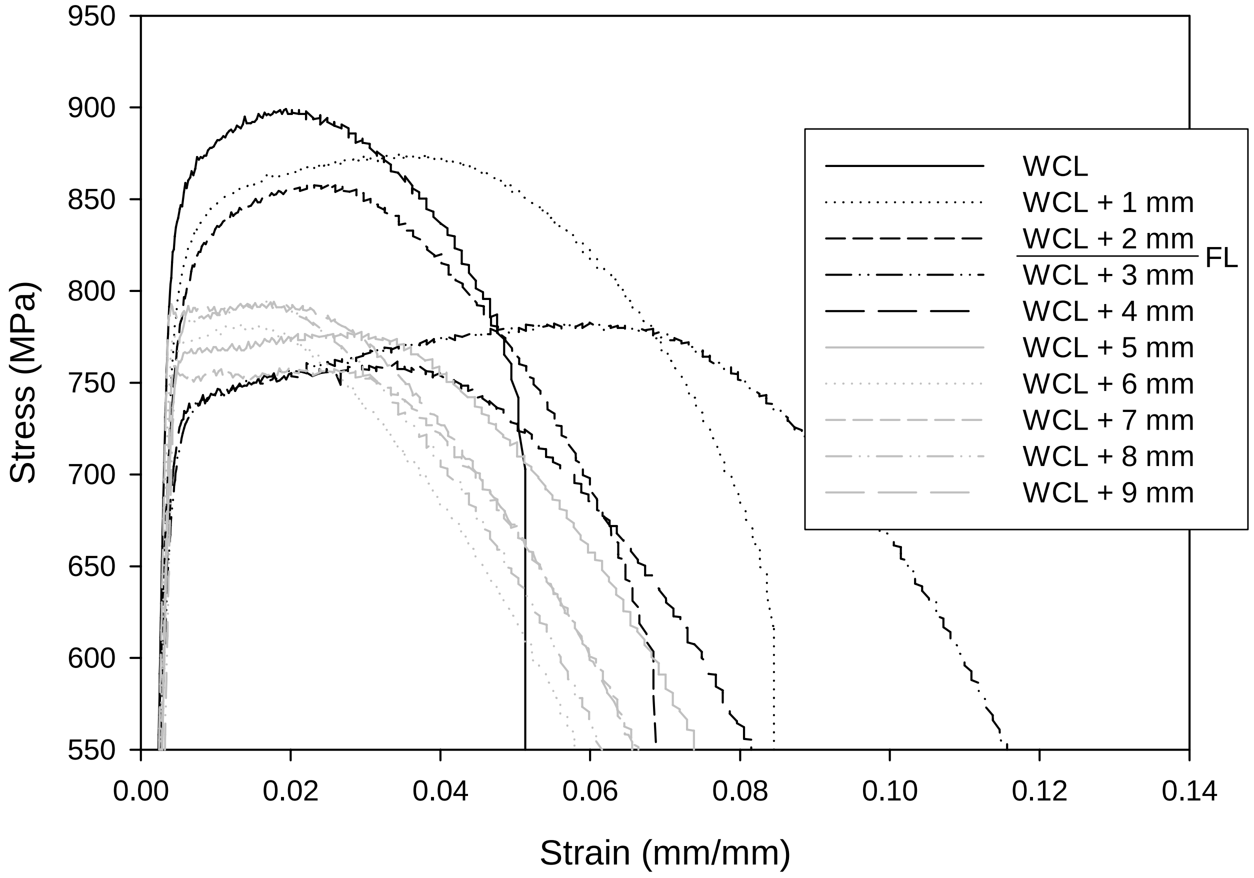
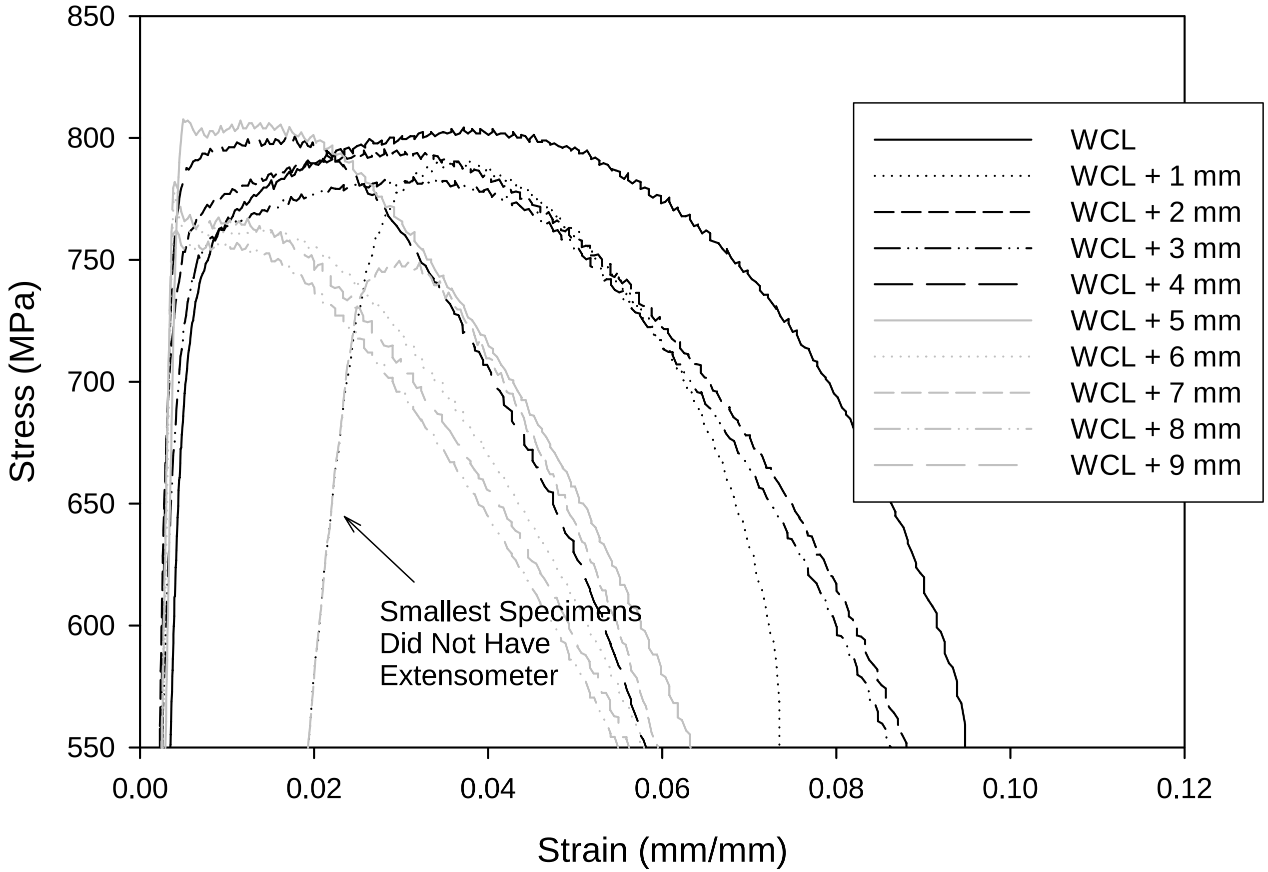
Weld 2a Dual Torch



Tandem Weld 2b



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Testing Conclusion

- HAZ Softening in X-100 is Real (W1)
- HAZ Softening Can Be Minimized (W2a & W2b)
  - Process
  - Pipe Material
- Hardness Alone Misses Changing Y/T
- Properties Derived from Weld 1 Micro-Tensiles Were Used for Weld Area Models

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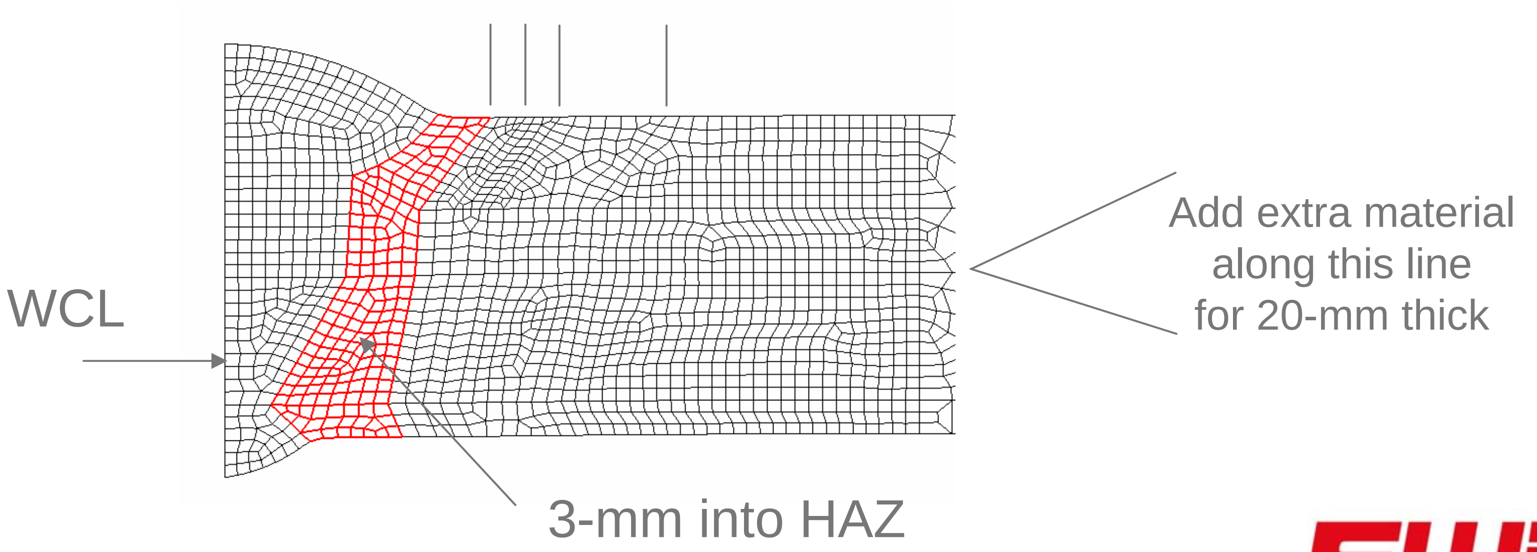
Models of HAZ Width

Main Models for HAZ Size Effect

- Reinforcement on Cap and Root
- 4 Sizes of HAZ (10% Lower Strength)
- Ramberg-Osgood Smooth Stress-Strain Curves
- Pressure First, Then Applied Strain



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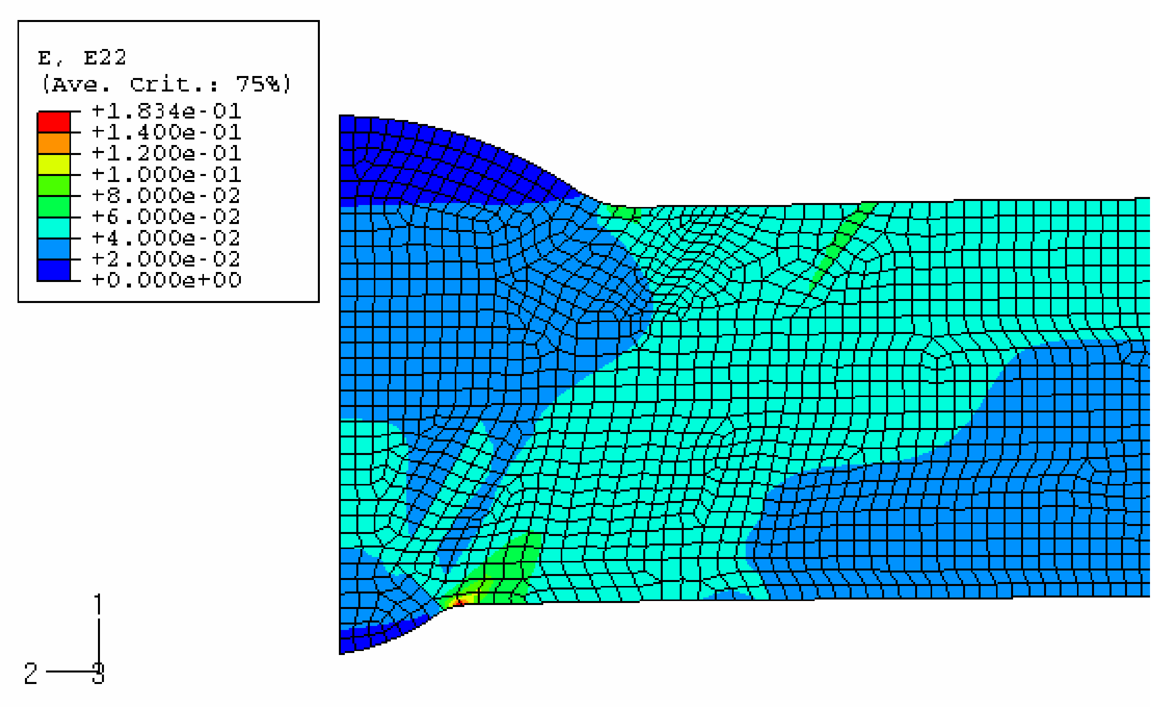
No Pressure Results – 4% Remote Strain

- Results in Axial Strain (E22)
- Widest HAZ
- Localized Strains at Corners & HAZ Edges



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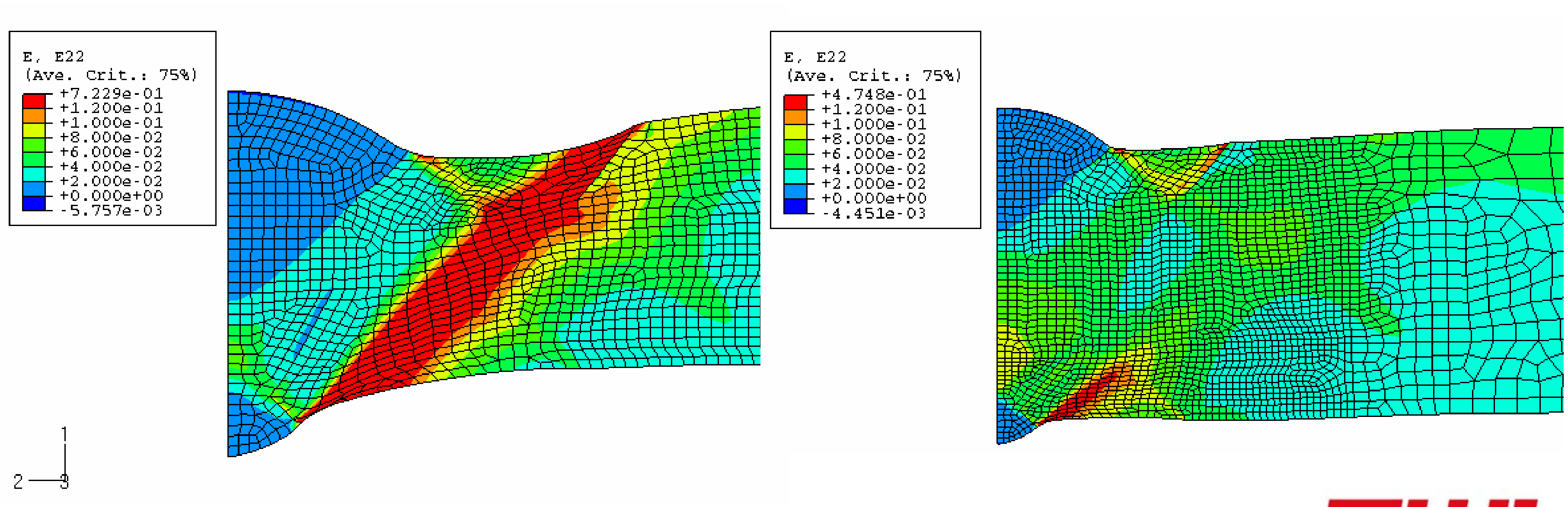
Effect of Thickness (Very Wide HAZ)

- Pressure to 70% SMYS + 4% Strain
- 10-mm Has Big Shear Band
- 20-mm Does Not



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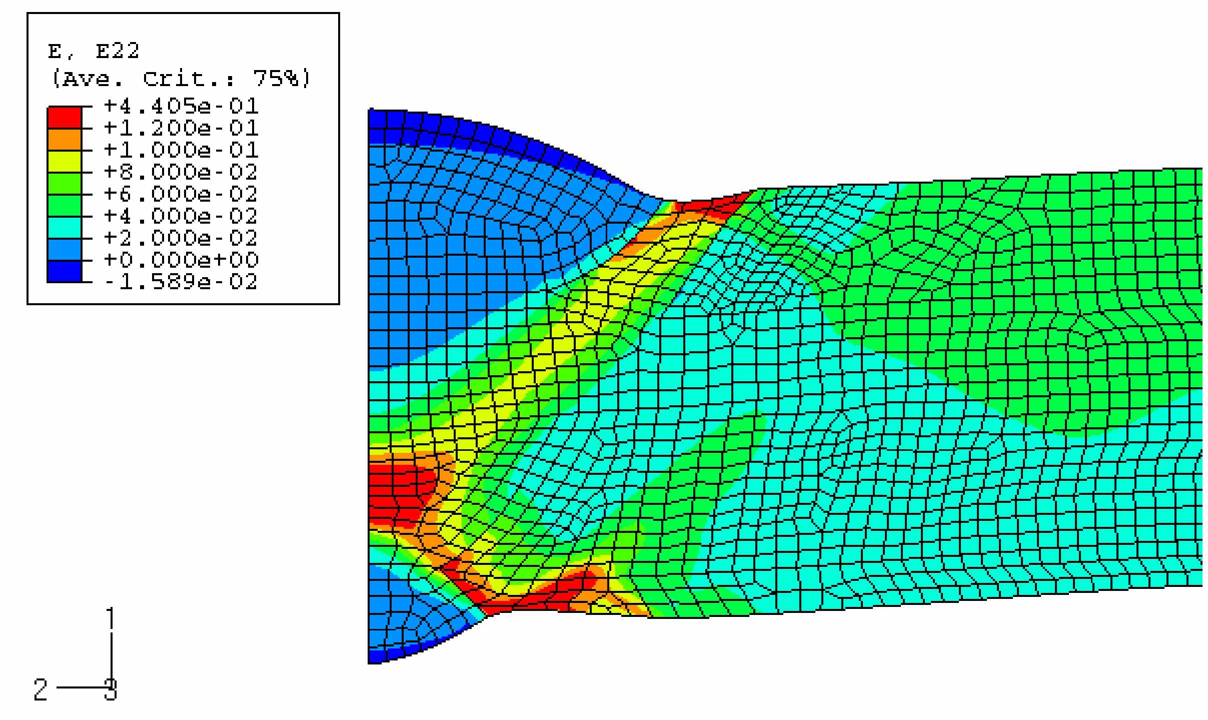
Effect of Just Matching Weld

- Narrow HAZ in 10-mm Pipe
- Shear Bands Cross in Weld Center



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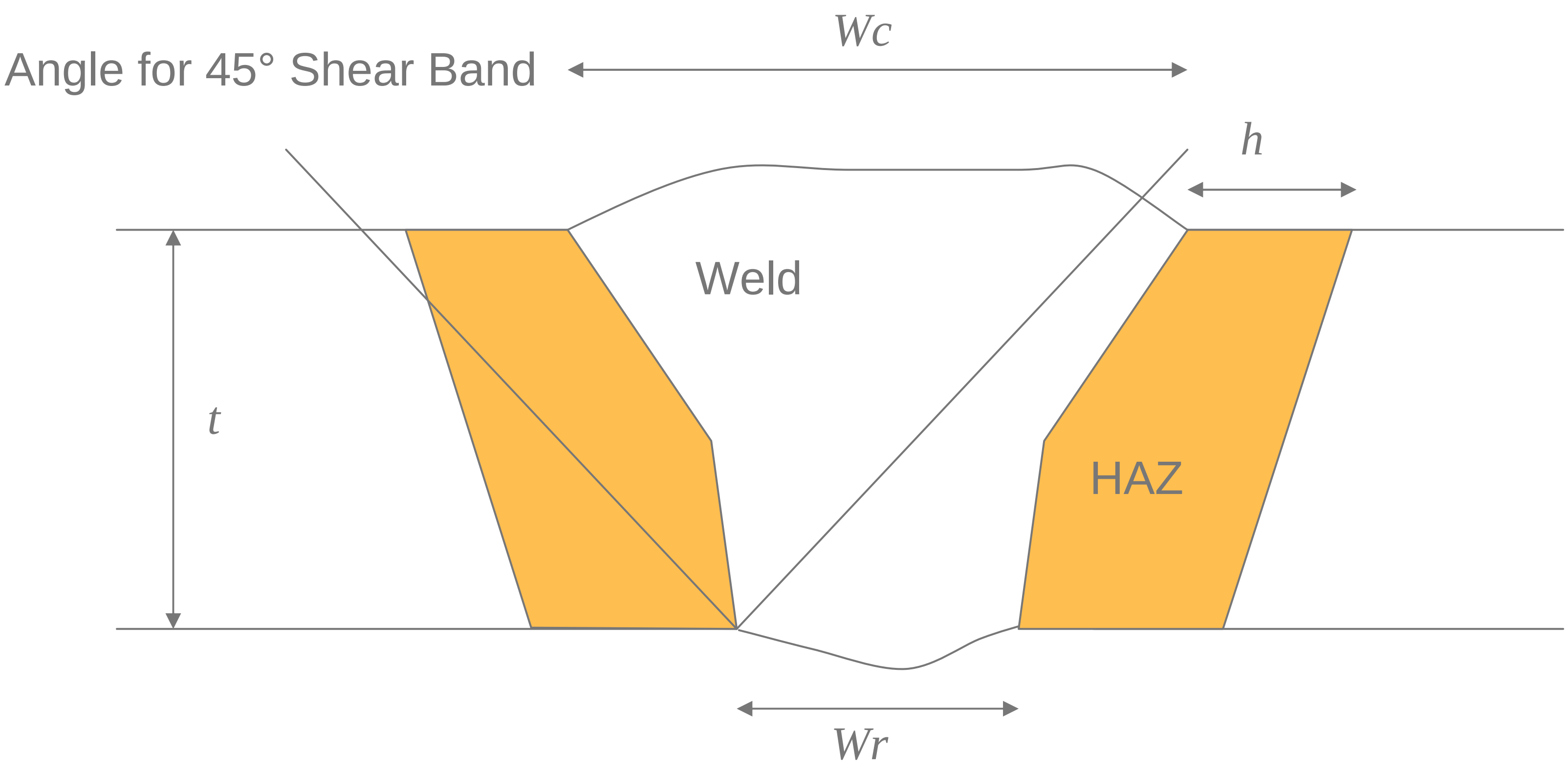
HAZ SCF – 3-mm Out from Root

Thick	Weld	Hoop%Y	Small	Medium	Large	Extra
10-mm	10% Over	0	1.15	1.17	1.19	1.35
10-mm	10% Over	35	1.40	1.48	1.52	2.80
10-mm	10% Over	70	1.90	2.00	2.35	5.25
10-mm	Match	35	2.58	2.69	2.75	2.89
10-mm	Match	70	4.45	4.61	4.62	5.06
20-mm	10% Over	35	1.30	1.47	1.66	2.11
20-mm	10% Over	70	1.63	1.98	2.34	3.21

WCL SCF – Where Shear Bands Cross

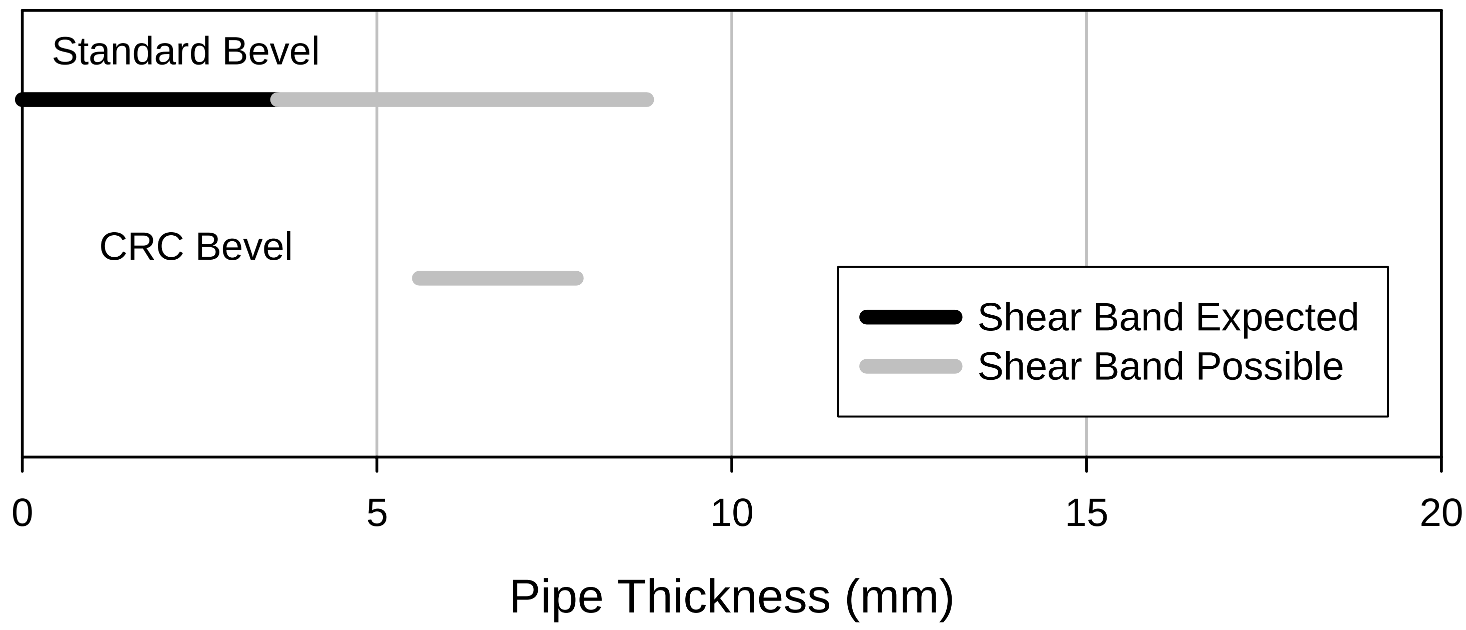
Thick	Weld	Hoop%Y	Small	Medium	Large	Extra
10-mm	10% Over	0	1.13	1.15	1.18	1.21
10-mm	10% Over	35	1.36	1.46	1.53	1.56
10-mm	10% Over	70	1.82	2.07	2.14	1.86
10-mm	Match	35	2.57	2.71	2.82	2.84
10-mm	Match	70	4.25	4.74	4.88	4.37
20-mm	10% Over	35	1.16	1.19	1.24	1.46
20-mm	10% Over	70	1.41	1.46	1.54	1.98

Shear Band Location

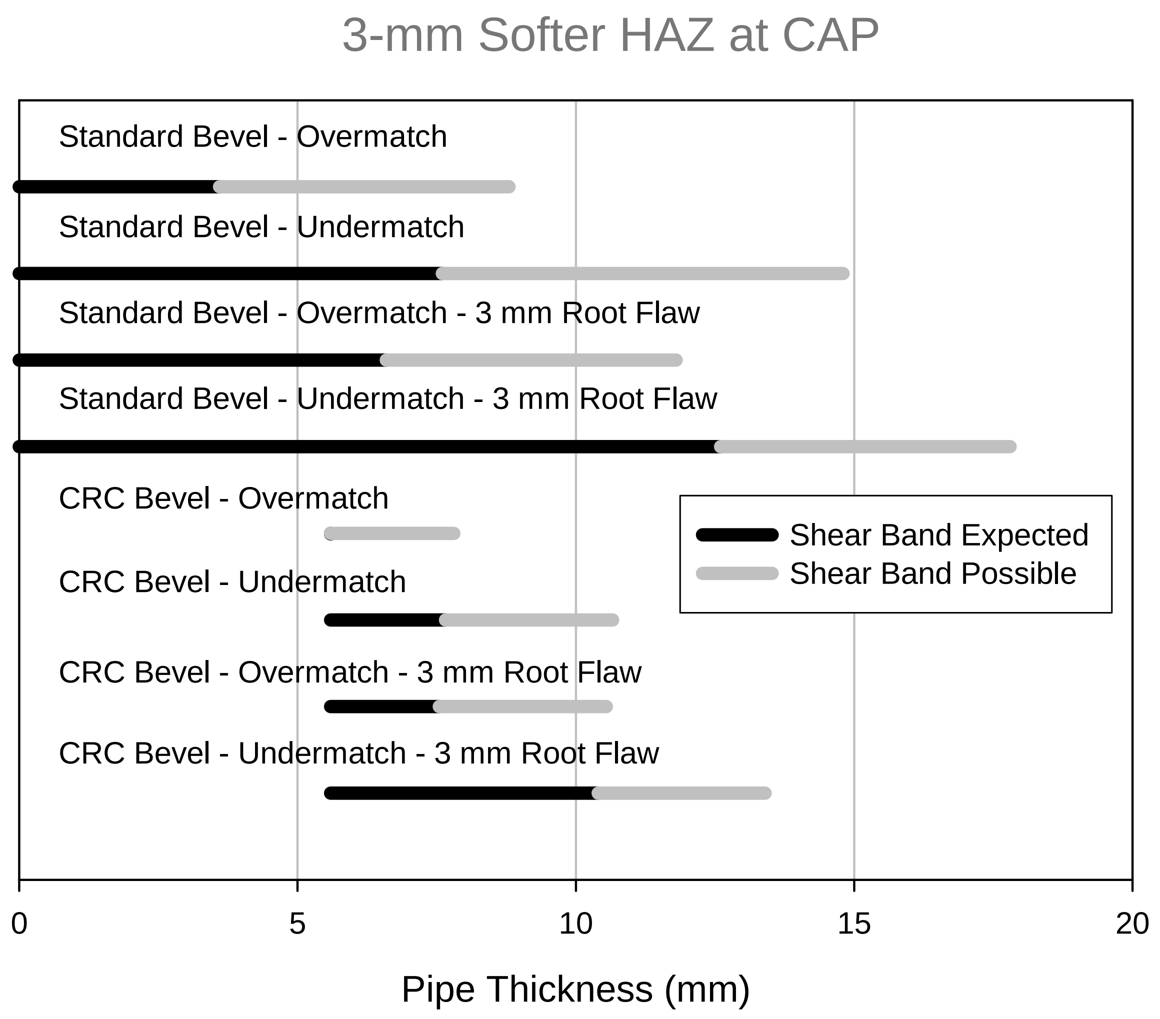


Shear Band – Bevel Effect

- 3-mm HAZ
- Range of Cap and Root Widths Beyond Bevel



More Cases



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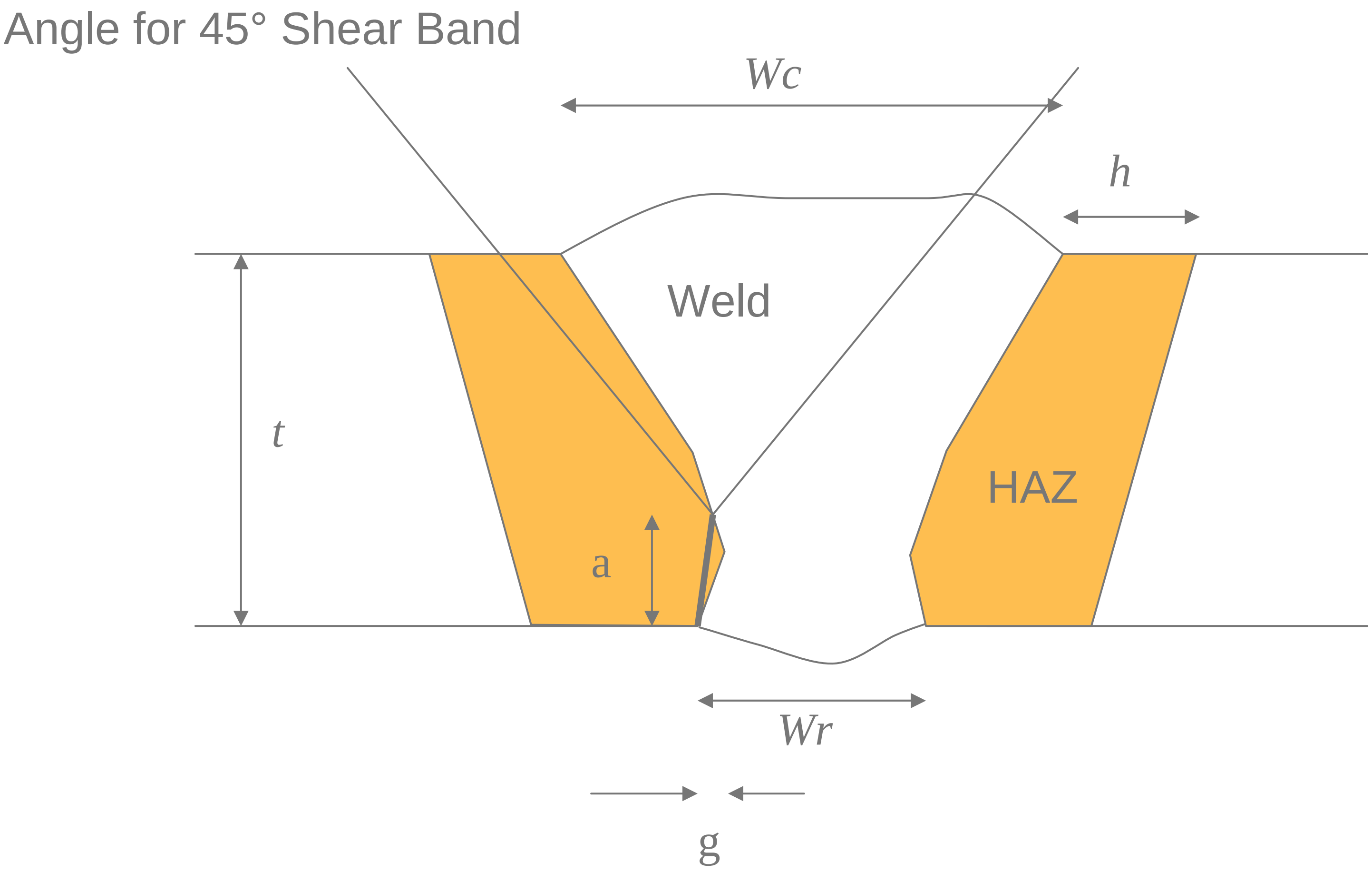
Shear Band from Root Flaw



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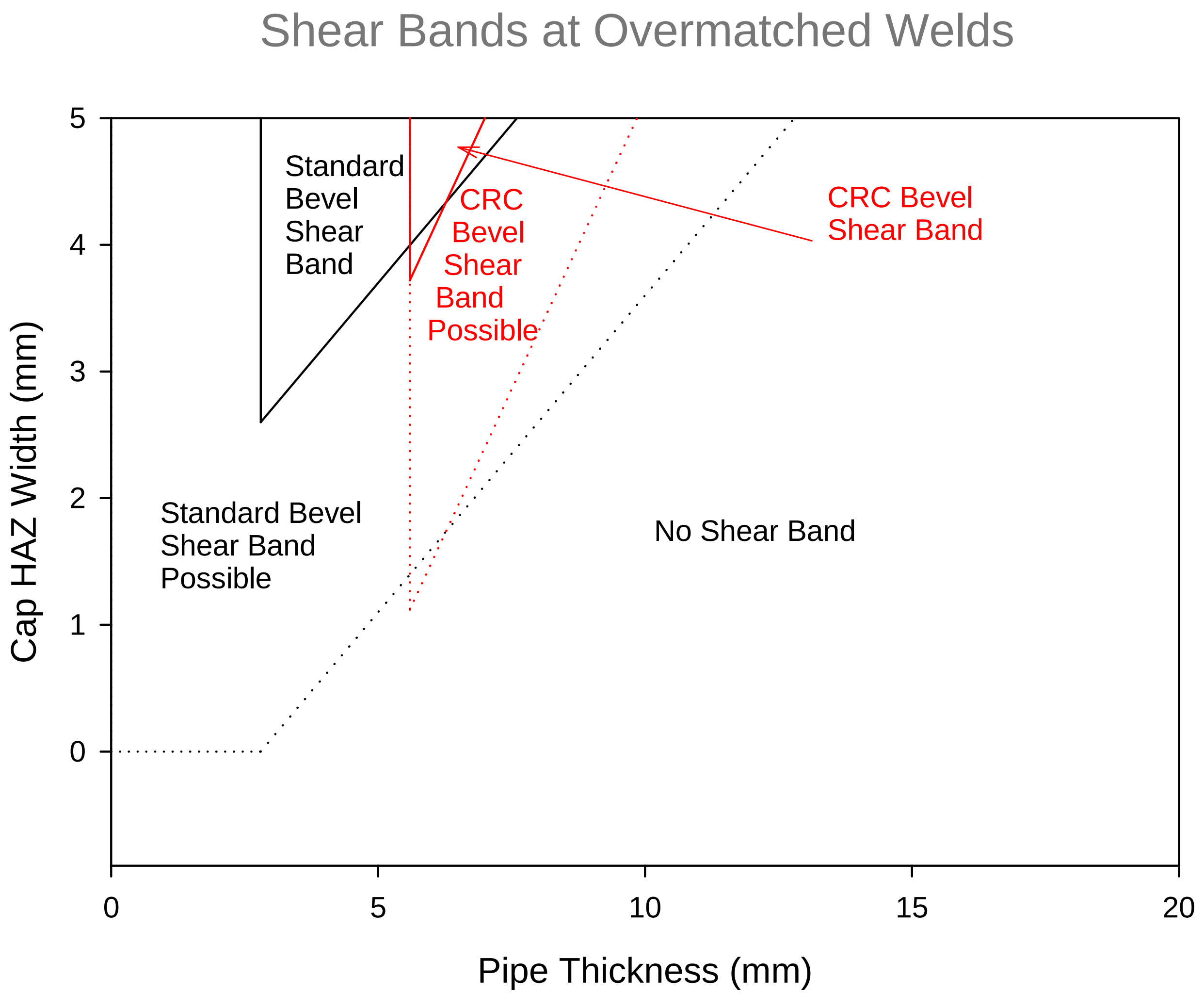
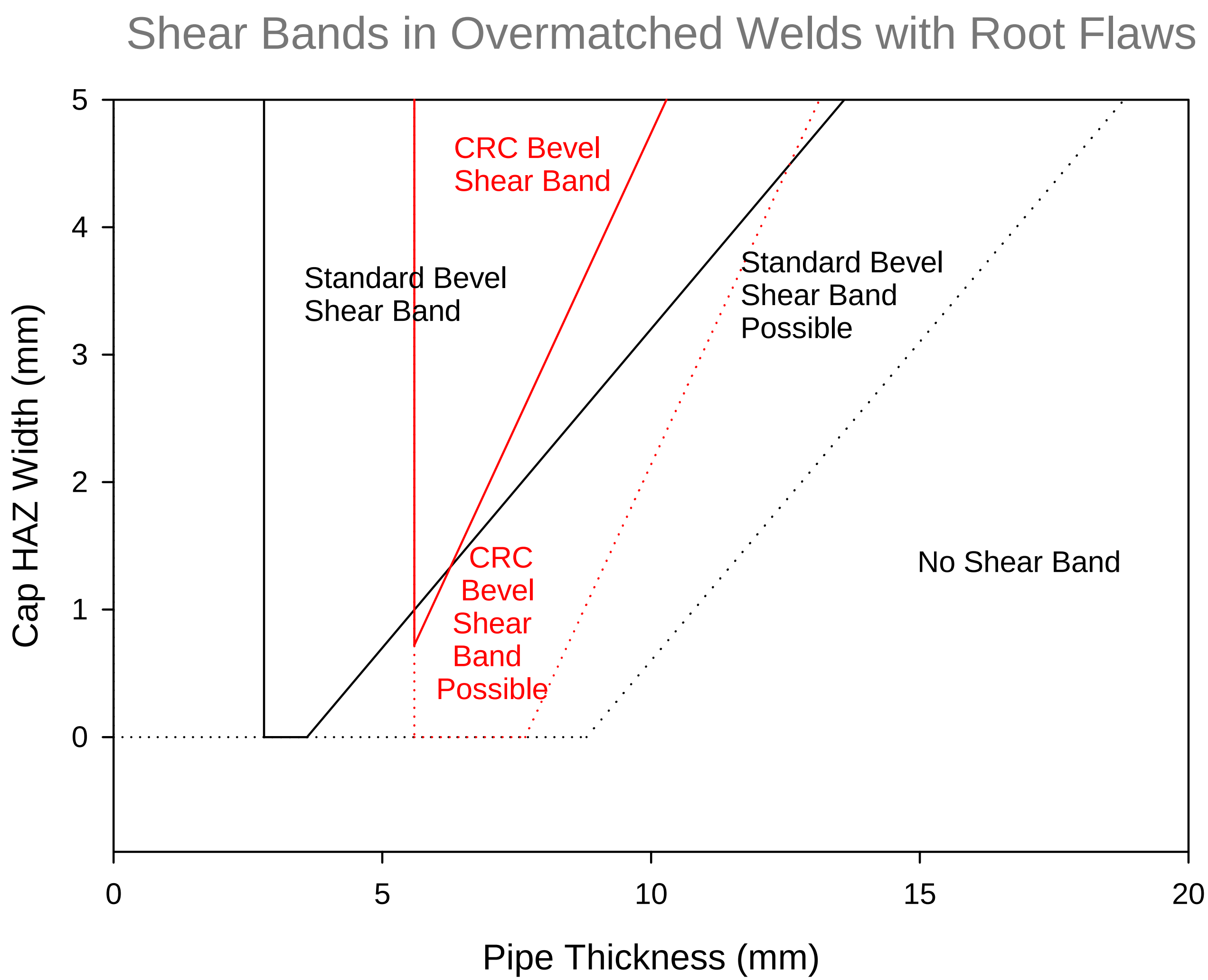
Shear Band Mechanism – No Flaws



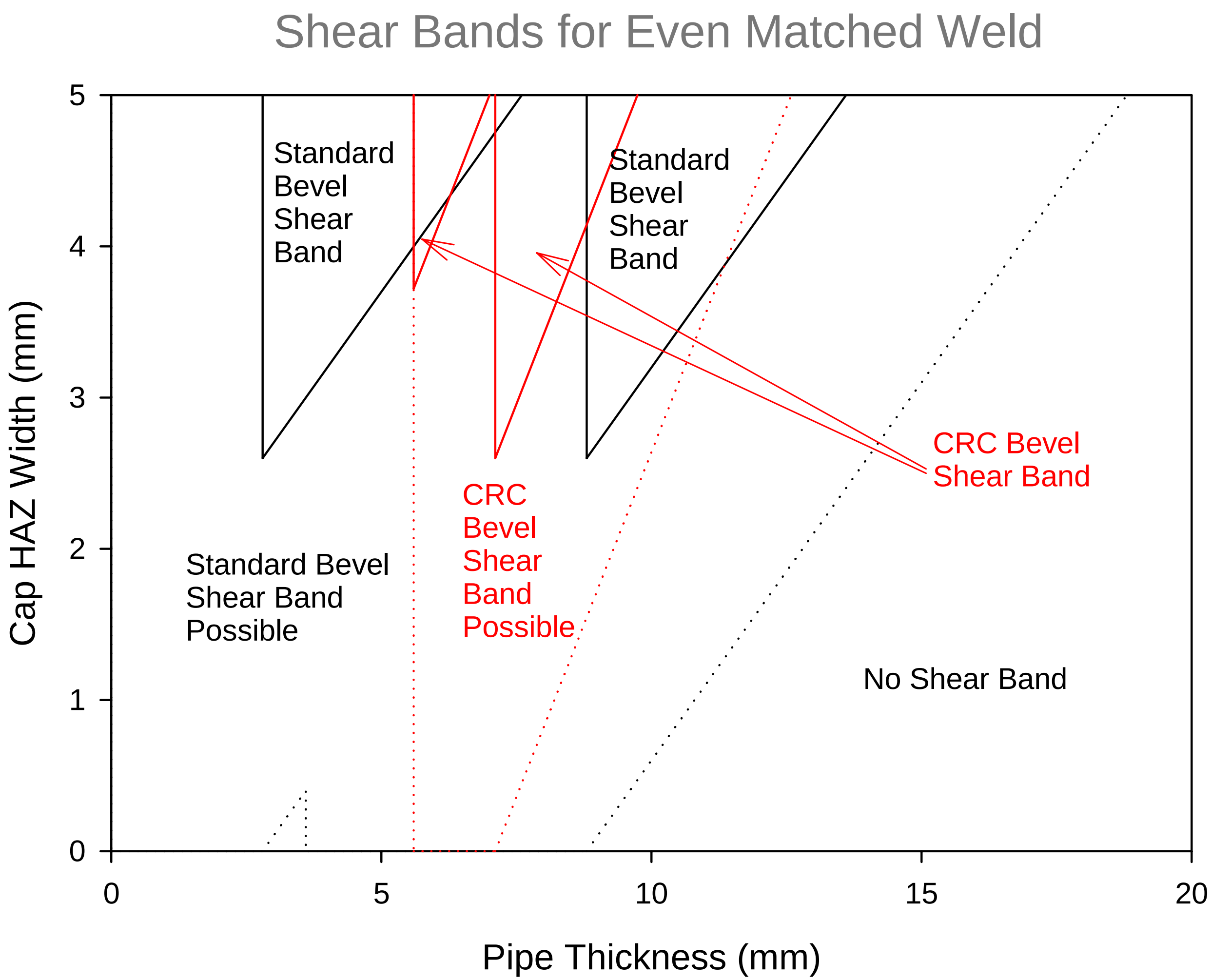
Shear Band Mechanism – 3-mm Flaw



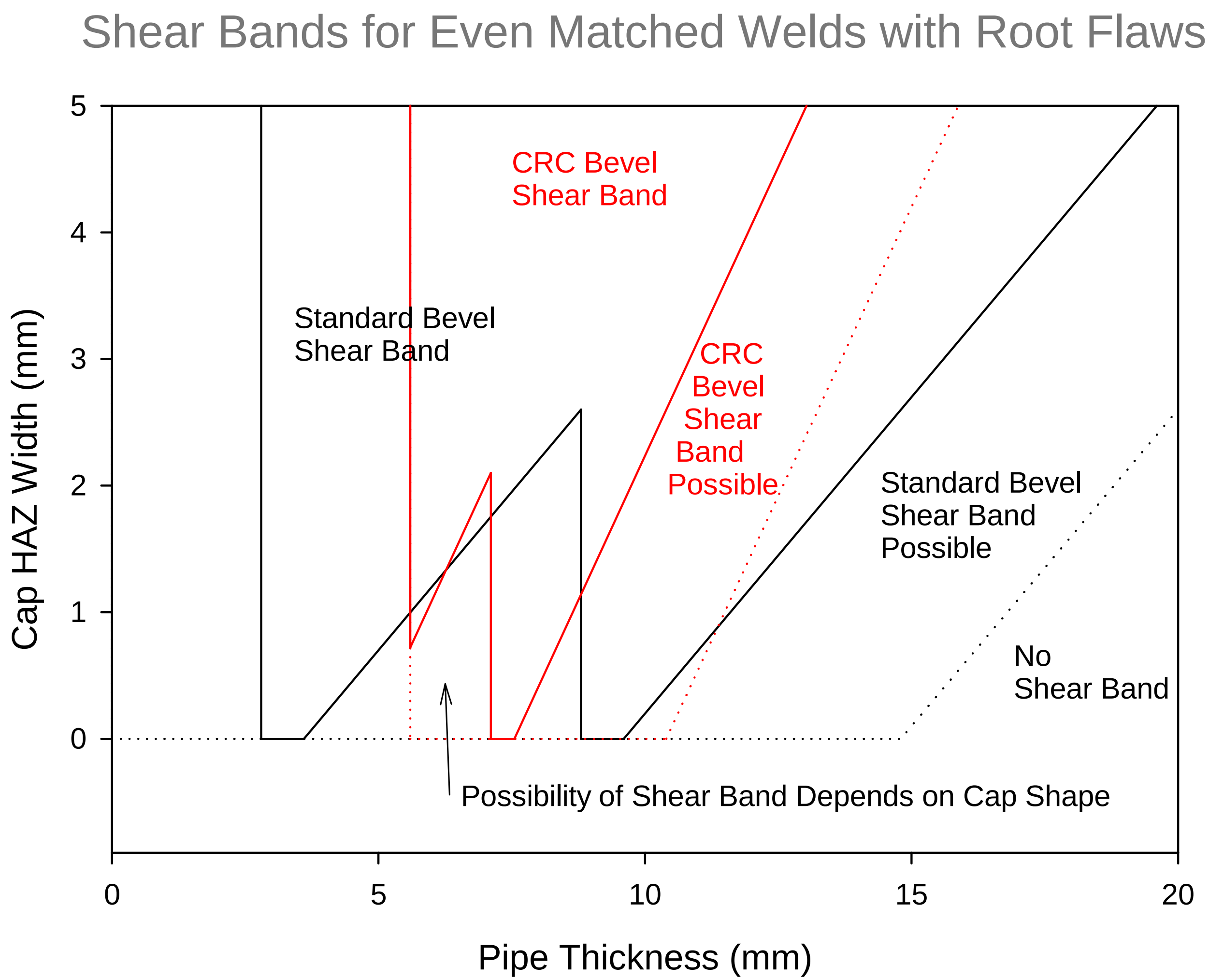
Conclusions on High Strain Concentration

- Thicker Welds Avoid High Strain Concentration Even with Low Strength HAZs
- Manual Welds with 60° Bevels Can Have More Strain Concentration than Automatic Welds
- Major Changes in Weld Area Strain Concentration Between Matched and 10% Overmatched

Even Matched Weld



3-mm Root Flaw for Even Matched Weld



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Guidance on Strain Concentration

- Baseline Strain Concentration Approximation (Conservative)
  - 1.2 for No Pressure
  - 1.5 for 35% of SMYS Hoop Stress
  - 2.0 for 70% of SMYS Hoop Stress
- Higher Strain Concentration if Undermatched or Even Matched
- Localized Strain Concentration Can Be Much Higher
  - Weld Toot Toe + Sharp Strength Transition

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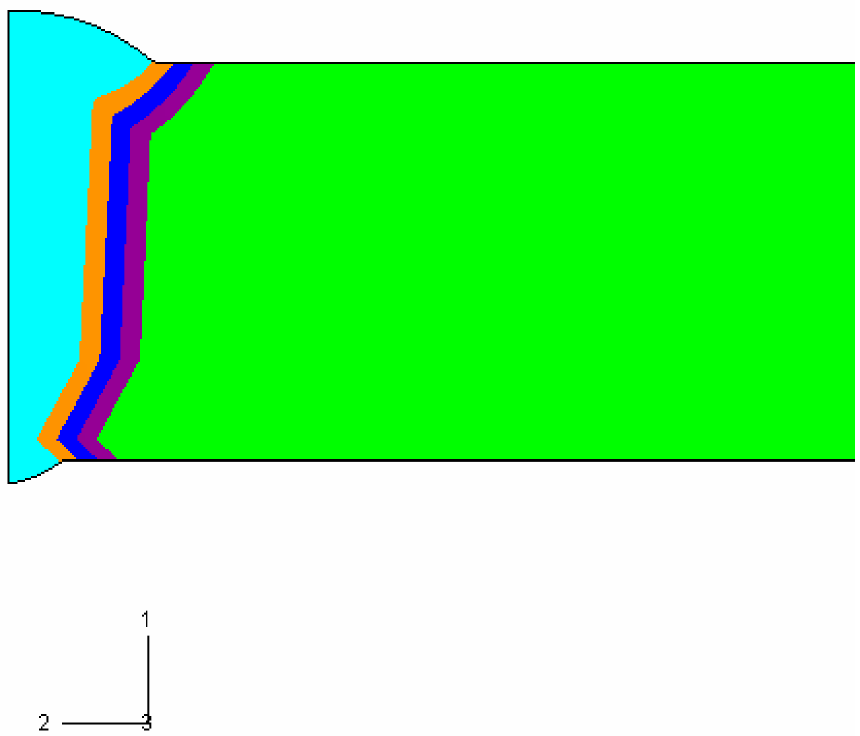
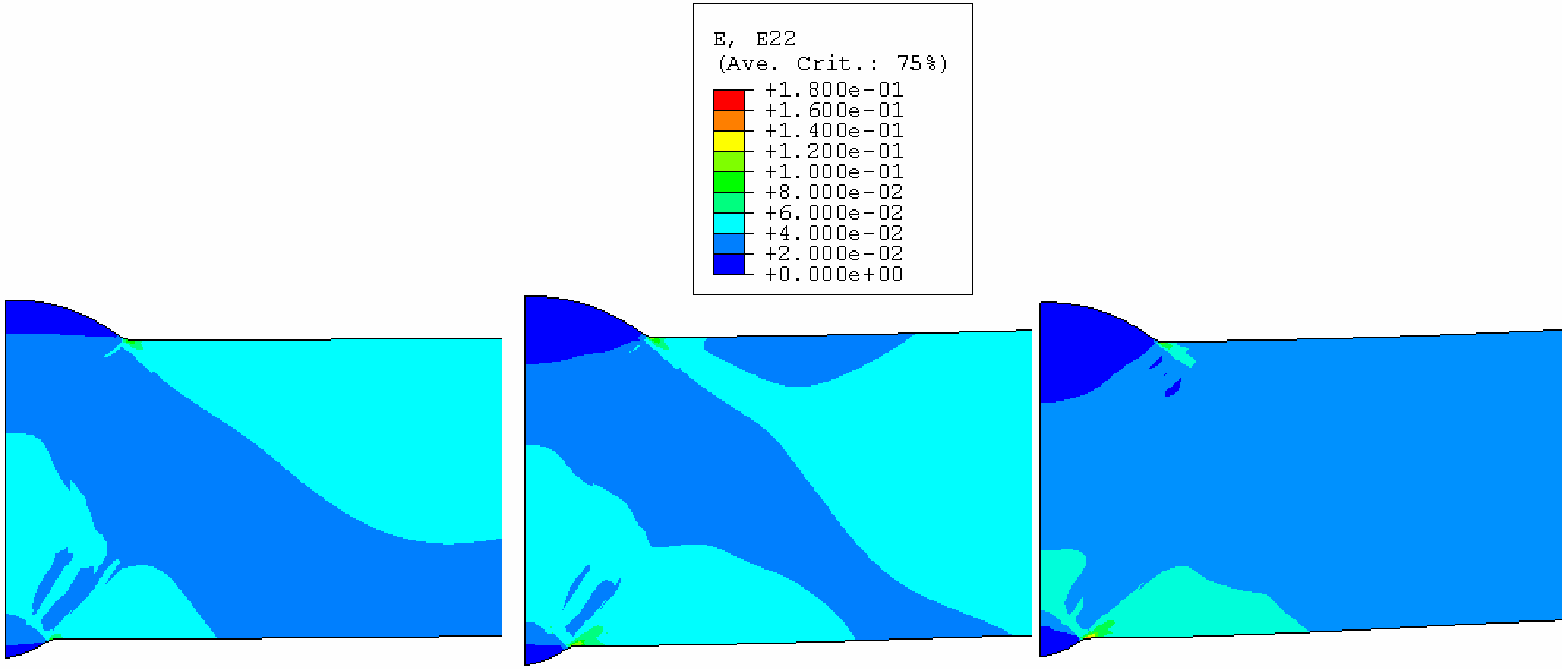
X-100 Models

X-100 Model

- Five Regions
  - Weld
  - FL to FL+1-mm
  - FL+1-mm to FL+2-mm
  - FL+2-mm to FL+3-mm
  - Base Metal
- Properties From Tests on Weld 1
- 20-mm Thick



All Isotropic

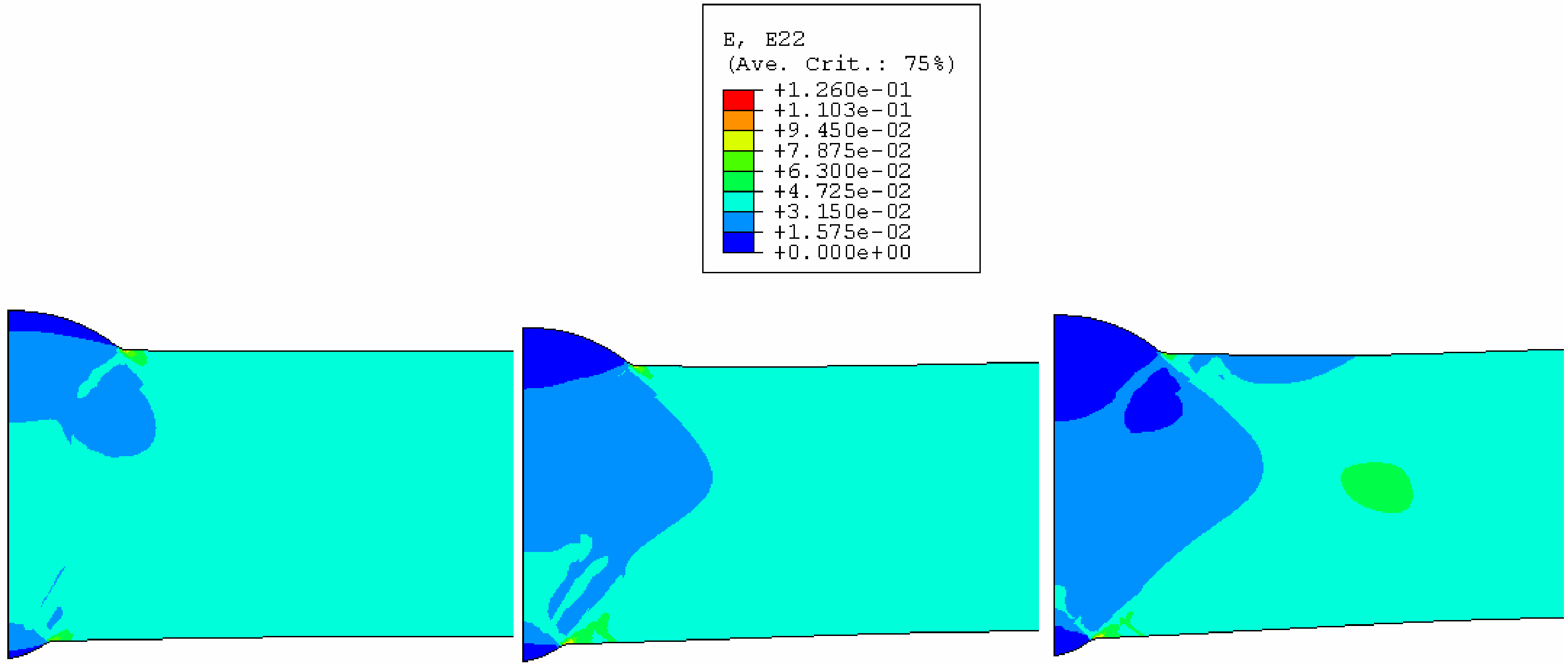


No Pressure

9.59-MPa Pressure

19.18-MPa Pressure

Base Metal Orthotropic



No Pressure

9.59-MPa Pressure

19.18-MPa Pressure

X-100 with Weld 1 Properties

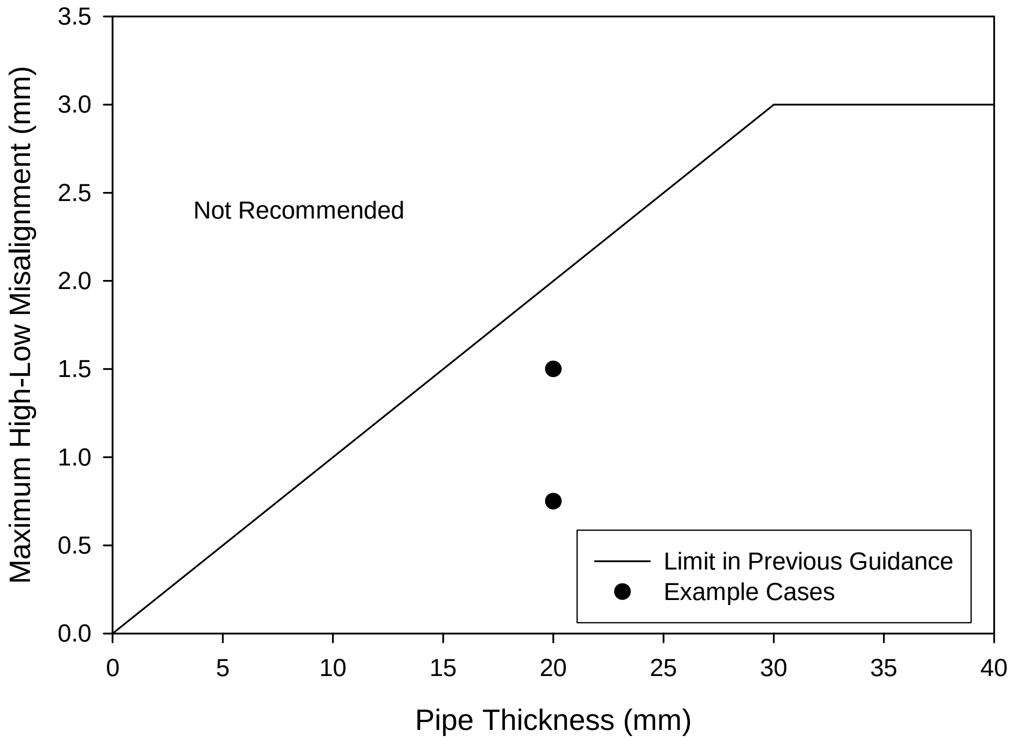
- Applied Weld 1 Tested Properties to Model
  - Including Softened HAZ
  - 20-mm Thick
- Strain Concentrations are Very Minor
  - Pressure Effect was Very Limited
- Base Metal Orthotropic Model is Most Like Tested Weld
  - No Effect of Pressure
  - Very Low Strain Concentration

Misalignment Effects

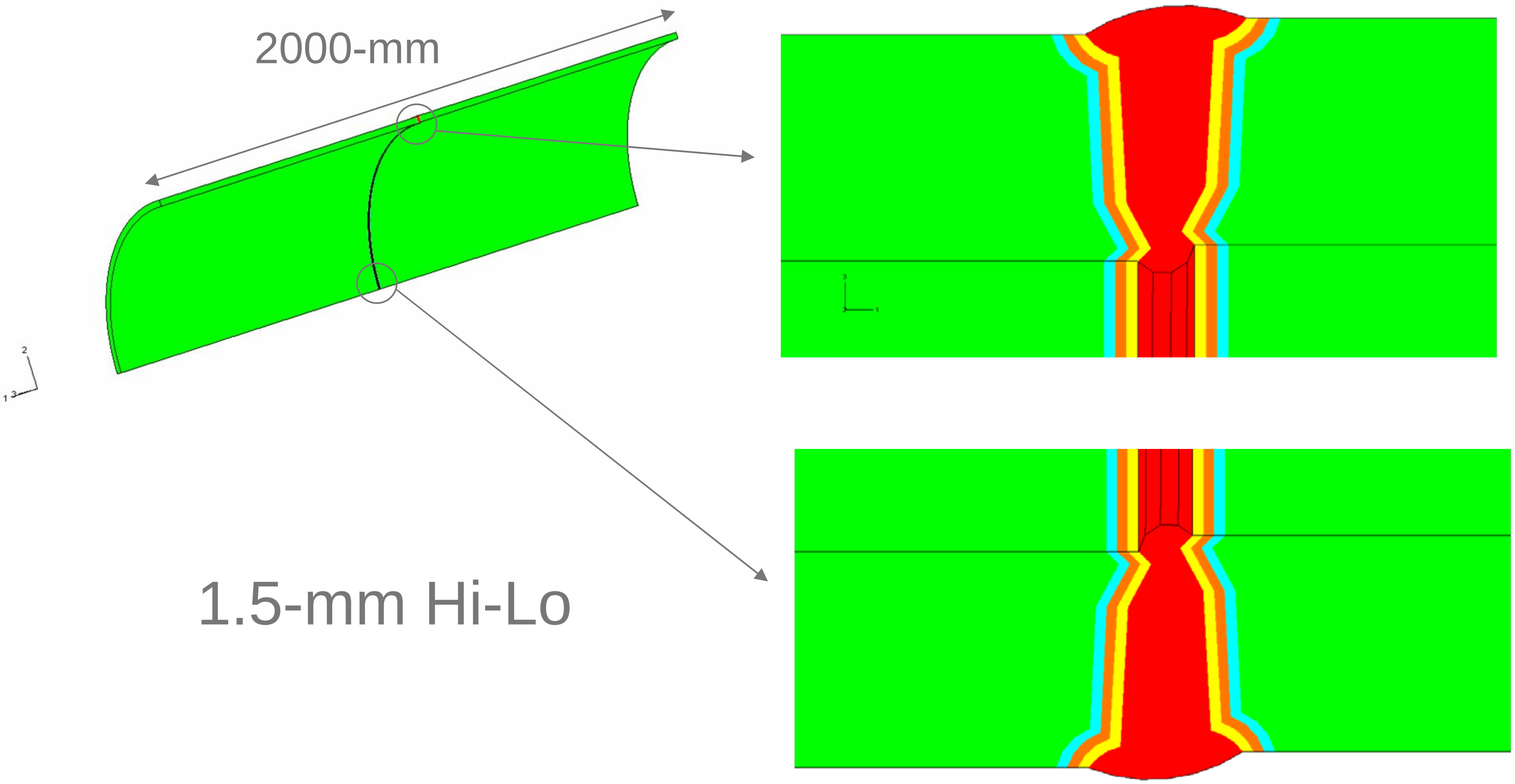
Misaligned Model

- Joined Circular Pipe to Oval Pipe
- Otherwise the Same as Previous X-100 Model
- Max. Misalignment
  - 1.5-mm high-low
  - 0.75-mm high-low
- Both X-100 and X-65

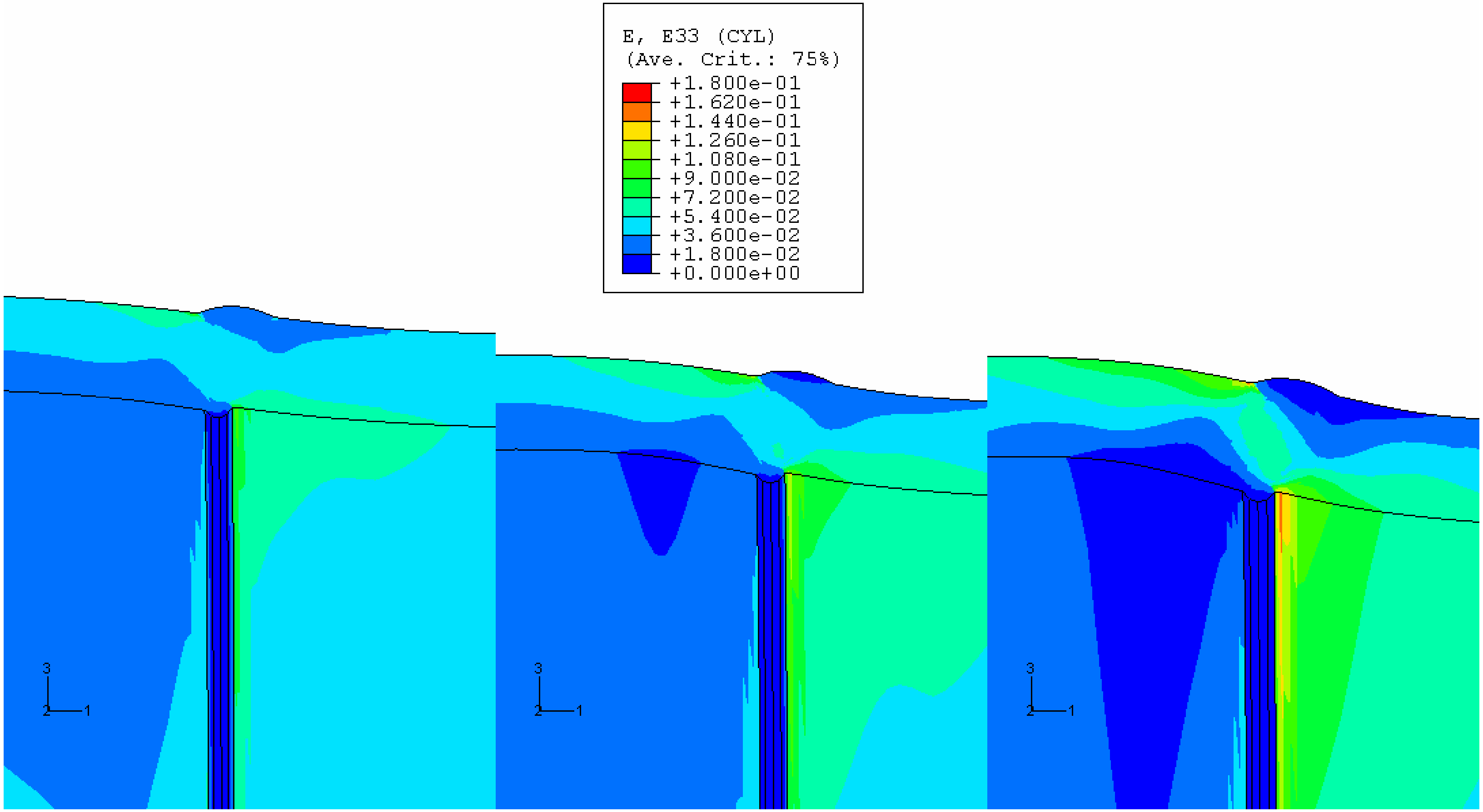
Hi-Lo Amounts



Model with Hi-Lo

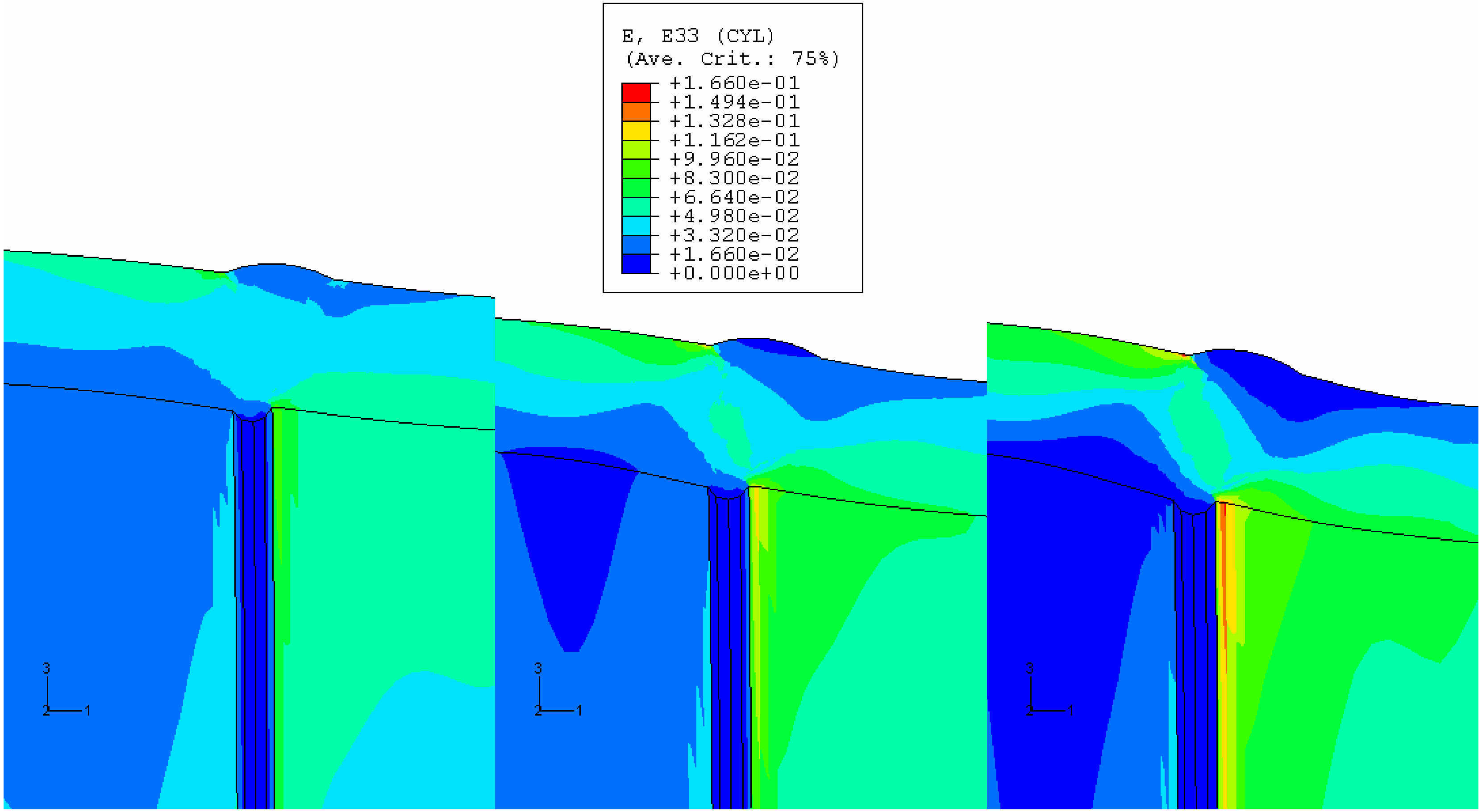


X-100 1.5-mm Hi-Lo Isotropic



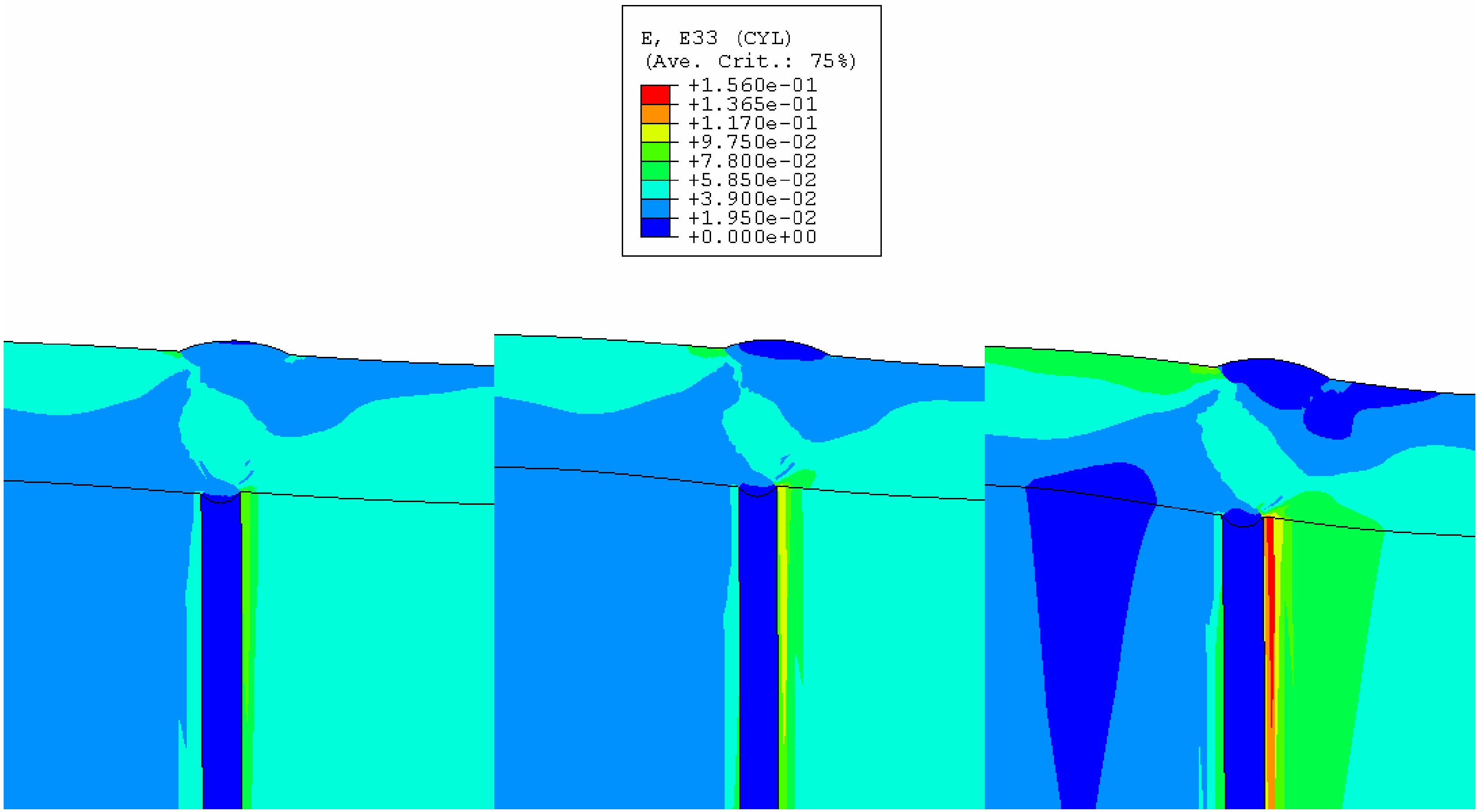
No Pressure | 9.59-MPa Pressure | 9.18-MPa Pressure

X-100 1.5-mm Hi-Lo BMO



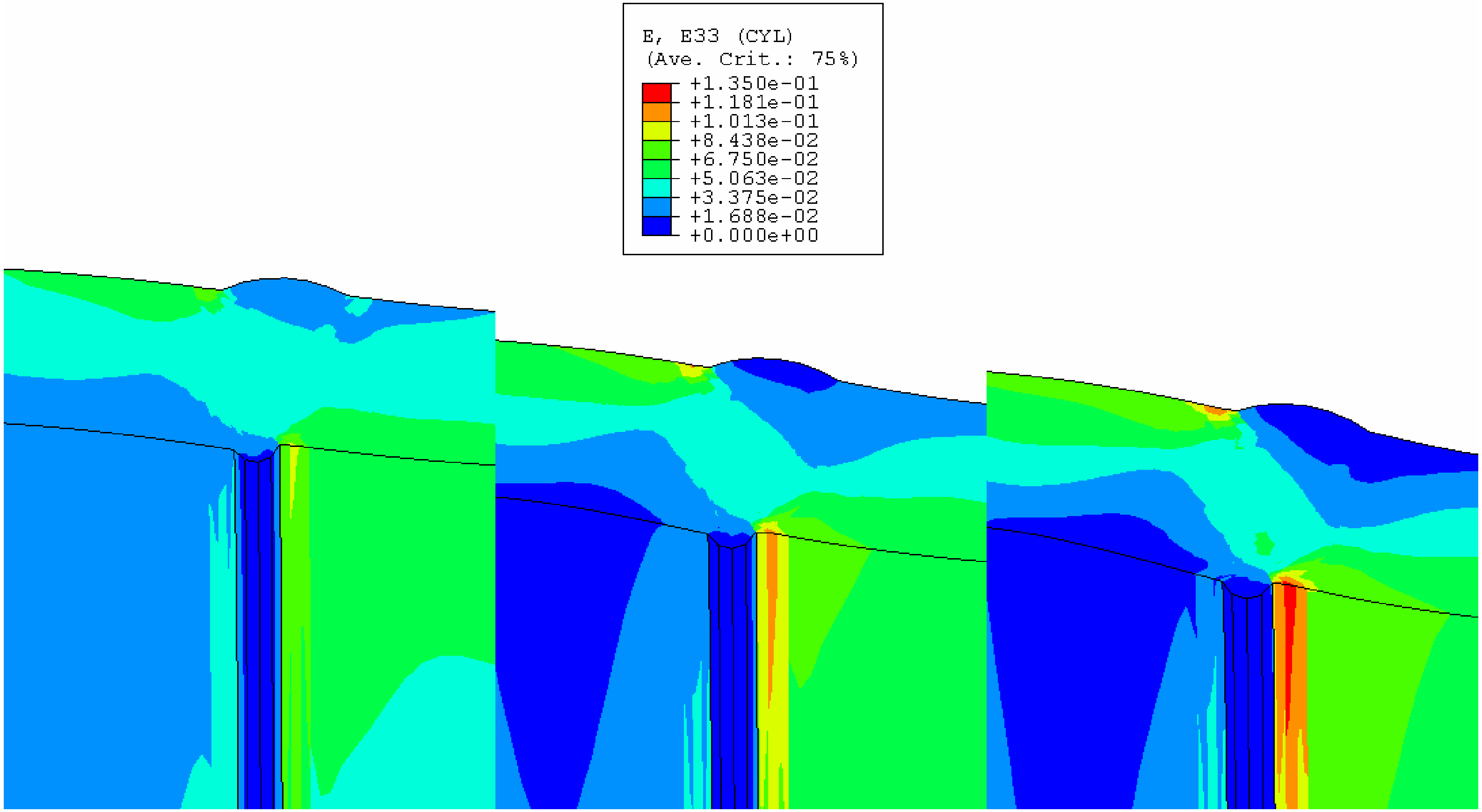
No Pressure 9.59-MPa Pressure 19.18-MPa Pressure

X-100 0.75-mm Hi-Lo BMO



No Pressure 9.59-MPa Pressure 19.18-MPa Pressure

X-65 1.5-mm Hi-Lo BMO



No Pressure   6.23-MPa Pressure   12.47-MPa Pressure

Conclusions for Hi-Lo

- Strain Concentrations Cross Weld Metal
  - ID High Side to OD Low Side
  - Concentration Even with Weld Overmatch
- Similar Concentration for X-100 and X-65
  - Little Effect of Change of Stress-Strain Curves
- Pressure Effect
  - Narrowing of High Strain Zone in Weld Metal

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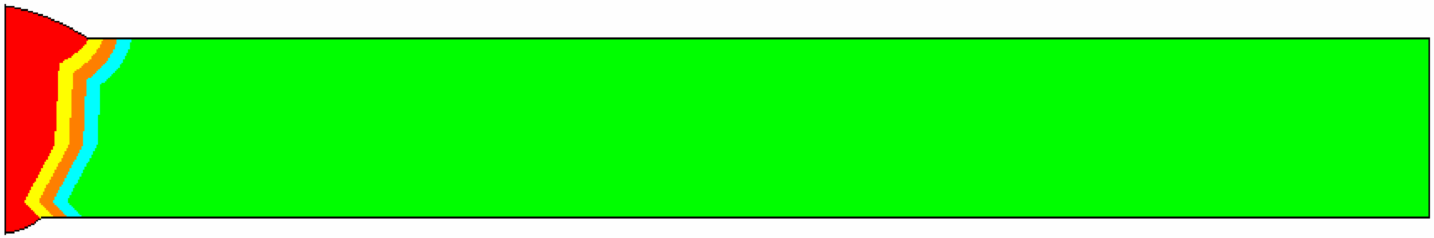
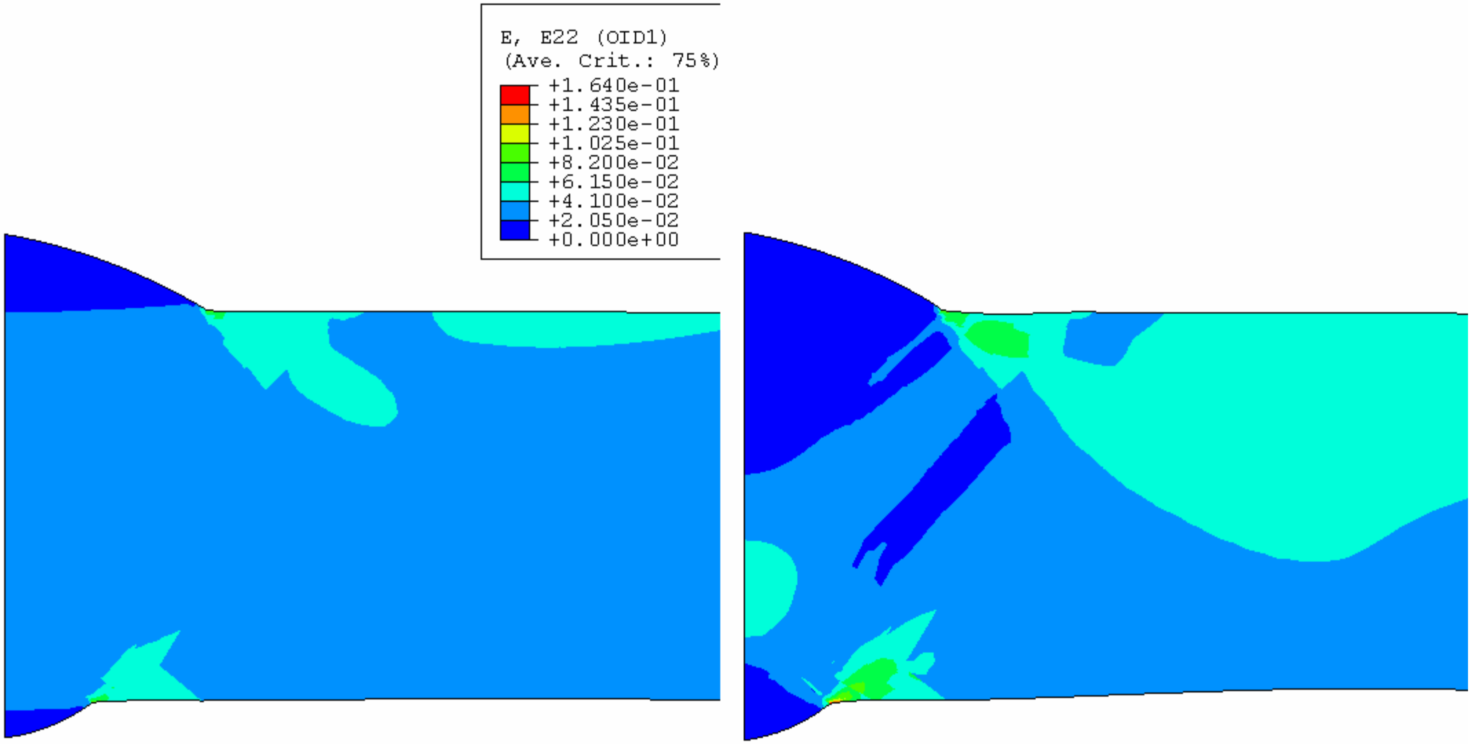
X-65 Cases in New Project

Model of X-65 Test Pipes



- Model Very Similar to X-100 Model
  - Thickness 12-mm
- Stress-Strain Curves from Kim, et al., Micro-Tensiles on X-65

Baseline X-65



No Pressure

29.19-MPa Pressure

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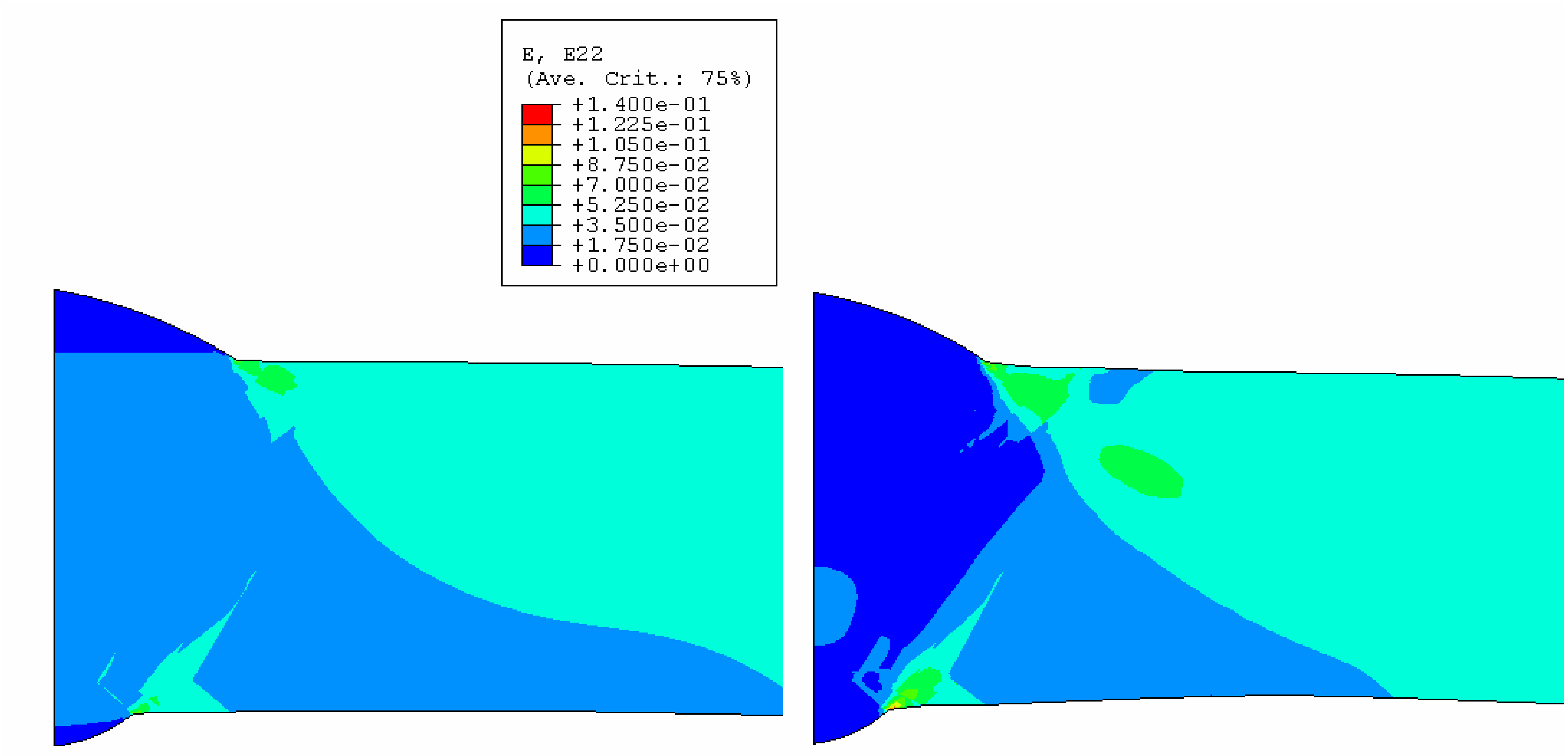
Higher Weld Overmatch



No Pressure | 29.19-MPa Pressure

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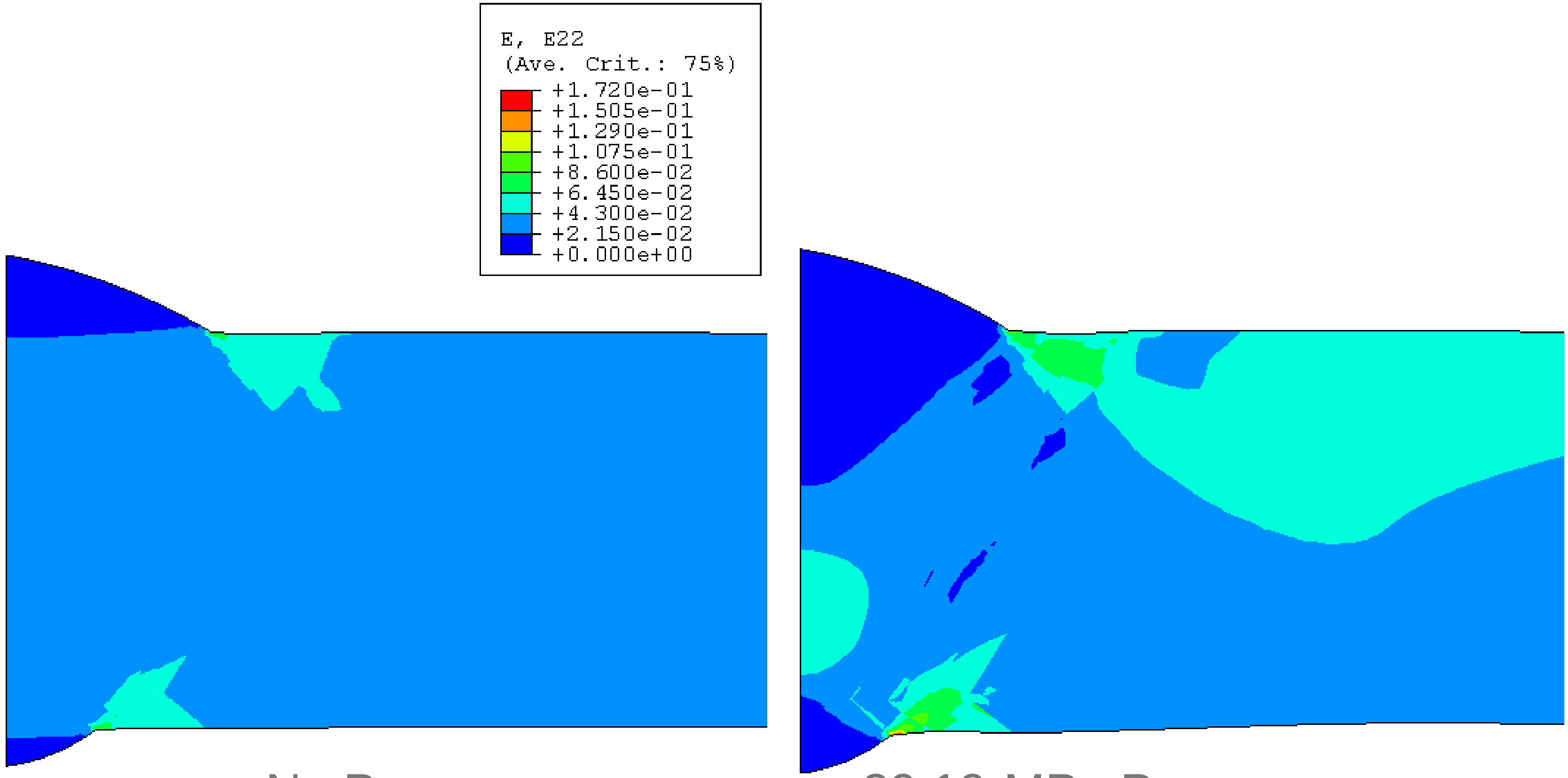
Base Metal Lower Y/T



No Pressure

29.19-MPa Pressure

Conclusions on X-65

- X-65 Tests with HAZ Notch Should Give Similar Results for
  - ID HAZ Notch
  - OD HAZ Notch
- X-65 Tests with Weld Metal Notch
  - Some Additional Strain Concentration Near ID
- No Large Effect of Base Metal Y/T on Strain Concentration
- Plan is to Test with Minimum Hi-Lo

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Constraint

CTOD Transferability

- CTOD Usually Based on Tests in High Constraint Geometry (Deep Notch, Bend)
- Recent Efforts to Test Lower Constraint, But Still Conservative Constraint
- What is Enough Constraint for a Pressurized Pipe with Plastic Strain?
- Lower Test Specimen Constraint Can Give Much Higher Measured Toughness

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Constraint Effects

- Primary Methods of Assessing Constraint
  - T-Stress
  - Q-Stress (Either Hydrostatic or One Direction)
  - Weibull Stress Equivalent
- Some Tests - Little Biaxial Effect
  - Either Ductile or Very Brittle
  - Nuclear Pressure Vessel Steels
  - Surface Crack
  - Biaxial Load Does Change Load vs. CTOD Applied
- Through Cracks - More Biaxial Effect

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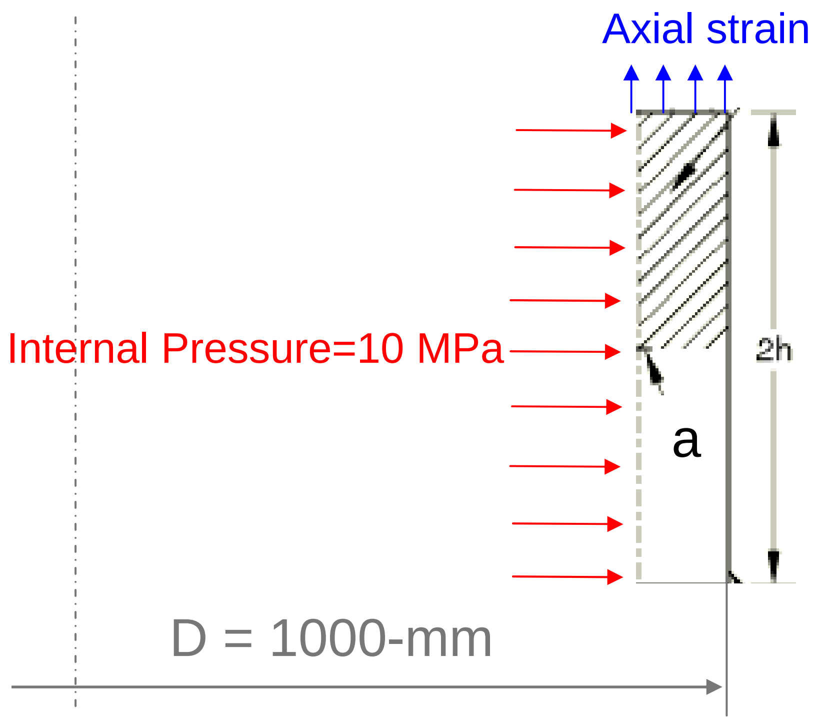
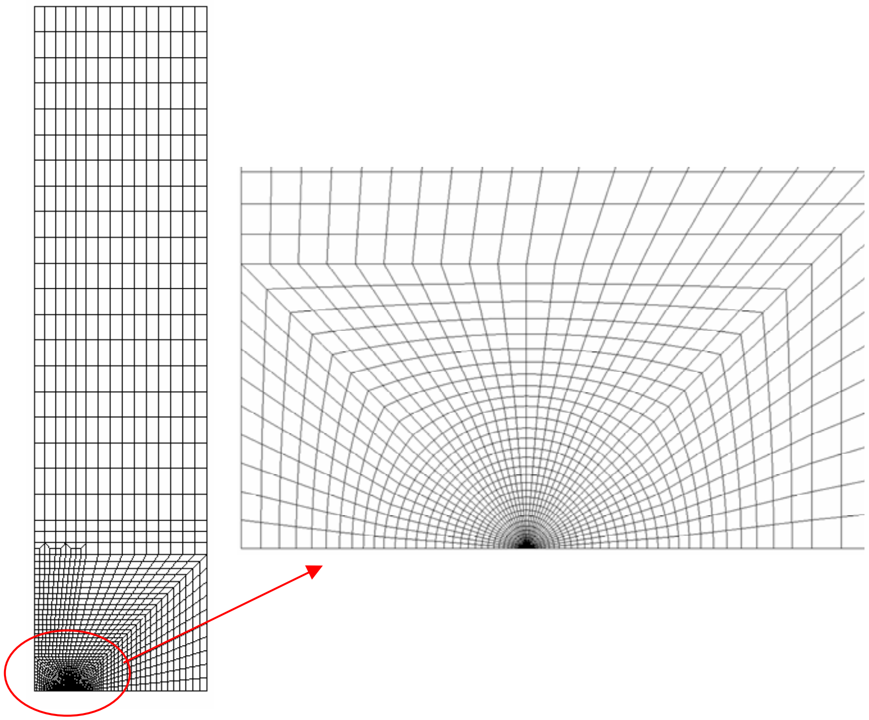
The Girth Weld Model

- Step 1: Apply Internal Pressure
- Step 2: Apply Axial Strain While Keeping the Internal Pressure Constant





a = 2-mm (Crack Length)
b = 10-mm (Pipe Thickness)
h = 40-mm (Axial Length)

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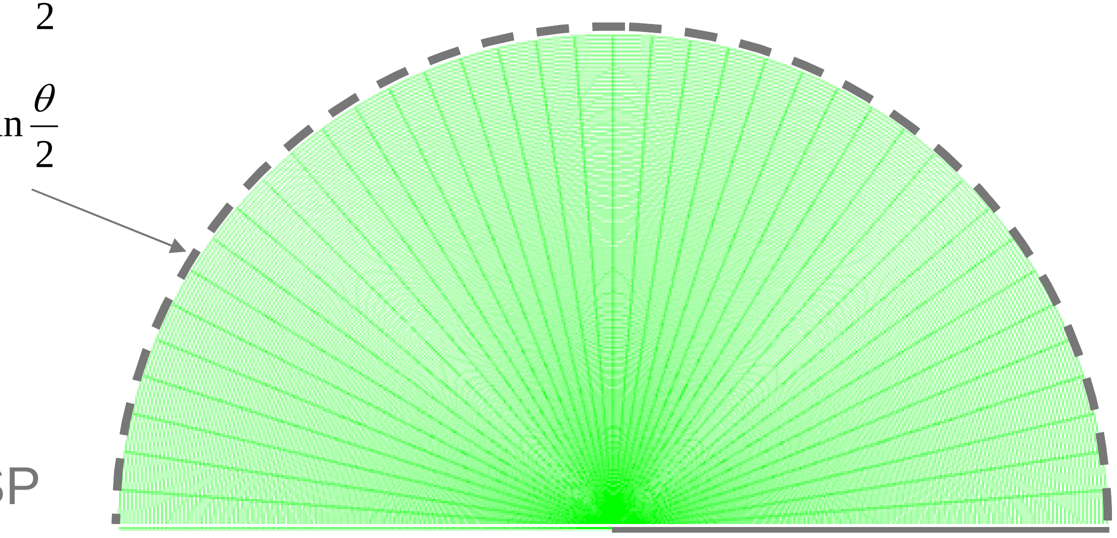
Reference Model for Q Calculation

$$U_x(r,\theta) = K_I \frac{(1+\upsilon)}{E}\sqrt{\frac{r}{2\pi}}(3-4\upsilon-\cos\theta)\cos\frac{\theta}{2}$$

$$U_y(r,\theta) = K_I \frac{(1+\upsilon)}{E}\sqrt{\frac{r}{2\pi}}(3-4\upsilon-\cos\theta)\sin\frac{\theta}{2}$$



Load was Applied through Abaqus User Subroutine DISP

30K Nodes

10K Elements

$$Q = \frac{\sigma_{\theta\theta} - \sigma_{\theta\theta,ref}}{\sigma_y}$$ Evaluated at $$r = \frac{2J}{\sigma_y}$$

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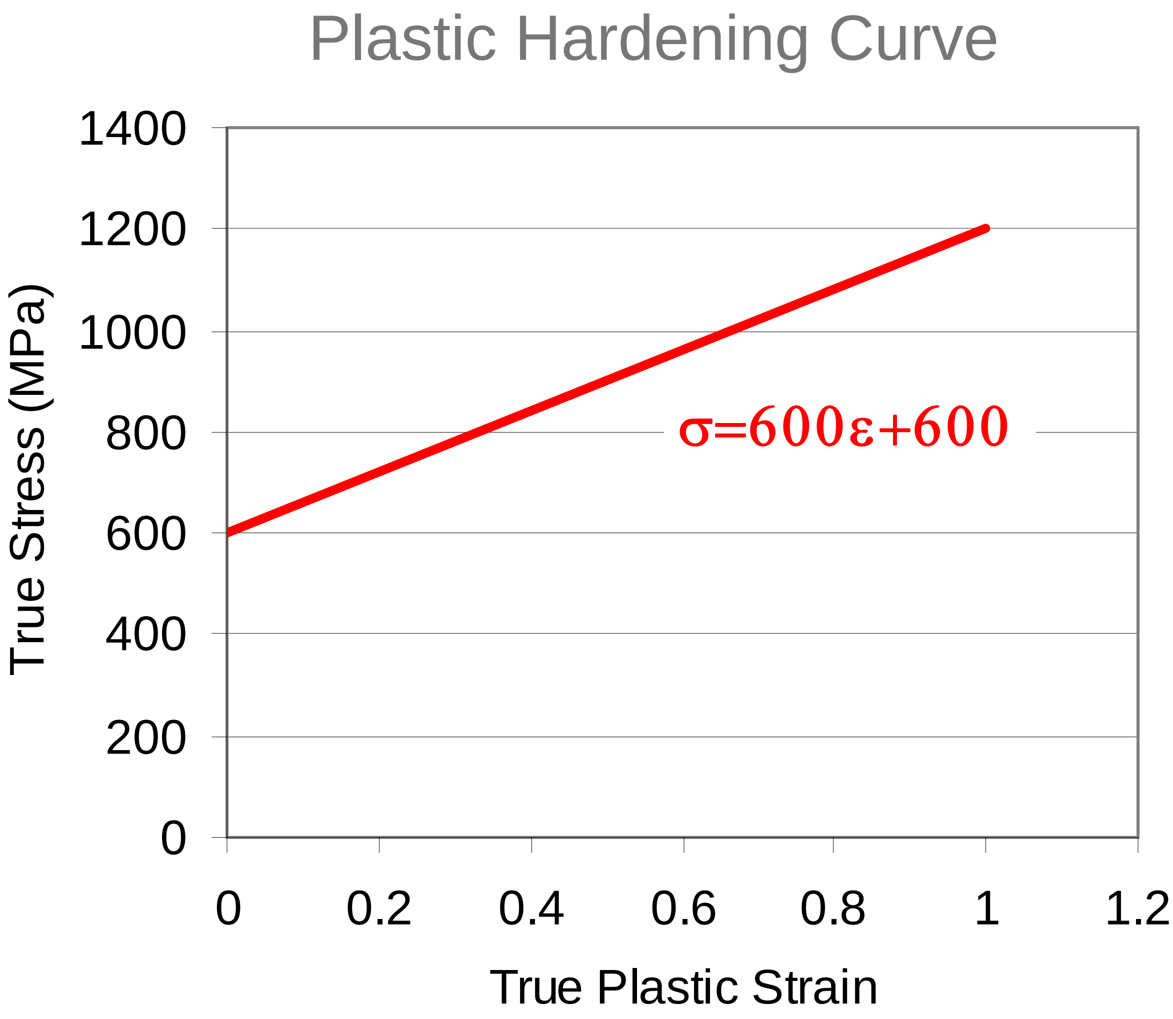
Material Property

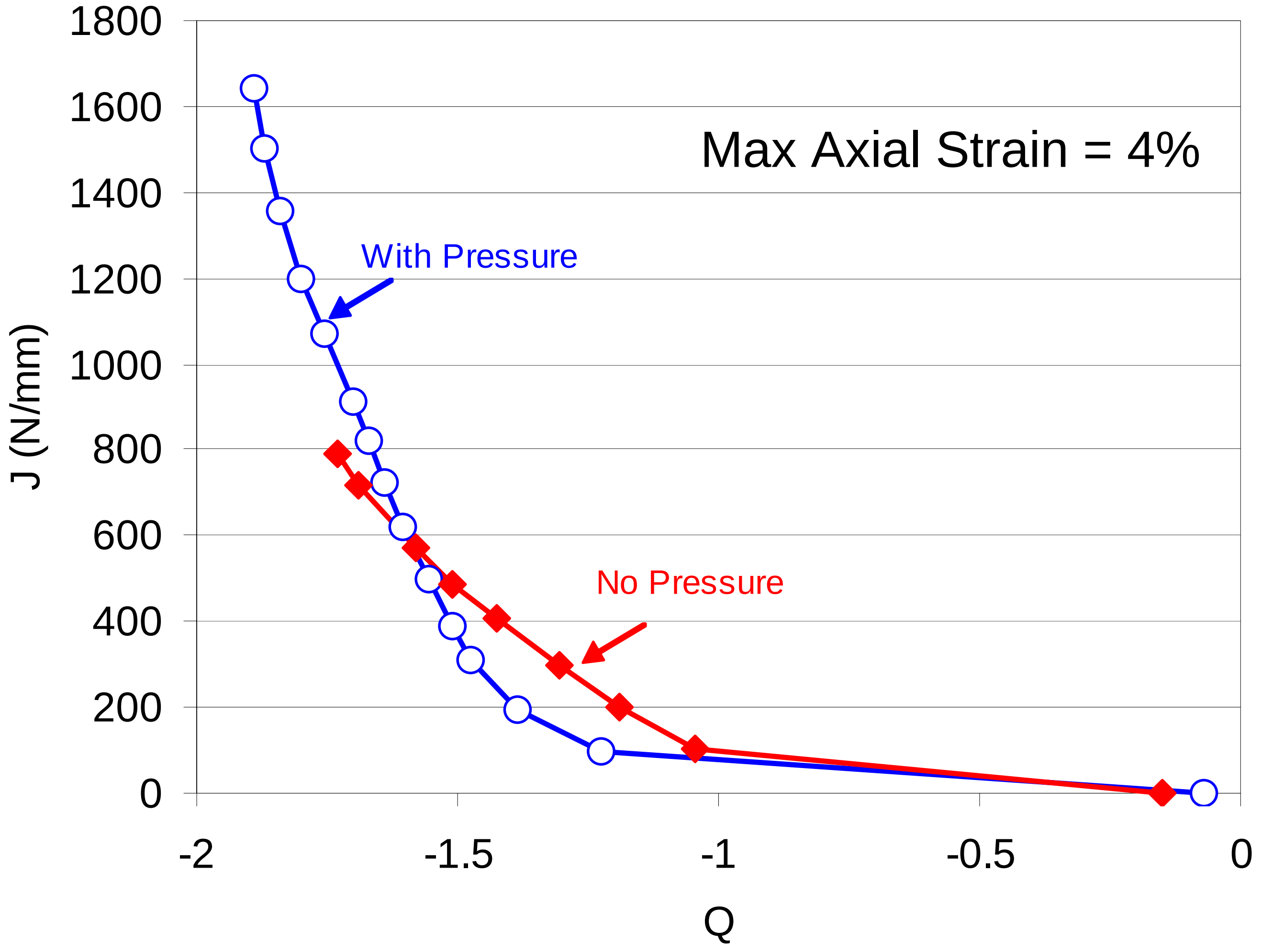


Linear Elastic Plastic Material

E=200 GPa

υ=0.3

J~Q Relationship



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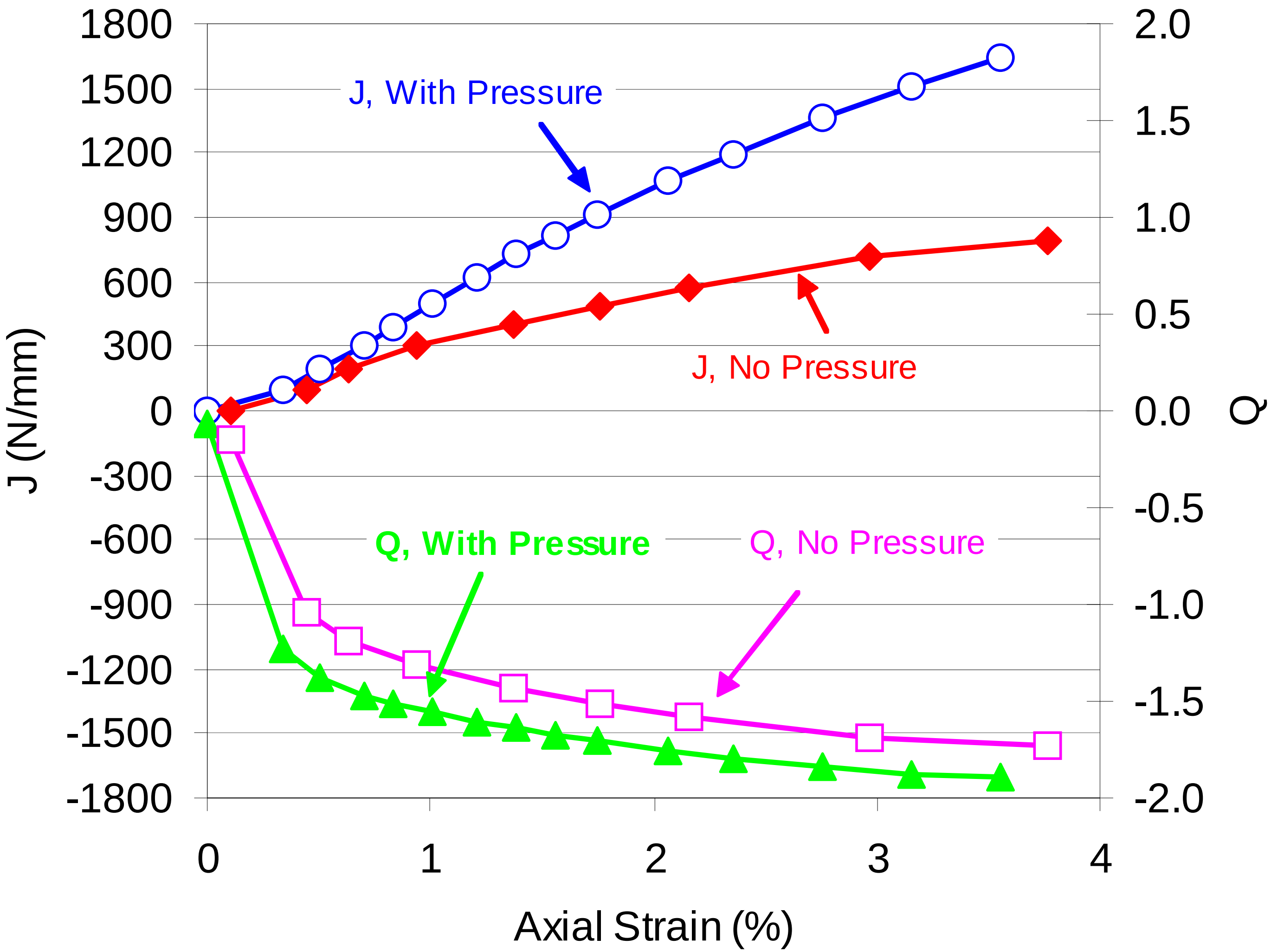
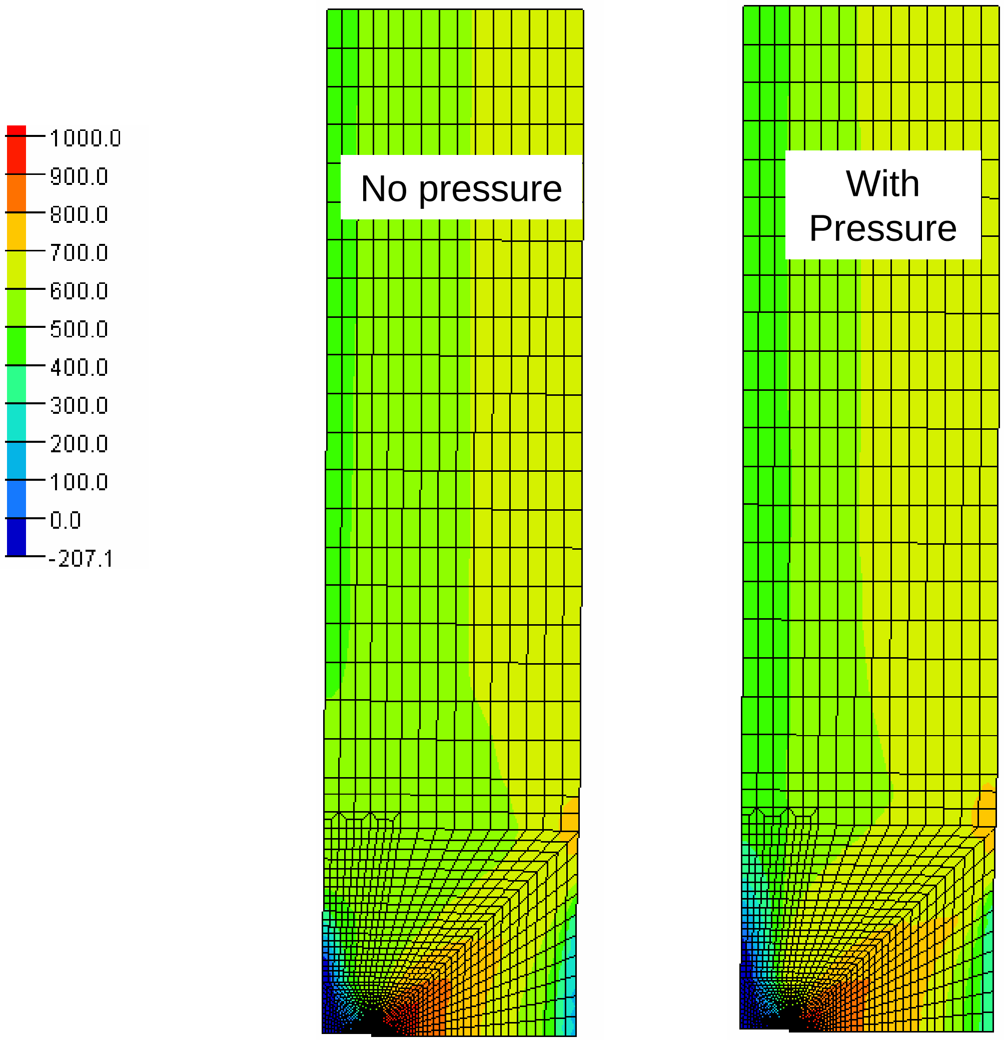
J, Q vs. Strain



1800
1500
1200
900
600
300
0
-300
-600
-900
-1200
-1500
-1800
J (N/mm)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Q
0
1
2
3
4
Axial Strain (%)
J, With Pressure
J, No Pressure
Q, With Pressure
Q, No Pressure

Axial Stress, at J=200 N/mm



Small Change in Axial Stress

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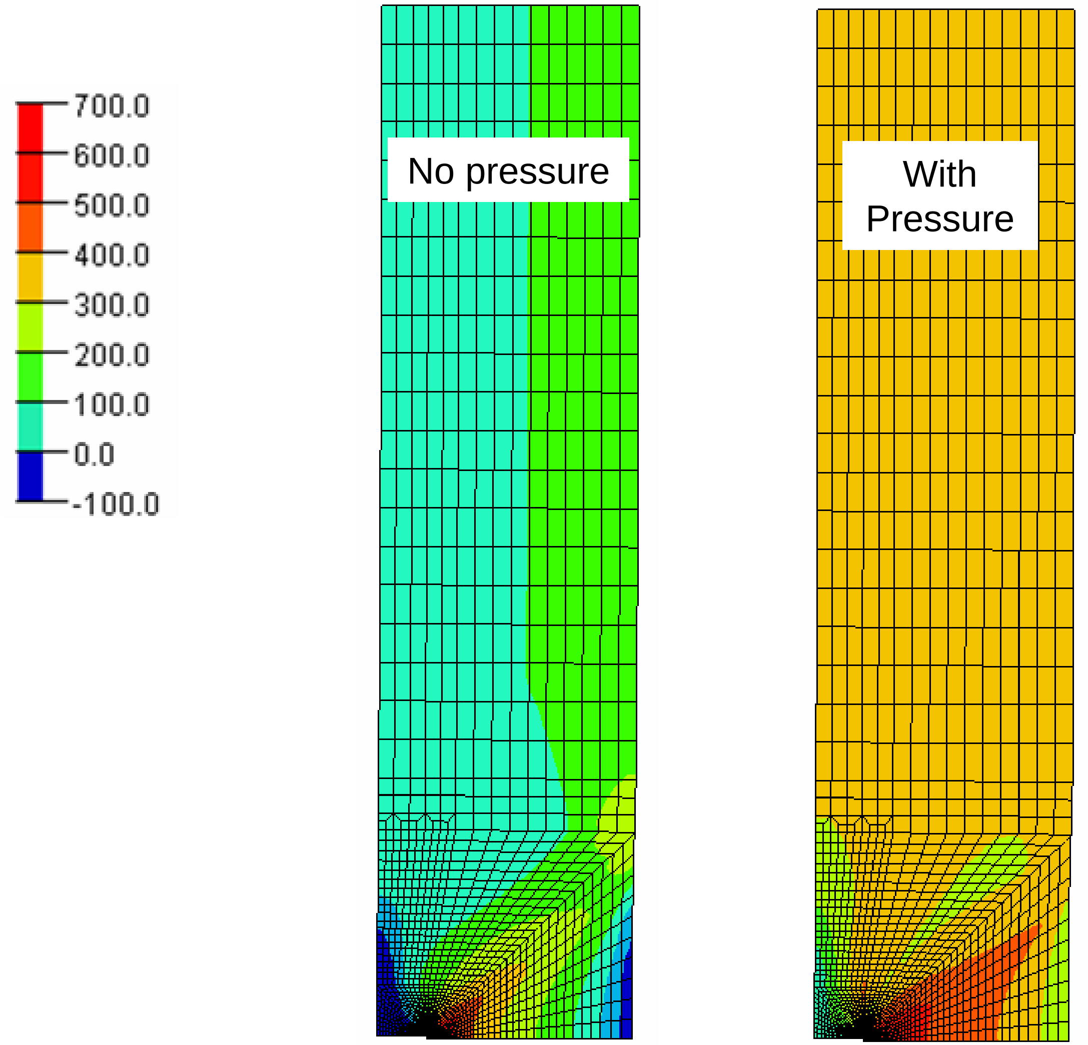
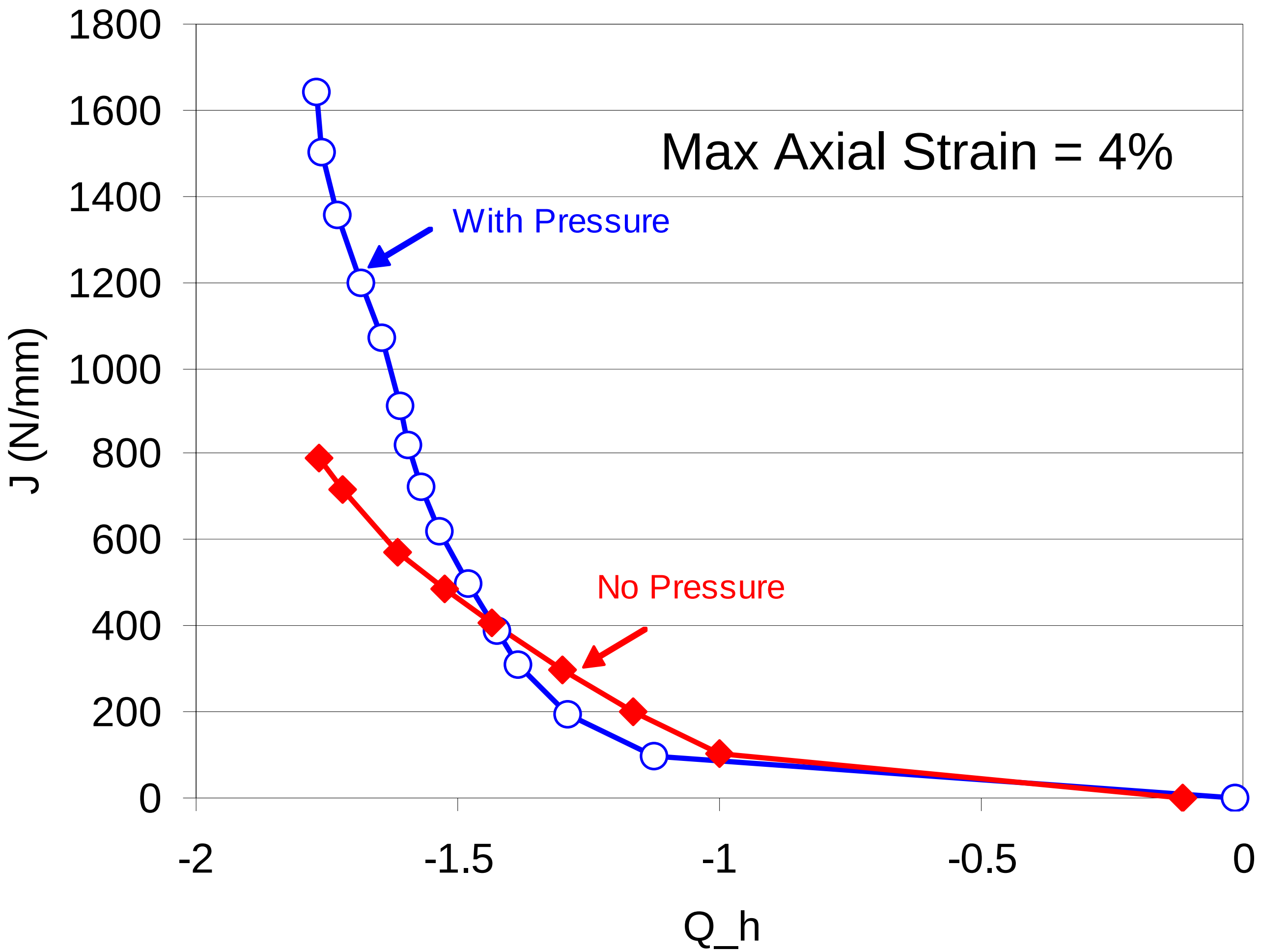
Hydrostatic Stress, at J=200 N/mm



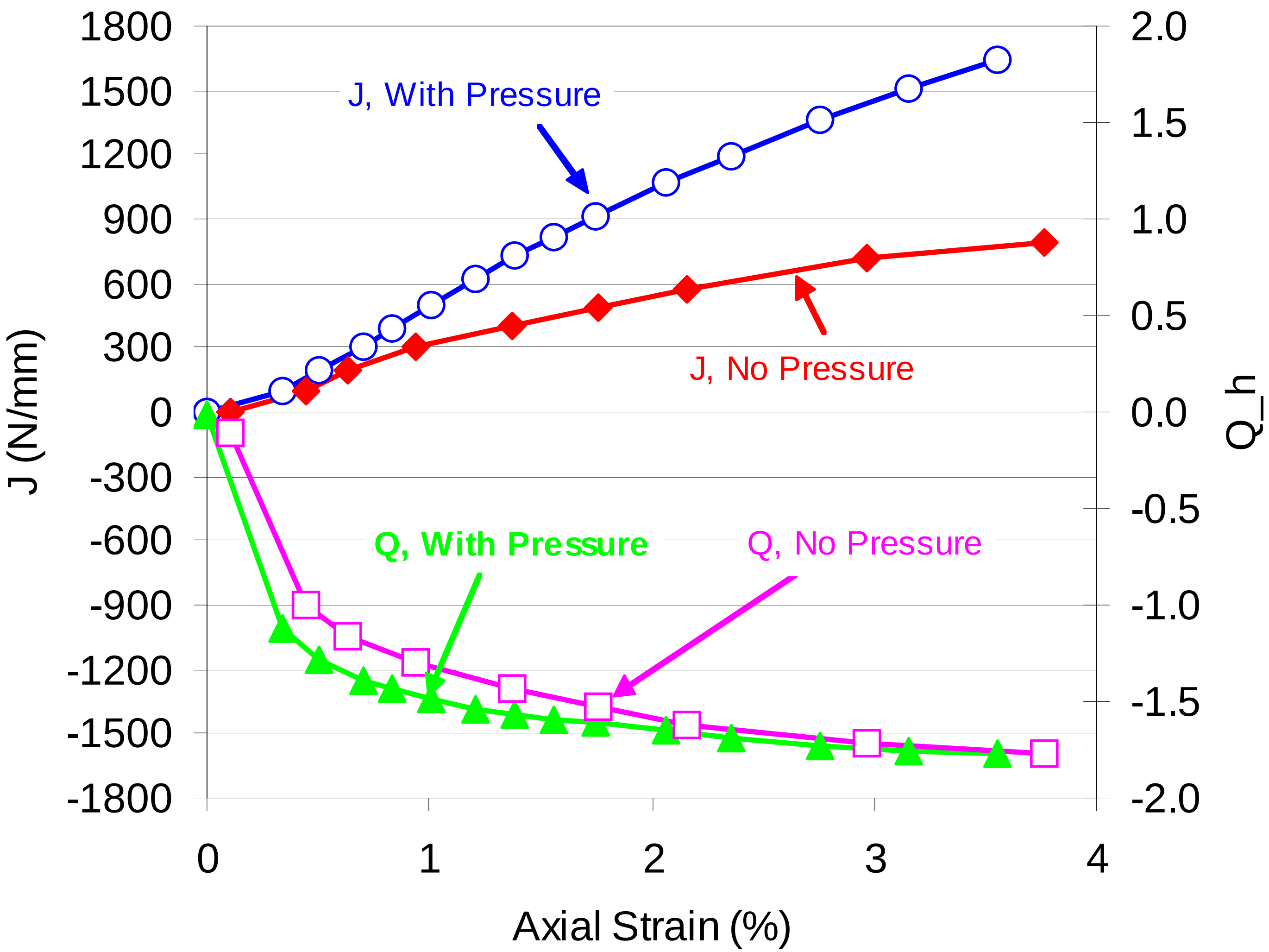
Large Change in σ_H

J~Q_h Relationship



Q Values Evaluated Using Hydrostatic Stresses

J, Q_h vs. Strain



Application to Pipeline Girth Welds

- Hoop Stress from Pressure Alone is Not a Major Driver of Constraint Change
- Stresses in Plane Perpendicular to Crack Tip Dominate Constraint

Constraint and Weld Qualification

- Constraint Matching Procedures (Effective CTOD) or Testing Procedures (SENT) Still Look Applicable to Girth Welds in Pressurized Pipelines
  - Biaxiality from Pressure Does Not Shove These Pipes Back to High Constraint
  - Pressure + Weld-Property-Induced Strain Concentration Should be Watched for its Constraint Effect

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Future of Strain-Based Design Program

DOT/PRCI Program

- X-65 Testing of Flaw+Pressure+Axial
- X-80 Testing of Flaw+Pressure+Axial
- CWP to Full Pipe Comparison
- Modeling of CTOD and Constraint
- Small-Scale Testing to Match
- Two Year Program with Four Contractors
  - C-FER
  - EMCC
  - EWI Microalloying
  - EWI

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