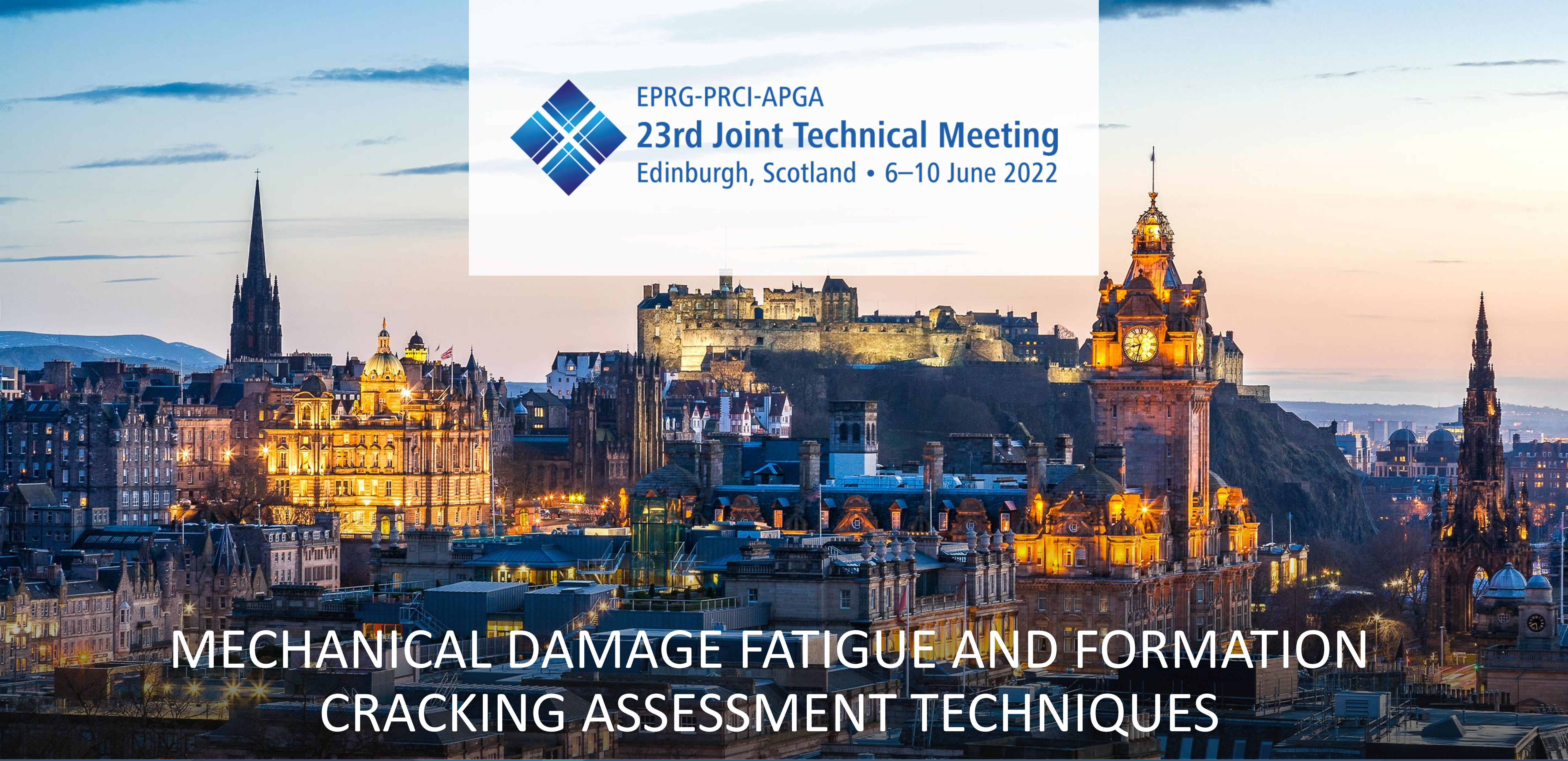
EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland • 6–10 June 2022

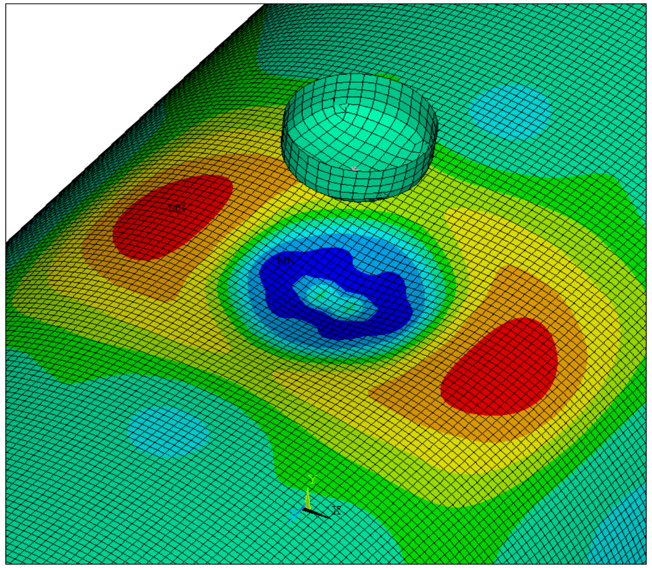


MECHANICAL DAMAGE FATIGUE AND FORMATION CRACKING ASSESSMENT TECHNIQUES

08 June 2022

PRCI Projects – Introduction

- This is an overview of PRCI MD-4-15 and MD-5-2 projects, part of the PRCI MD SRP
  - The MD-5-2 project was concieved to evaluate and improve various aspects of mechanical damage integrity methodologies implemented in API 1183
  - The MD-4-15 project demonstrated the performance of dent fatigue models for natural dents removed from service
- The scope of work
  - MD-5-2
    - assess and improve indentation strain prediction models
    - assess effect of ILI data variability on fatigue life and strain estimations
    - quantify safety factors inherent in different fatigue life estimation methods
  - MD-4-15
    - Remove dents from operating piplines
    - Subject them to cyclic loading trials
    - Compare API RP 1183 predicted lives to experimental lives



Indentation Strain – Introduction

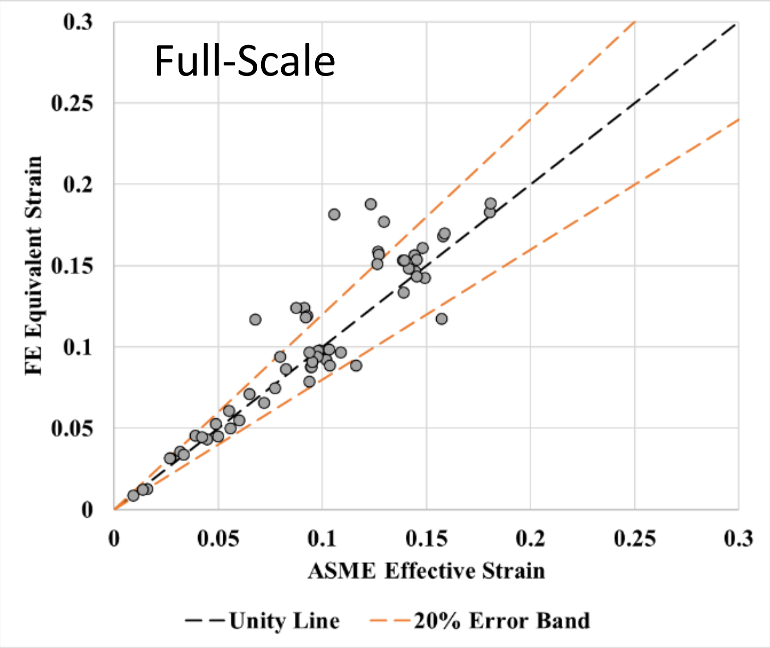
- Various models estimating dent formation strains are avaiable, two were considered in this project
  - ASME B31.8 Appendix R Effective Strain
  - "Blade Energy Partners Simplified Model" Effective Strain
- Both models in principle consider the reported dent shape to estimate pipe wall axial and circumfiential membrane and bending strain components
  - No circumferential membrane strain is offered in the ASME formulation
- Both models estimate directional strains to develop an effective or total strain formulation
  - This effective strain is a scalar measure of triaxial strain

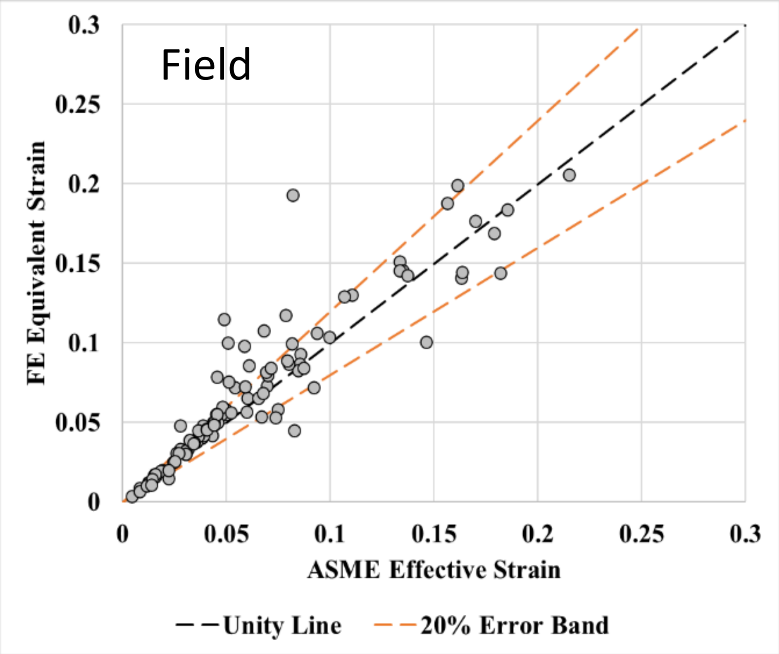
Indentation Strain – Evaluation

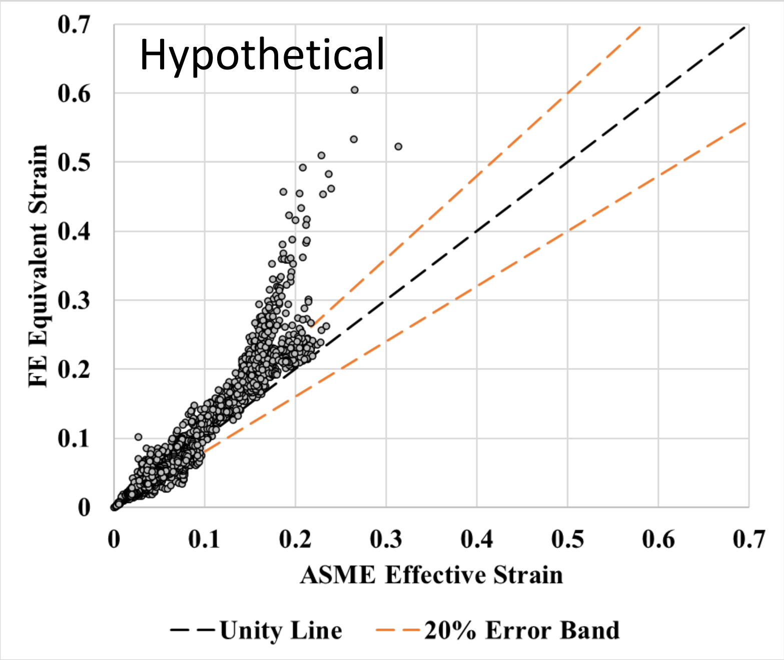
- Compare ASME and Blade strain estimates with those inferred from the validated BMT dent FE model
  - Consider 4600 hypothetical dents, 60 lab full-scale trial dents, 100 in-service field dents
  - Includes a range of pipe, dent geometries and restraint conditions
    - OD 114 to 1066mm
    - Depth 0.5 to 10% pipe OD
    - Indentation pressure 0 to 90% SMYS
    - Various indenter shapes
  - Extracted dent axial and transverse profiles through FE model dent apex to evaluate ASME and Blade effective strains
  - Extracted component strains from the FE model to calculate effective strains

Indentation Strain – ASME Strain Performance

- Good agreement (<20% error) with 76% hypothetical, 82% Full scale and 79% field dents
  - Divergence at higher strains

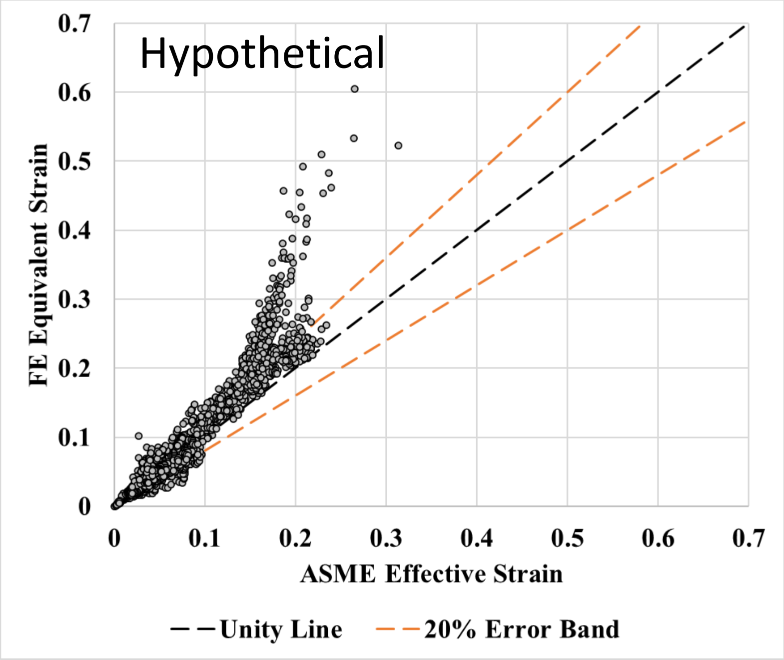




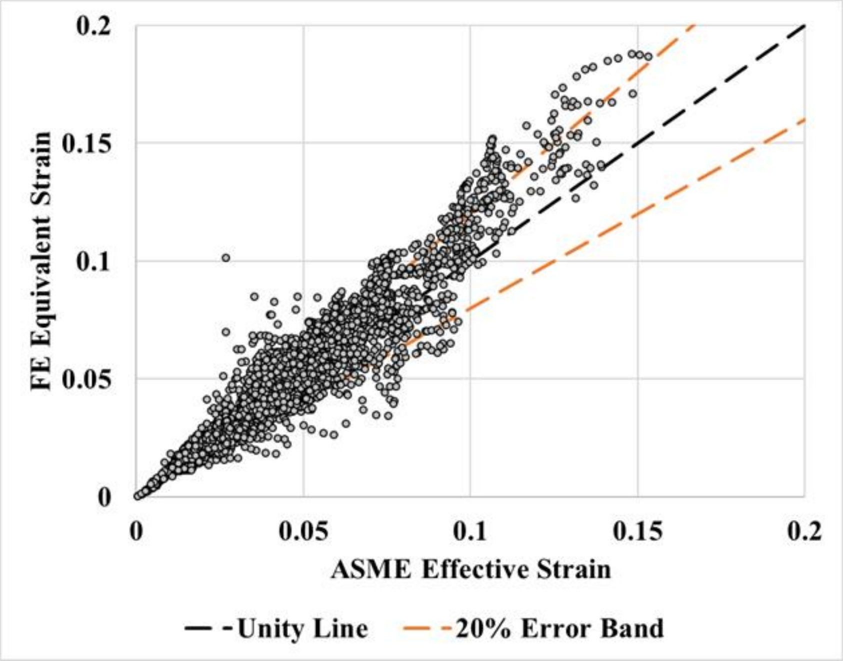


Indentation Strain – ASME Strain Performance

- Agreement of the ASME strains improve in the absence of deep and sharp dents
  - ASME axial membrane strain underpredicted

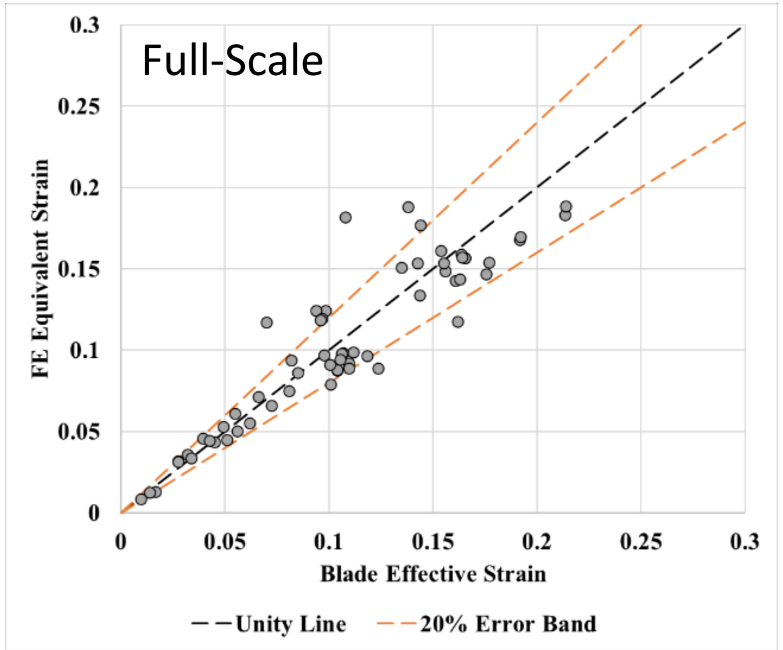


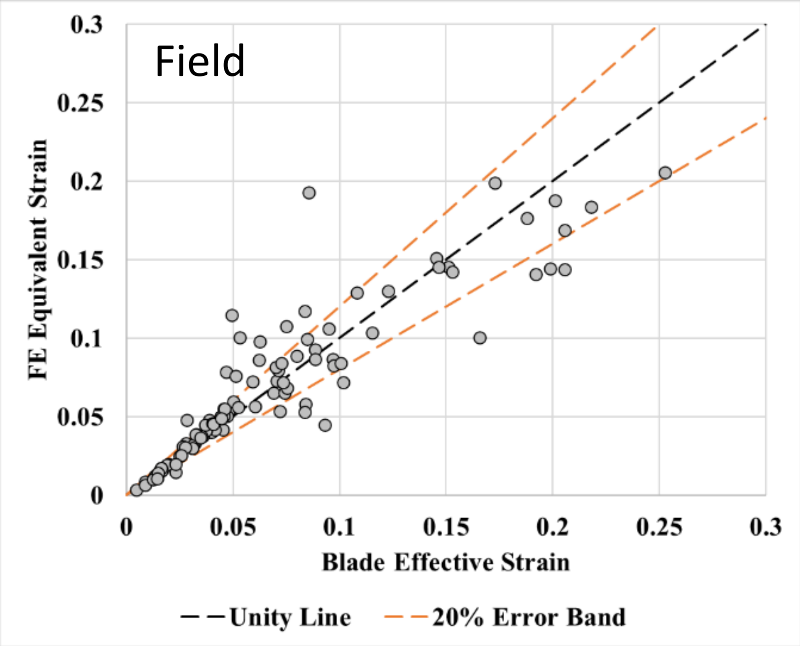
Hypothetical – No Deep and Sharp Dents

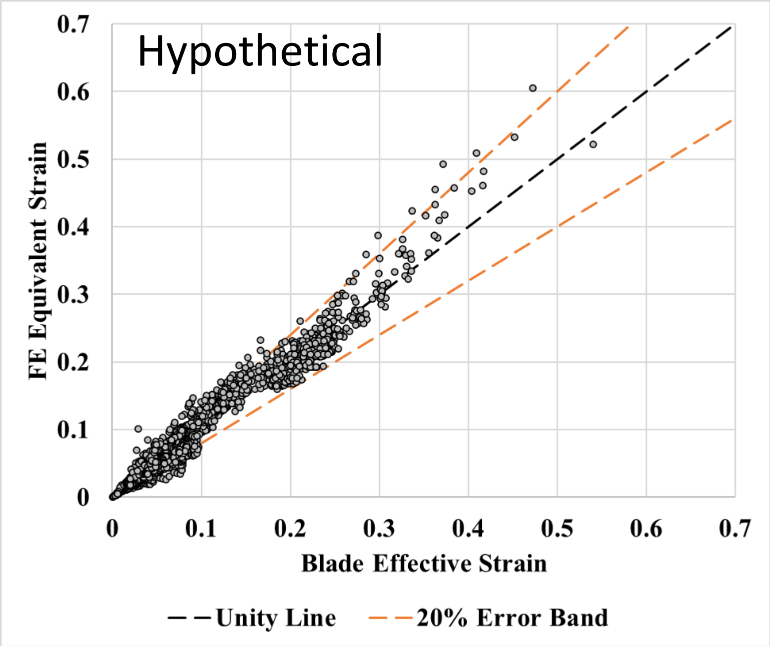


Indentation Strain – Blade Strain Performance

- Good agreement (<20% error) with 86% hypothetical, 83% Full scale and 77% field dents
  - Better agreement than the ASME, due to inclusion of circ. membrane and better axial membrane strain formulations

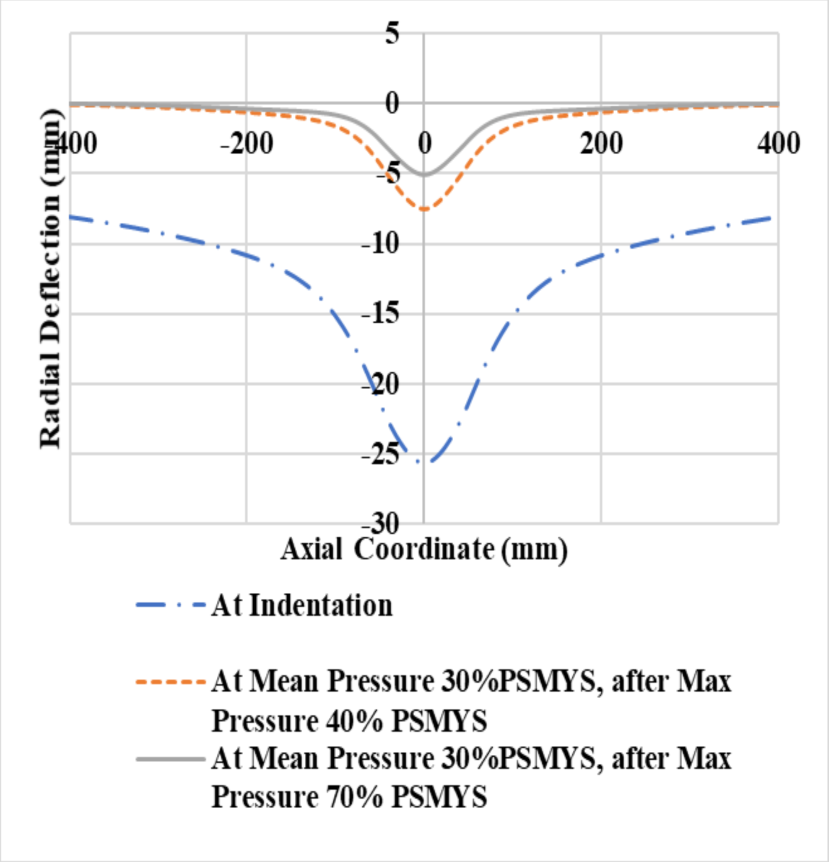






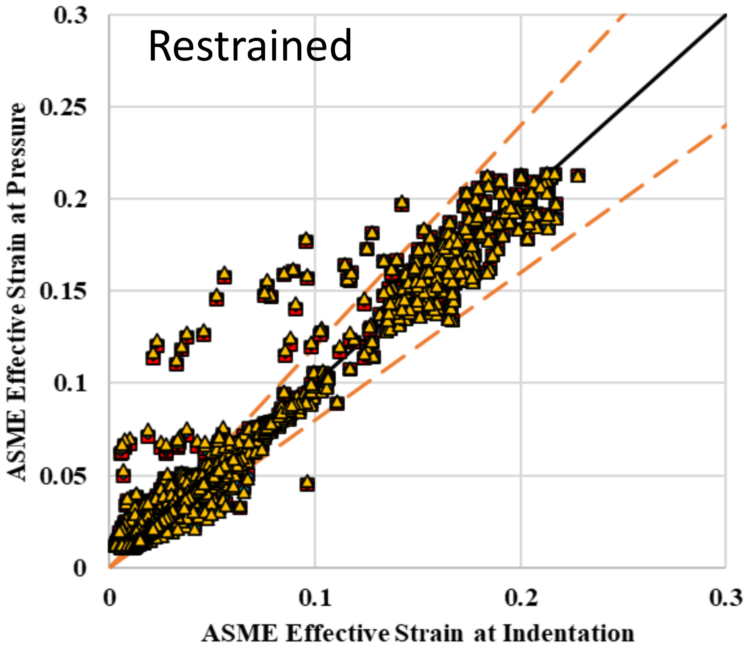
Indentation Strain – Consideration of Restraint

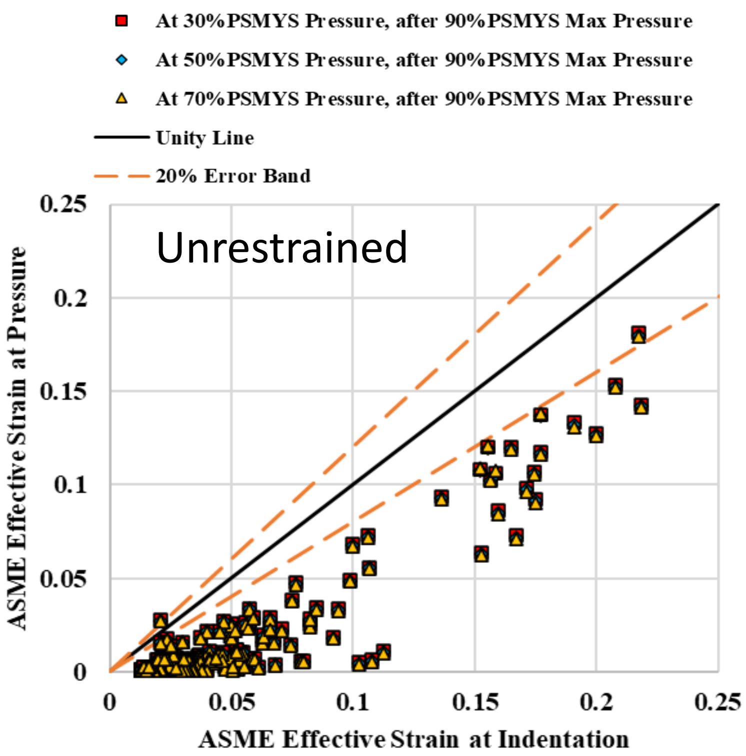
- Pipeline dent inspection data may or may not represent and restrained dent
  - Significant difference between the reported shape of restrained and unrestrained dents
  - Shape of the dent in a pipeline to a given depth is related to
    - Indentation pressure and pipe geometry (D/t)
    - Restraint condition
    - Maximum operational/test pressure
- Indentation strain based on ILI data for unrestrained dent does not represent the maximum dent strain

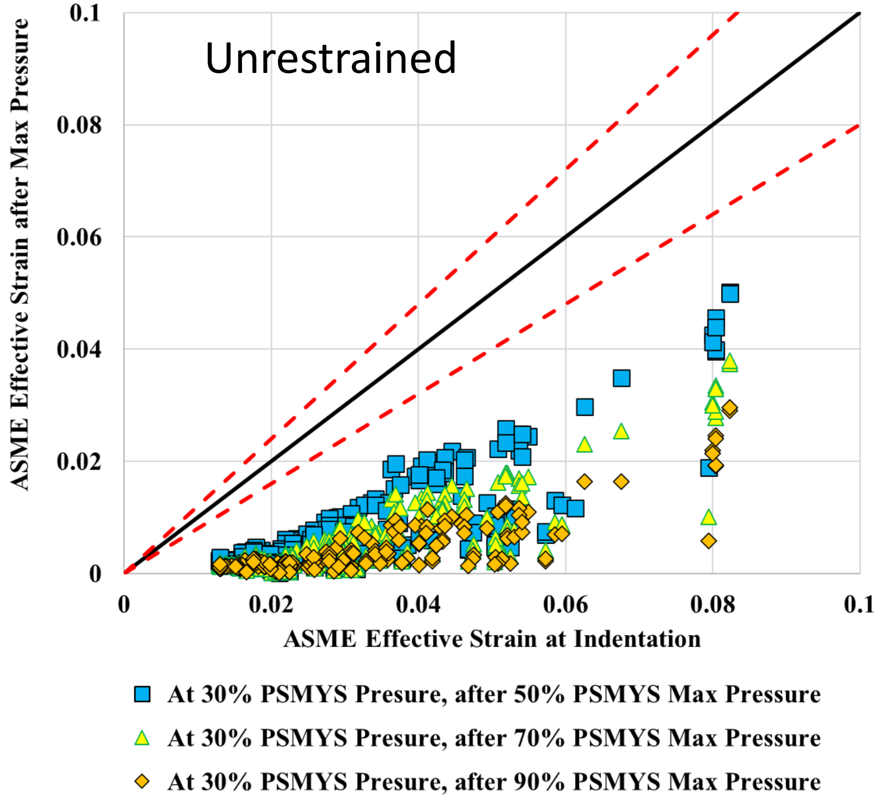


Indentation Strain – Consideration of Restraint

- The effect of restraint and pressure history is significant on dent formation strain
  - Regardless of indention strain estimation technique …. Dent change shape due to change in pressure
  - Higher historic maximum pressure (Pressure test) will promote greater shape change



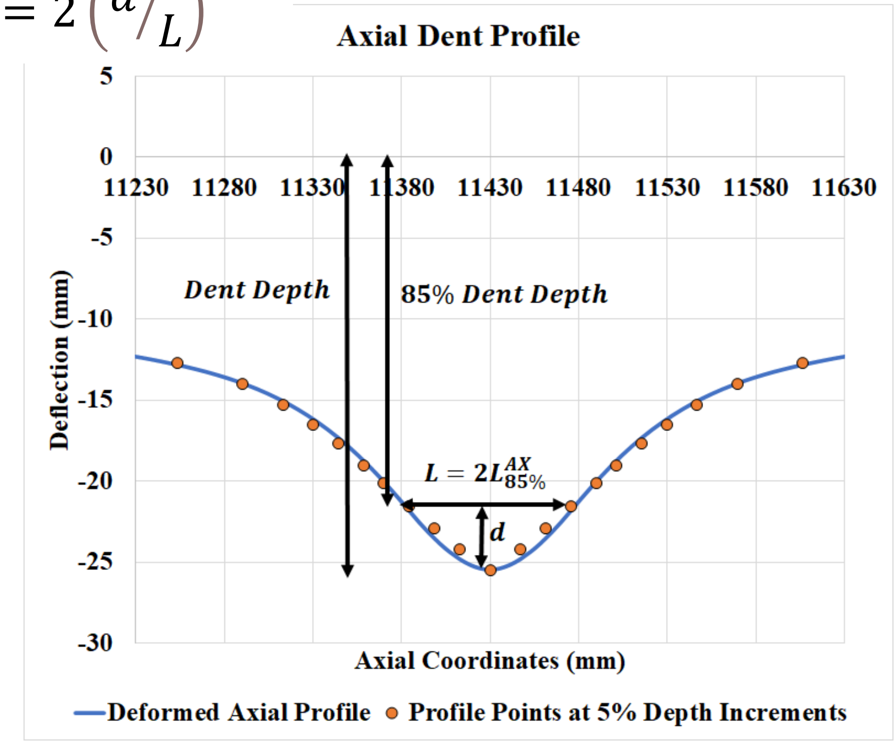




Indentation Strain – ASME Strain Improvement

- Improvements in axial and circ membrane strain estimations presented

$$\varepsilon_3 = 2\left({}^{d}/_{L}\right)^2$$



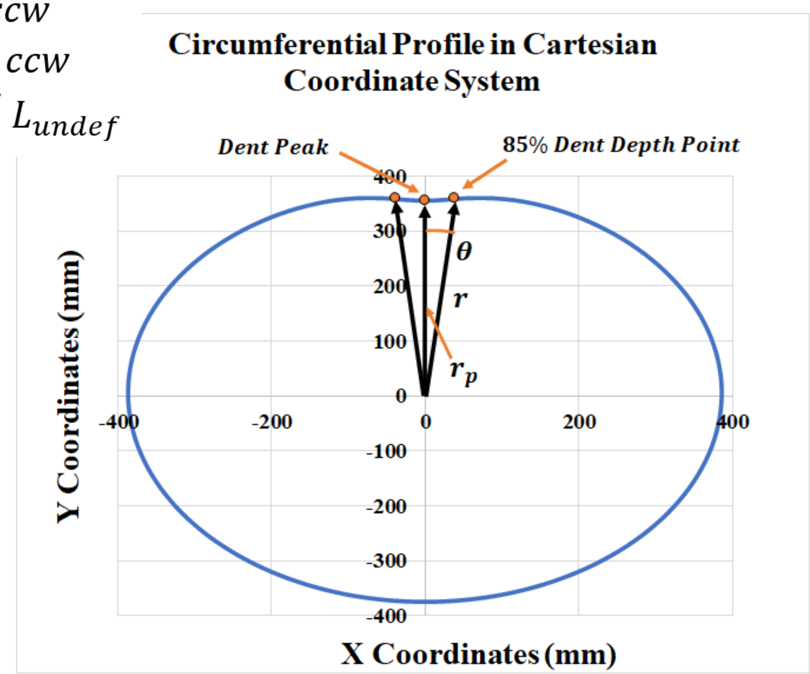
$$L_S = \sqrt{r^2 + r_p{}^2 - 2\, r\, r_p\, \cos\theta}$$

$$L_0 = r\sqrt{2(1 - \cos\theta)}$$

$$L_{def} = L_S\, cw + L_S\, ccw$$

$$L_{undef} = L_0\, cw + L_0\, ccw$$

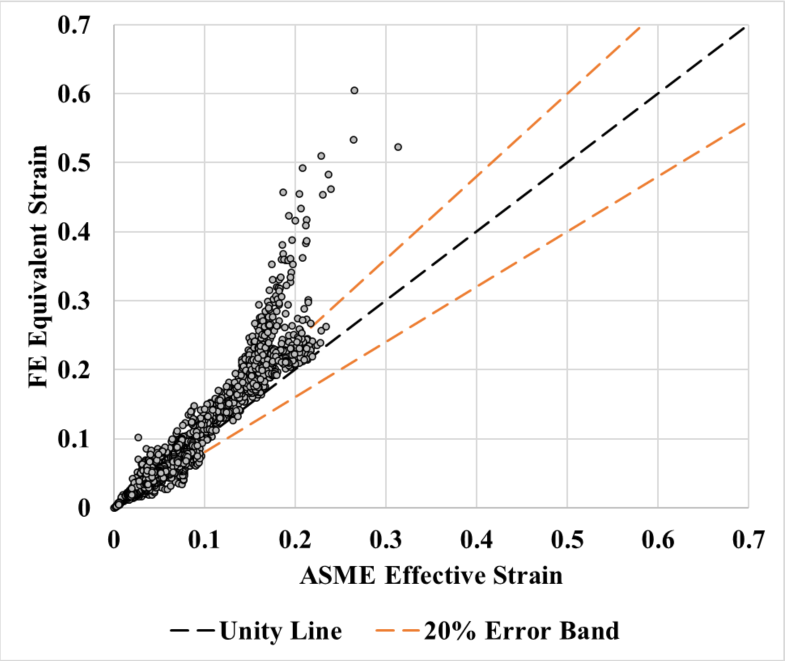
$$\varepsilon_4 = \left(L_{def} - L_{undef}\right) / L_{undef}$$



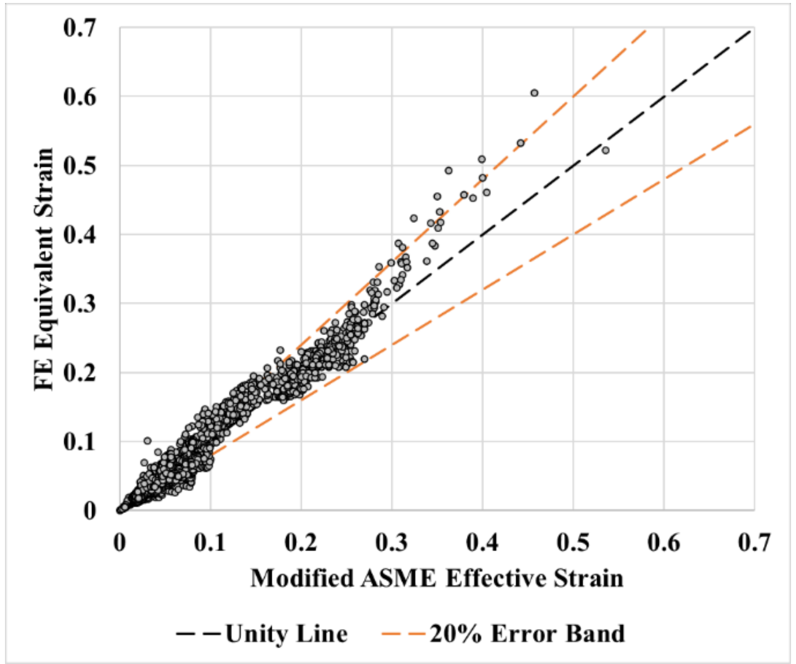
Indentation Strain – ASME Strain Improvement

- Improvements in axial and circ membrane strain estimations presented
  - Demonstrated for hypothetical dent data set

ASME Approach

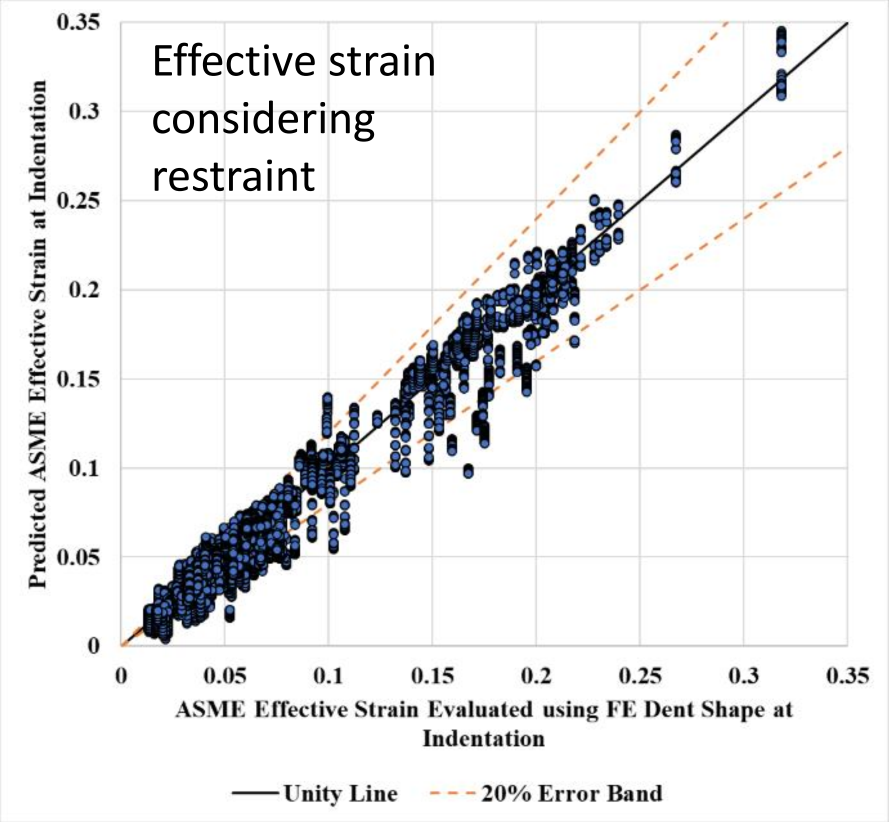


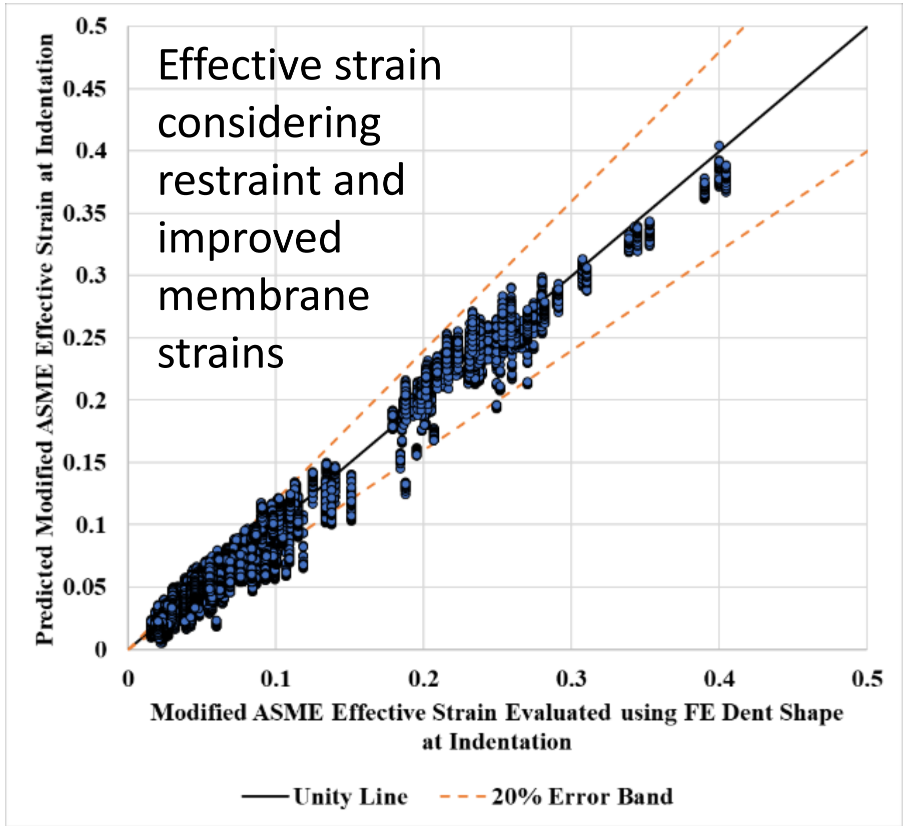
Modified ASME Approach



Indentation Strain – ASME Strain Improvement

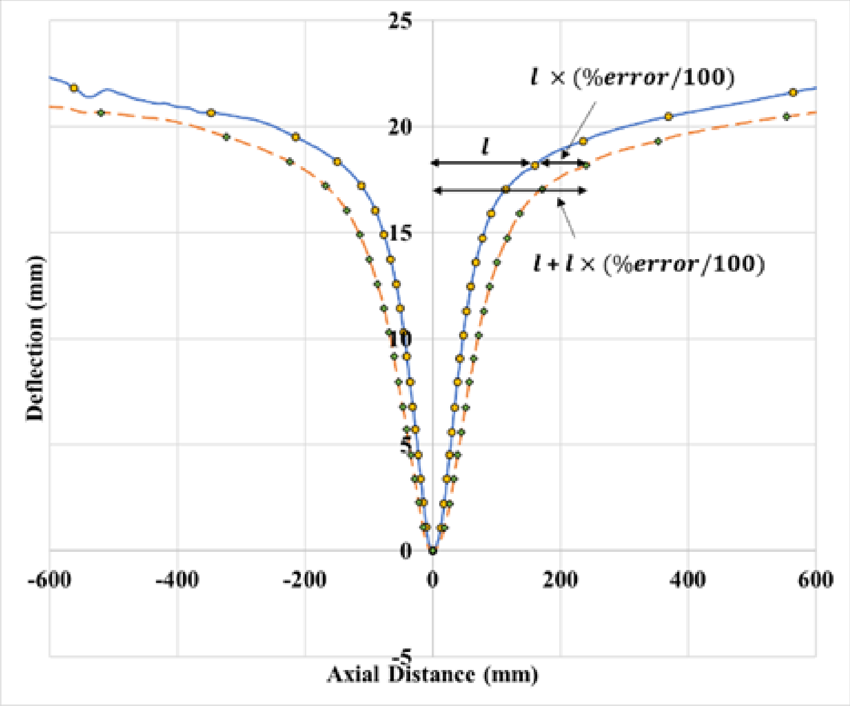
- Developed method to estimate indentation strain from unrestrained dents
  - Stepwise improvements in ASME strain estimations presented for hypothetical dent data set

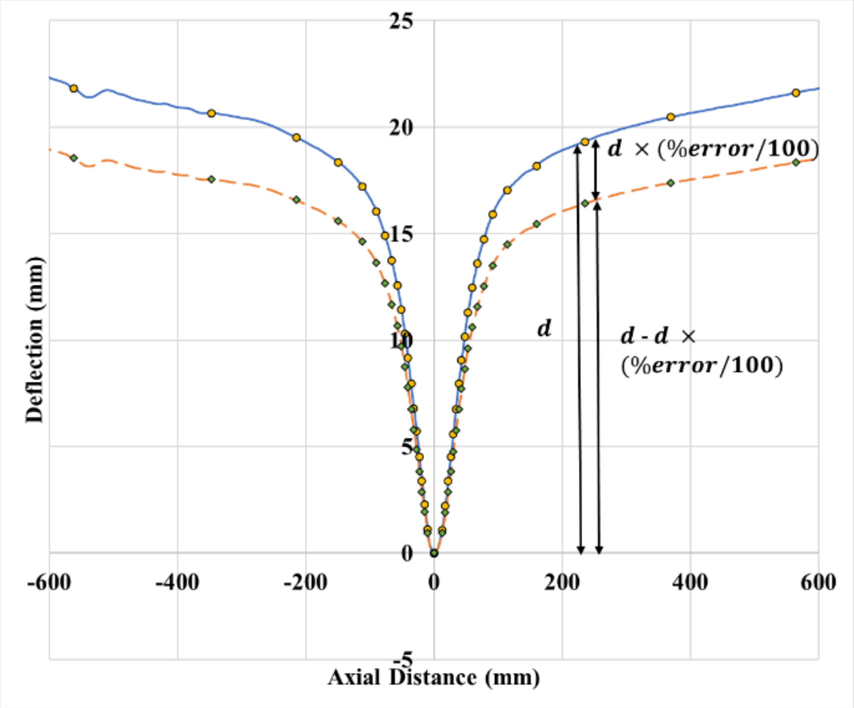




Dent Shape Variation Impact

- Measurement of dent shape can include variability
  - The effect of this variability was considered on shape-based fatigue and strain criteria
  - Monte Carlo simulation was applied to explore impact of measurement variability

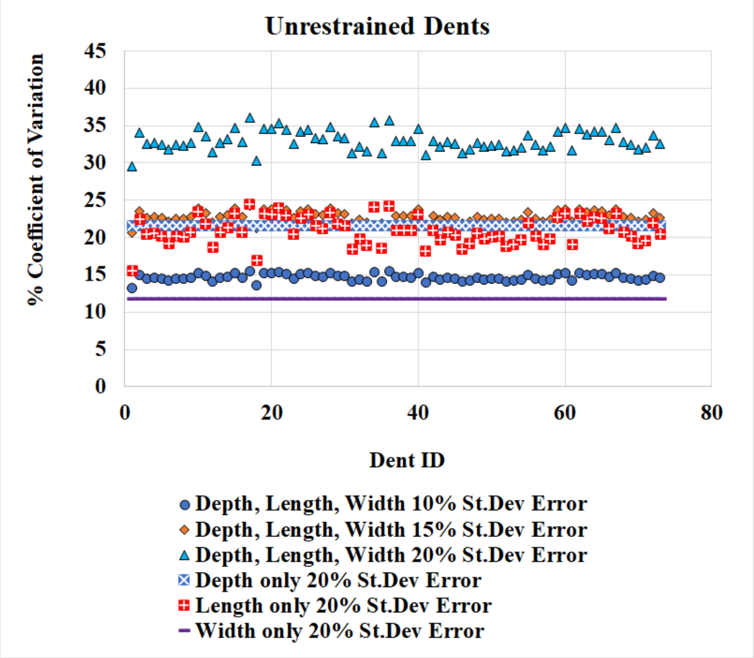




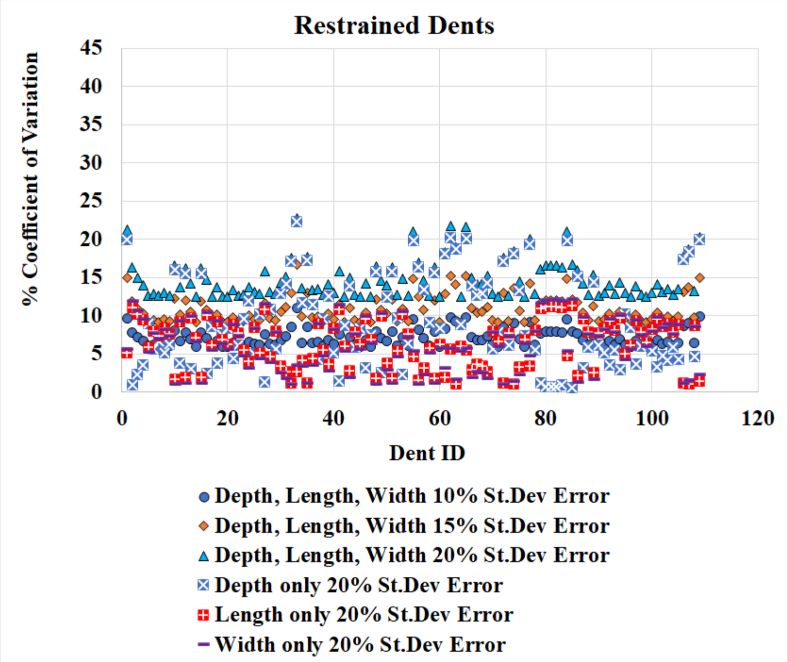
Dent Shape Variation Impact

- The effect of this variability was considered on shape-based fatigue and strain criteria
  - For 914mm (36 in) pipe
    - Fatigue life variation similar to measurement variation …. Unrestrained dents more impact
    - Indentation strain variation double measurement variation

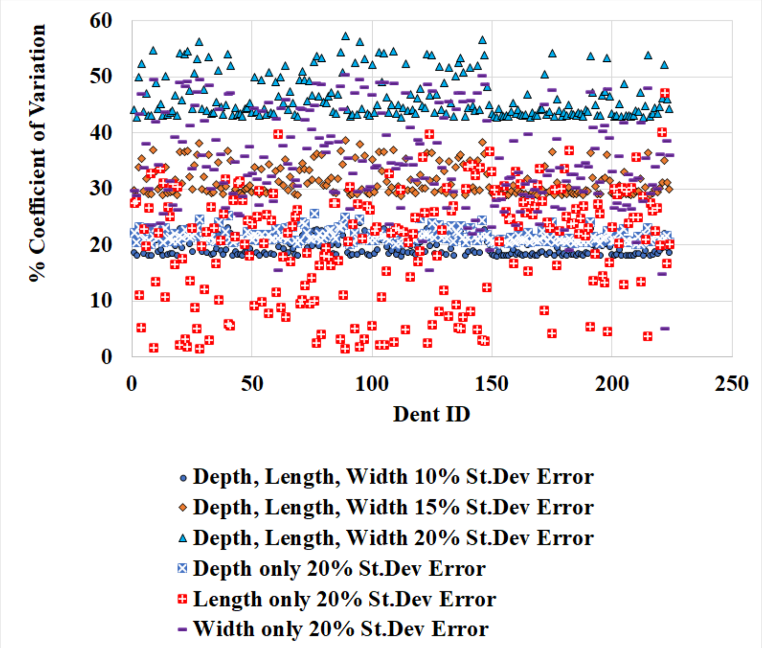
Fatigue life



Fatigue life

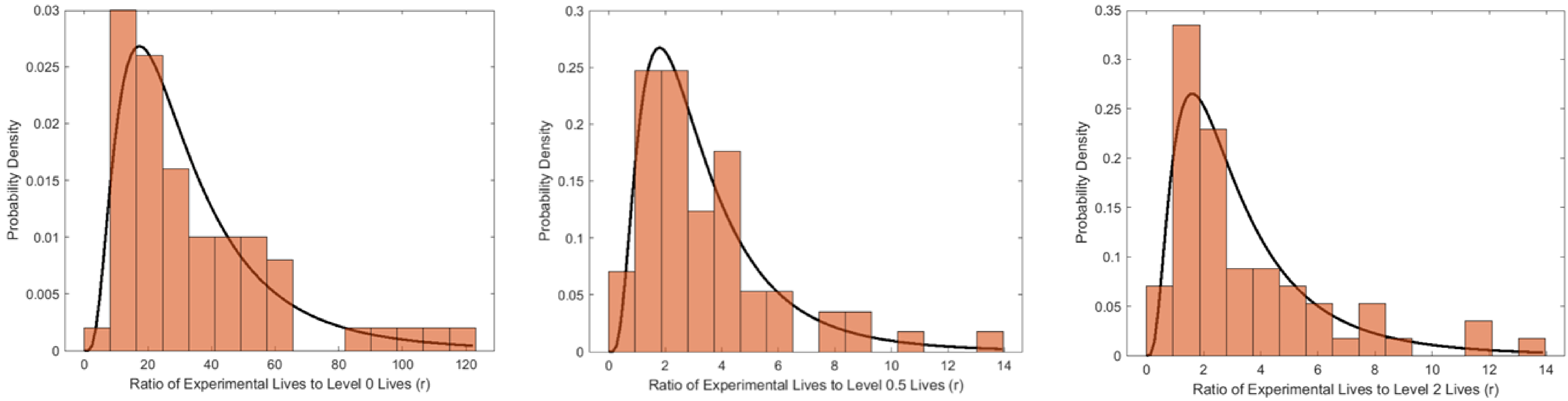


ASME Indentation Strain



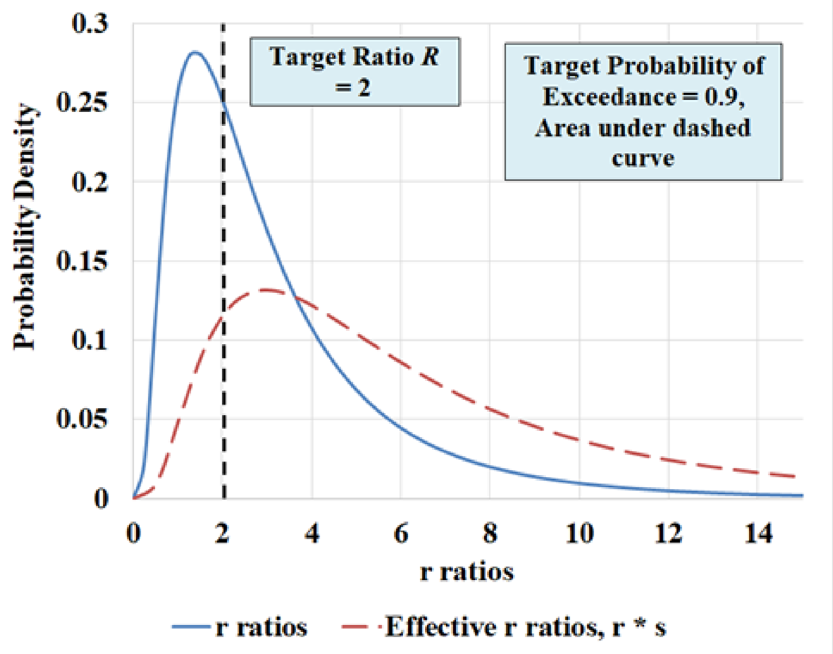
Fatigue Life Conservatism

- The inherent safety of fatigue life calculations was considered
  - Defined safety factors (model bias) inherent in API RP 1183 fatigue life calculations
  - Compared calculated fatigue lives with experimental data for 127 dents in pipe with OD from 273 to 1016 mm (10 to 42 inches)
    - 61 plain dents, 29 dents interacting with metal loss, 37 dents interacting with welds



Fatigue Life Conservatism

- Scaled fatigue life ratio distributions to develop target levels of safety
  - Defined fatigue life scaling factor required for each technique to achieve target level of safety (model bias) at specified level of certainty



Scaling Factor Matrices				
	Level 0, Mean			
	Probability of Exceedance of Target Safety Factor α = 0.8			
Target Safety Factor (R)	Plain Dents	Dents Interacting w/ Metal Loss	Dents Interacting w/ Weld. Reduction Factor = 10	Dents Interacting w/ Weld. Reduction Factor = 5
10	1	1	1	1
15	1	1	1	1
25	1.6	1.22	1	1
	Level 0.5, Mean			
	Probability of Exceedance of Target Safety Factor α = 0.8			
Target Safety Factor (R)	Plain Dents	Dents Interacting w/ Metal Loss	Dents Interacting w/ Weld. Reduction Factor = 10	Dents Interacting w/ Weld. Reduction Factor = 5
2	1.25	1	1	1
3	1.88	1.04	1	1
6	3.76	2.08	1	1.05
	Level 2, Mean -1sd			
	Probability of Exceedance of Target Safety Factor α = 0.8			
Target Safety Factor (R)	Plain Dents	Dents Interacting w/ Metal Loss	Dents Interacting w/ Weld. Reduction Factor = 10	Dents Interacting w/ Weld. Reduction Factor = 5
2	1.36	1.02	1	1
3	2.04	1.53	1	1
6	4.08	3.07	1	1.1

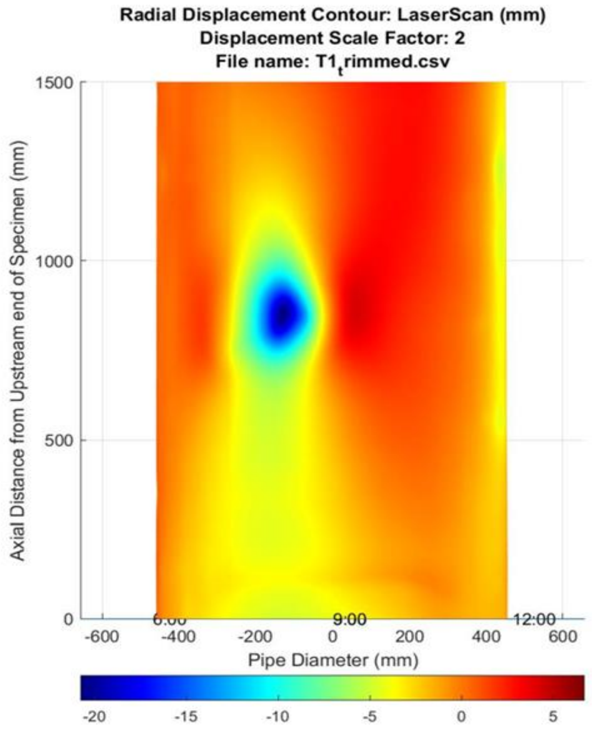
Fatigue Life Prediction of Field Dents

- Understanding of Dent Fatigue Developed Considering
  - Physical trials (PRCI MD-4-2, MD-4-11 and MD-4-14)
  - Full scale dent fatigue testing (approx. 150 tests)
  - Field observations and metallurgical investigations
- Development of tools to assess life (PRCI MD-4-9)
  - Validate based upon physical trial data
  - Consider a range of behaviors (> 400,000 FE models)
  - Regression equations develop Non FEA assessment tools
  - Behavior bounds develop screening tools
- Objective
  - Generate full scale dent fatigue test data on dents removed from service illustrating behavior relative to
    - lab fabricated dents
    - API RP 1183 assessment tools (Level 2 analysis)

Fatigue Life Prediction of Field Dents

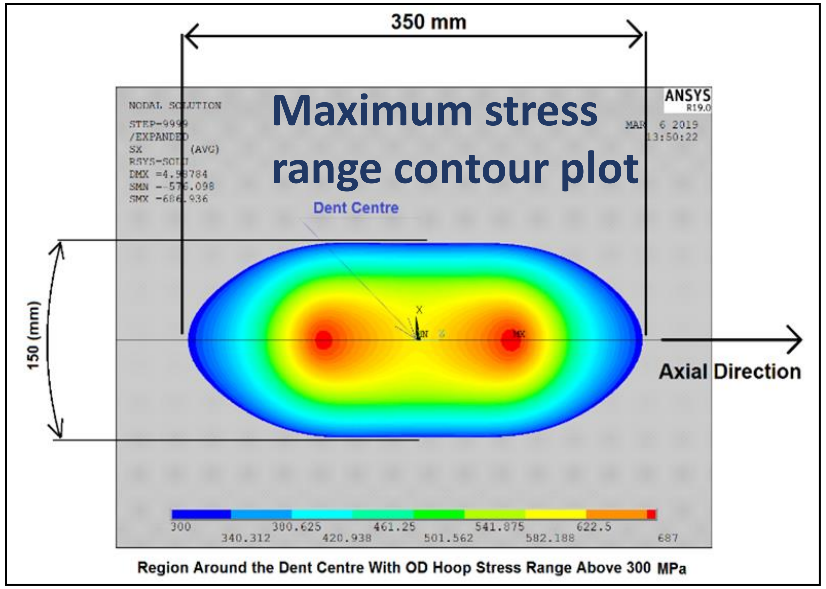
- Fatigue Testing of Field Dents (25 features)
  - OD - 5 (250, 609, 813, 914, 1016 mm) (10", 24", 32", 36", 40")
  - D/t – 4 (49, 96, 115, 128)
  - Dent Depths – 0.6% - 11%
  - Grades – 2 (X-52 & X-60)
  - Vintage – 1963-2007 (1960's, 1970's, 2007)

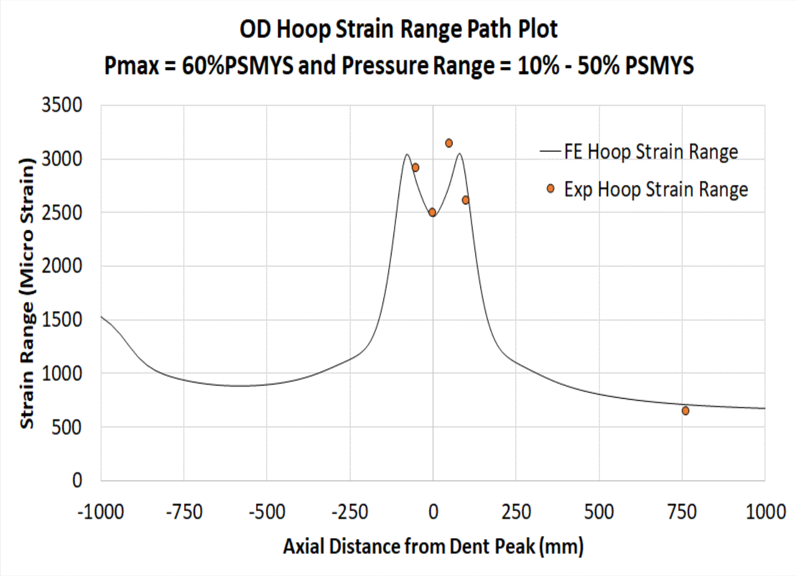
Pipe OD (inch)	Wall Thickness (inch)	D/t	# of Tests	Grade	Vintage	Range of Dent Depths, ILI (%OD)	Range of Dent Depths, Laser Scan (%OD)
10.75	0.219	49	3	X52	2007	2.6-11.6	3.0-11.4
24	0.250	96	9	X52	1968	0.8 to 5.6	0.8 to 4.9
32	0.281	114	1	X52	1963	1.6	0.6
36	0.312	115	5	X52	1979	2.5 to 4.4	0.7 to 3.3
40	0.344	116	2	X60	1979	0.9 to 1.3	1.2 to 1.8
40	0.312	128	5	X52	1968	0.7 to 2.4	0.9 to 3.2

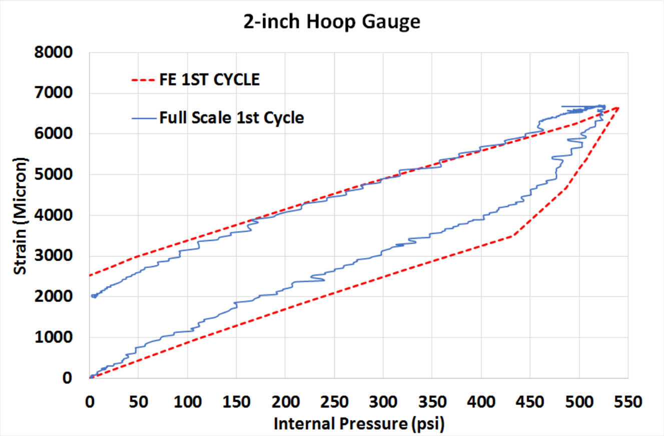


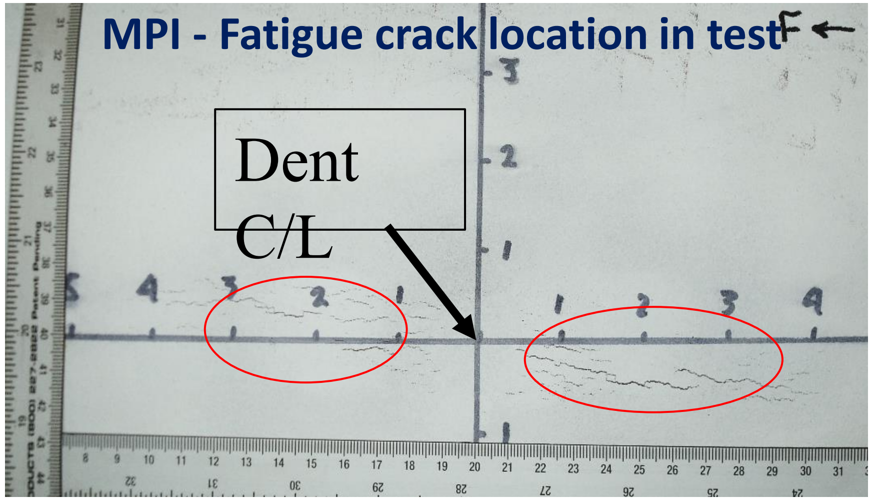
Fatigue Life Prediction of Field Dents

- Compare FE and experimental dent response
  - Pipe wall strain response
  - Cacking location and surface



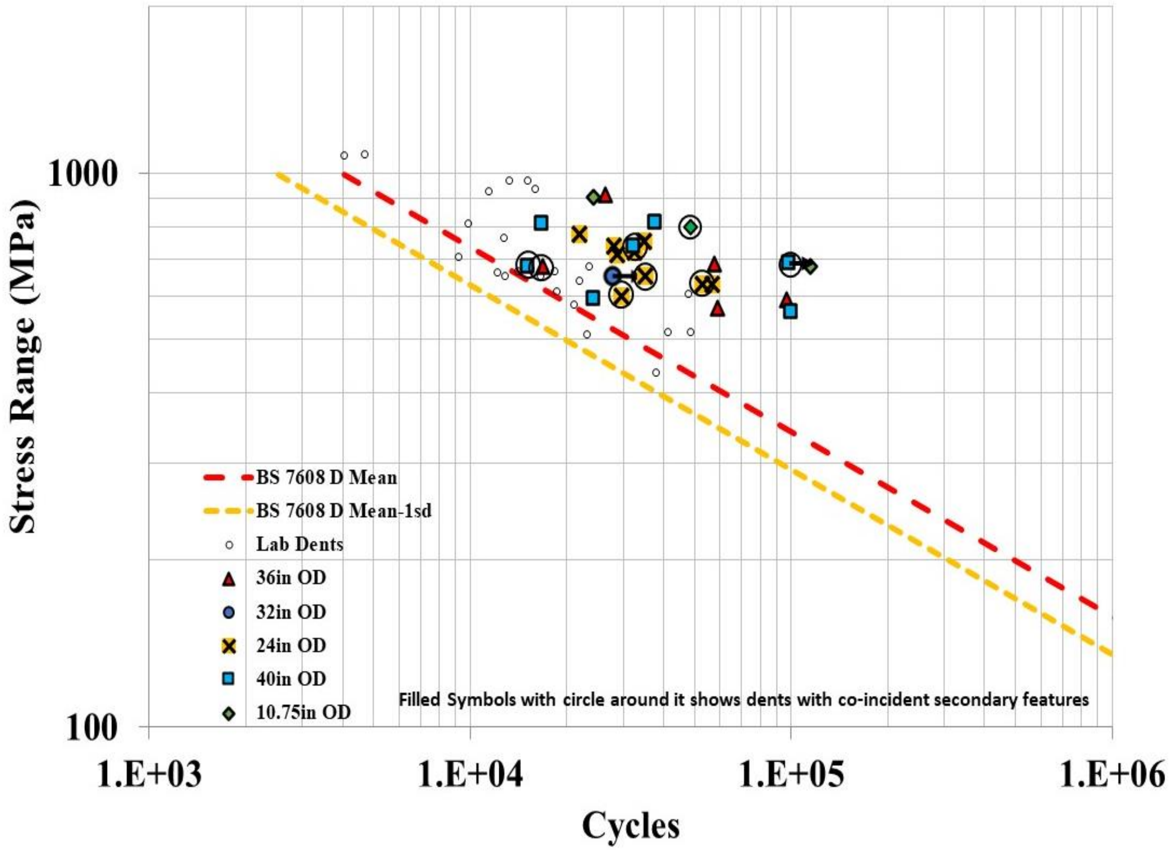






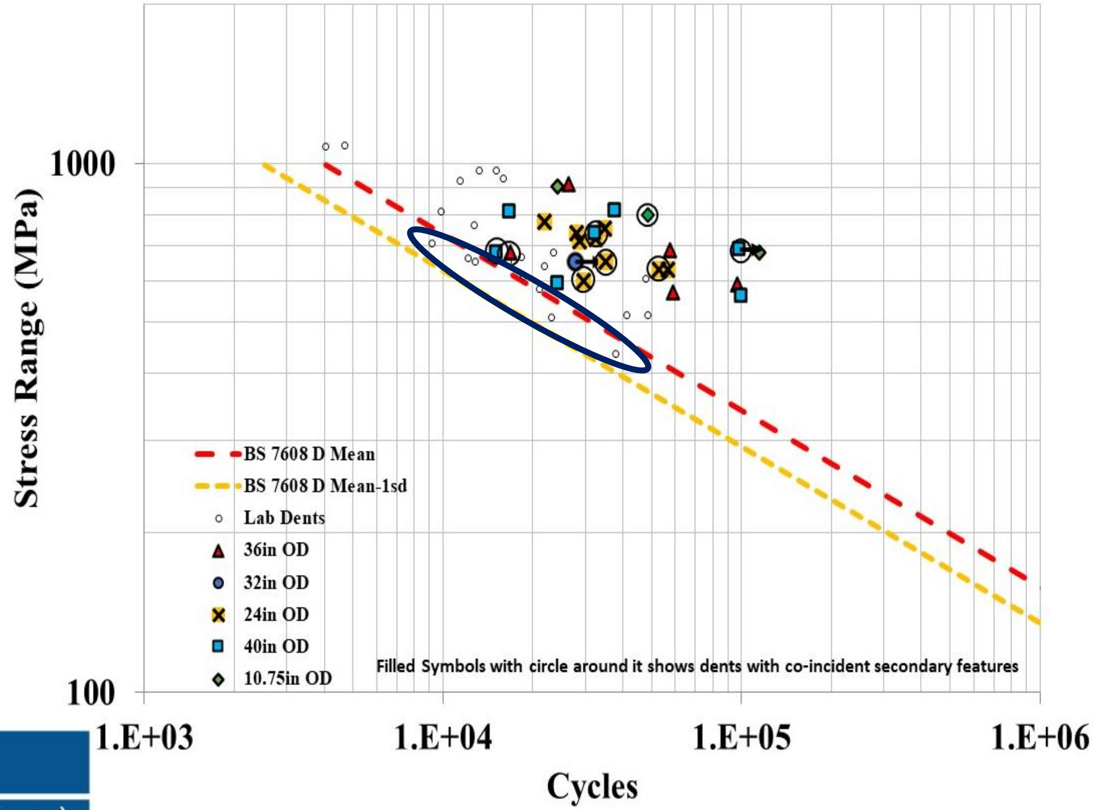
Fatigue Life Prediction of Field Dents

- Comparison of test data vs modeled life
  - Field dent fatigue life test data – Solid symbols
  - Test lab developed dents - Small hollow symbols
  - All field dents tested in the current project are above the SN curves – conservative life predictions
  - Slightly higher variability in field dents
    - Lab dents on pipe OD (18”-24”) created under controlled test conditions
    - Field dents on pipe OD (10”- 40”) – real world samples formed under different conditions collected from different operators



Fatigue Life Prediction of Field Dents

- Level 2 fatigue life as per API RP 1183
  - Level 2 predictions ~ 4.5X lower (conservative) for tested field dent fatigue life estimate
  - BS7608 Class D mean-1sd curve selected in MD-4-9 to provided lower bound for all tests.
    - 5 lab test results that lie below Class D mean curve
  - With additional 25 tests an argument can be made to use less conservative Class D mean SN curve ⇨~ 1.65X estimated fatigue life increase



Feature	Level 3 Based on SN Curve		Level 2
	Fatigue Life (Average) Actual /Prediction	Fatigue Life (Average) Actual / Prediction	Fatigue Life (Average) Actual / Prediction
	Class D Mean SN Curve	Class D Mean-1sd SN Curve	Class D Mean-1sd SN Curve
Plain Dents	4.2	6.7	4.5

Fatigue Life Prediction of Field Dents

- Field dent testing used to consider API RP 1183 Level 2 fatigue assessment
  - Metal loss interaction ~ 4.6X for dent metal loss interaction
  - Girth weld interaction ~ 15.9X for dent girth weld interaction
  - Long seam interaction ~ 31X for dent long seam interaction
    - Dent weld interaction includes 10X reduction factor
    - It may be appropriate to reduce 10X factor for long seams if there is no previous history of defects/issues

Feature	Level 3 Based on SN Curve		Level 2
	Fatigue Life (Average) Actual /Prediction	Fatigue Life (Average) Actual / Prediction	Fatigue Life (Average) Actual / Prediction
	Class D Mean SN Curve	Class D Mean-1sd SN Curve	Class D Mean-1sd SN Curve
Dents Interacting with Metal Loss	3.7	5.9	4.6
Dents Interacting with Long Seam Welds	15.6	25.3	31.1
Dents Interacting with Girth Weld	13.1	21.3	15.9

Concluding Remarks

- Work from PRCI / PHMSA sponsored research (MD-5-2)
  - Provides means of improving indentation strain estimation
    - Considers strain components, pressure and restraint condition
  - Indicates that ILI dent shape measurement variability from ILI trials produce
    - Fatigue life variation approx. 15% restrained dents and 35% for unrestrained dents
    - Indentation strain variation approx. 60% for restrained dents
      - Unknown for unrestrained dents
  - Safety factors and associated confidence levels defined for API RP 1183 fatigue life assessment approaches
    - Screening and assessment approaches (Level 0, Level 0.5 and Level 2)
    - for plain dents and dents interacting with secondary features (weld and corrosion)
- Work from PRCI sponsored research (MD-4-15)
  - Demonstrated that API RP 1183 techniques work well for field dents
  - Illustrate conservatism of the analysis approaches that may be considered

Thank you for your attention.

This work was funded in part, under the Department of Transportation, Pipeline and Hazardous Materials Safety Administration. The views and conclusions contained in this document should not be interpreted as representing the official policies, either expressed or implied, of the Pipeline and Hazardous Materials Safety Administration, the Department of Transportation, or the U.S. Government.