Project De-Brief Presentation

Improve Dent/Cracking Assessment Methods

DOT-PHMSA Contract 693JK31910011POTA

PRCI Contract PR214-203806

Supported by:

- US Department of Transportation
  Pipeline and Hazardous Materials Safety Administration
- Pipeline Research Council International

LEADING PIPELINE RESEARCH

Disclaimer

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- **Execution of the project was completed by BMT**
- **Project Management by PRCI**
- **BMT Team**
  - Sanjay Tiku, Arnav Rana, Aaron Dinovitzer
- **Technology Advisory Panel (MD SRP)**
  - Mark Piazza — API (Previously Colonial Pipeline Company)
  - Timothy H.Burns — Shell Midstream
  - Marcus LeRoy — Marathon Petroleum
  - Jing Ma — ExxonMobil Pipeline Company
  - Rick Wang — TC Energy

Presentation Outline

- **Agenda**
  - Project Overview
  - Scope
  - Results
    - *Improvement of Indentation Crack Formation Strains*
    - *Impact of ILI Dent and Interacting Feature Sizing Variation*
    - *Dent Fatigue Life Assessment Safety Factor Quantification*
  - Concluding Remarks/Summary

Project Overview

- **Objective – Enhancement of previously developed tools being adopted in an industry recommended practice (API RP 1183) for pipeline MD integrity assessment and management considering:**
  - Enhancement of indentation crack formation strain estimation,
  - Understanding the role of ILI measurement accuracy on dent integrity assessment, and
  - Quantification of assessment method conservatism to support safety factor definition.
- **Supports knowledge transfer and development of standards**

Scope

- **Major tasks**
  - **Task 2**: Improvement of Indentation Crack Formation Strains
    - *Evaluation of ASME B31.8 Dent geometric strain*
    - *Comparison with FE models*
    - *Restrained dents vs unrestrained dents*
    - *Dent strain “cracking” criteria*
  - **Task 3**: Impact of ILI Dent and Interacting Feature Sizing Variation
    - *Impact of the variation of ILI measured dent size/shape on dent strain and fatigue life estimate*
  - **Task 4**: Dent Fatigue Life Assessment Safety Quantification
    - *Define conservatism inherent in the fatigue life assessment tools incorporated in API RP1183*
  - **Task 5:** Sample Calculations
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Scope

- PHMSA Project Funding: $353,084.00
- Project Duration – 10 quarters (after time extension)

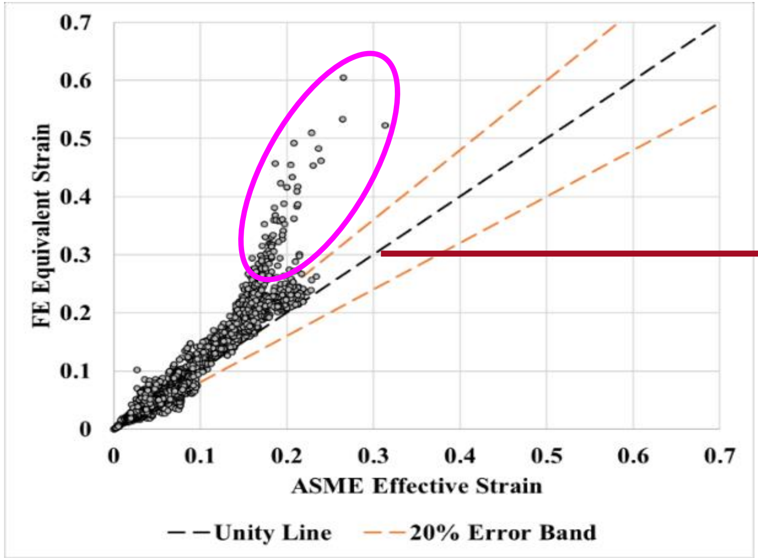
Results - Improvement of Indentation Crack Formation Strains

- **Compared ASME B31.8 dent geometry strain with FE models**
  - *Data source*
    - Hypothetical dents FE dataset
    - Field dents ILI data/ FE data
    - Full-scale dents FE data
  - **Data range**
    - *4.5” - 42”OD*
    - *0.5% - 10% depth*
    - *Restrained & Un-restrained dents*
    - *Varying mean pressure & max pressure*

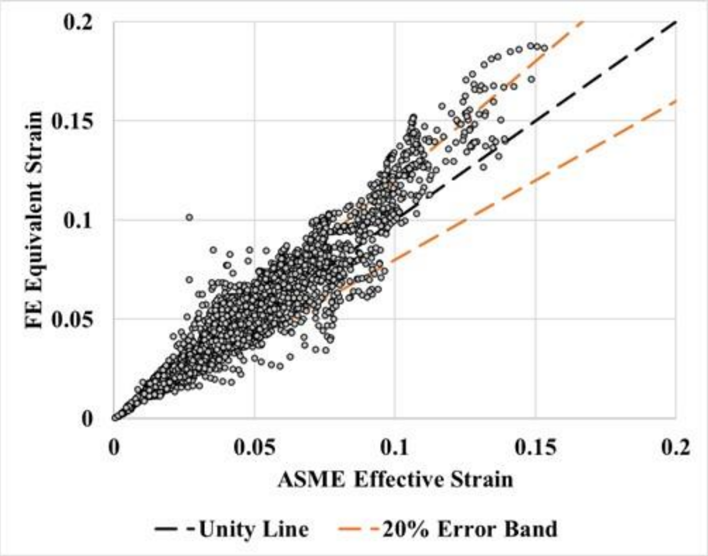
Results - Dent Indentation Strain - Restrained Dents

- ASME B31.8 dent indentation strain estimation diverges for deep dents (>6% depth) with radius of curvature (0-200 mm/8inch)

ASME Strain (All dents)



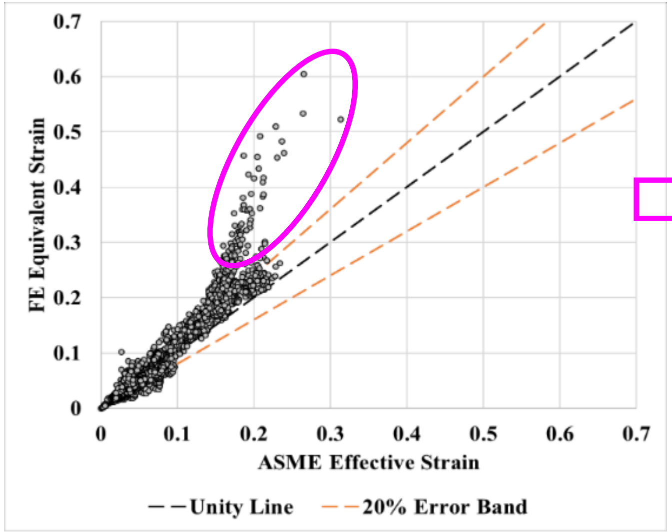
ASME Strain (w/o deep & sharp dents)



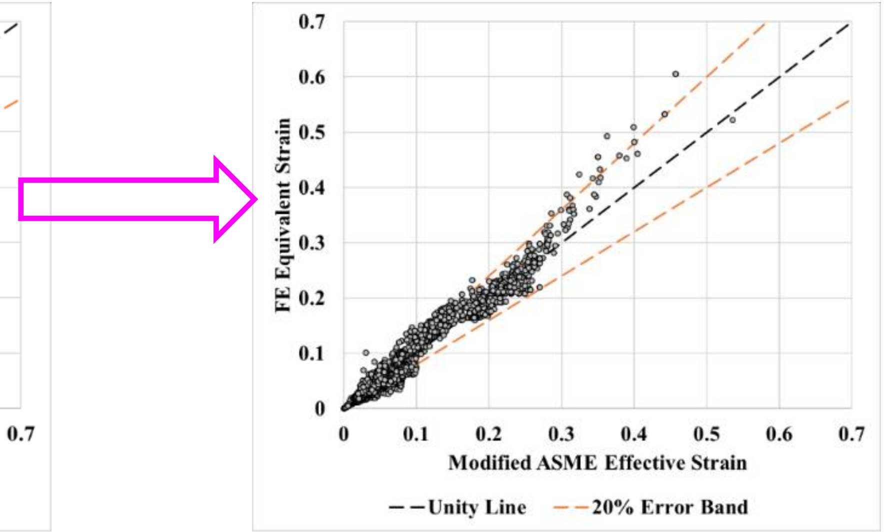
Results - Dent Indentation Strain - Restrained Dents

- BMT modification (defining axial & transverse lengths closer to dent peak; incorporation of axial & circumferential membrane strains)
- Able to predict indentation strains for deeper/sharper dents

ASME Strain

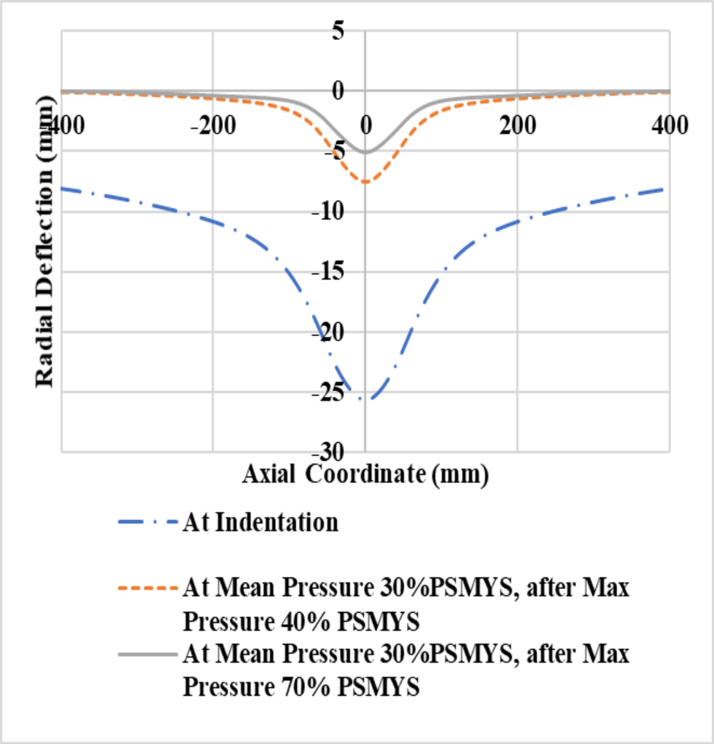


Modified ASME Strain



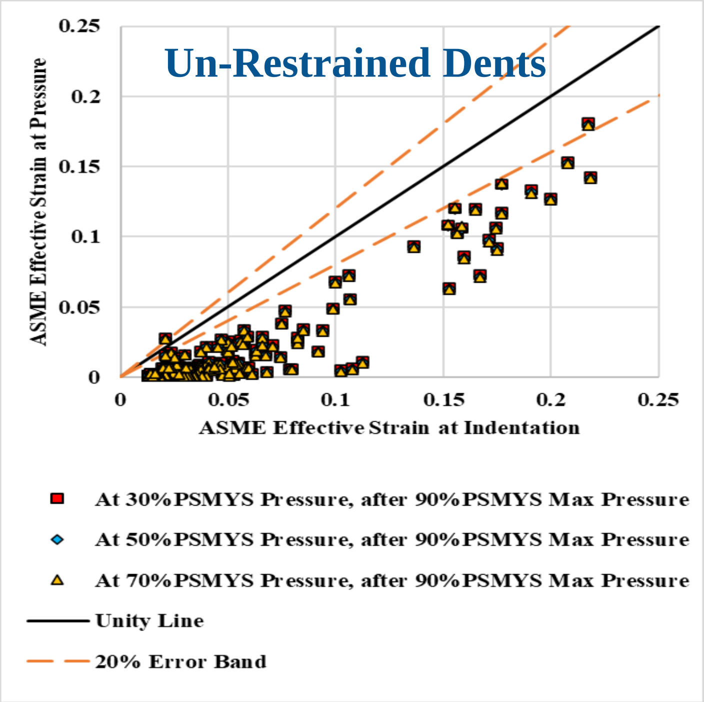
Results - Dent Indentation Strain – Unrestrained Dents

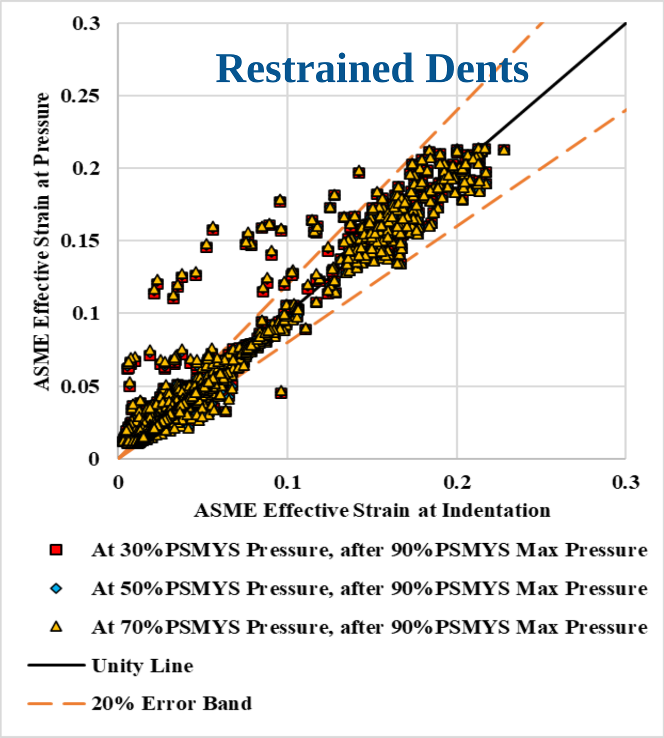
- For restrained dents the geometry remains same (Indenter in contact with the pipe)
- For unrestrained dents the geometry is very different from that at indentation as indenter is not in place
- Dent ILI data is extracted under pressure, and the dent might have seen a variety of pressure loads after indentation. Therefore, the geometry of the dents might differ from that at indentation
- ASME strains calculated from ILI geometry data for unrestrained dents will not reflect the indentation condition



Results - Dent Indentation Strain – Unrestrained Dents

- ASME strains calculated from ILI geometry data for unrestrained dents do not reflect the indentation condition

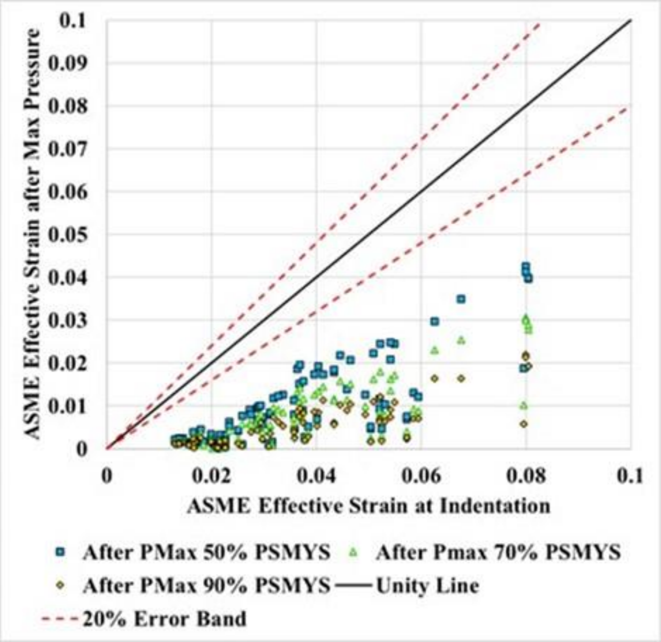




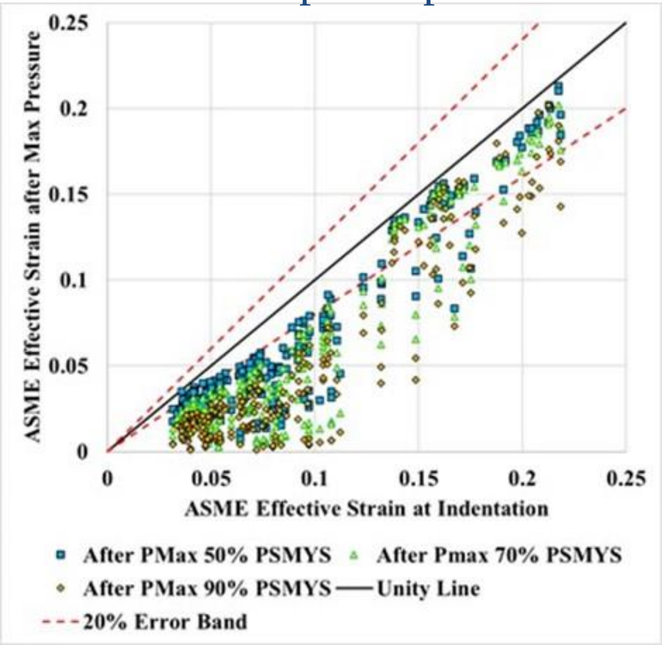
Results - Dent Strain – Unrestrained Dents

- **Dent strain measurement for unrestrained dents get affected by maximum pressure seen by the dent**

Shallow Smooth Dents



Deep Sharp Dents

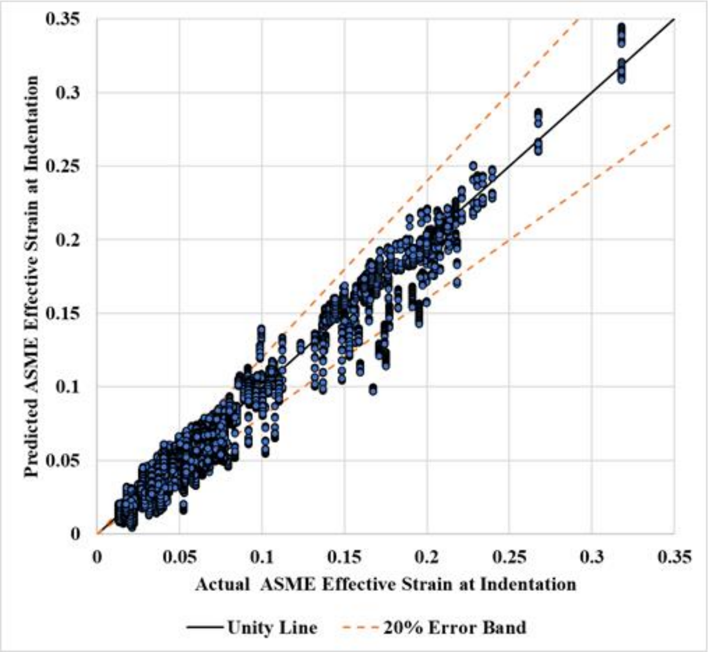


Results - Indentation Strain - Unrestrained Dents

- Regression equations developed correlating ASME indentation strain and ASME strains @ various pressures

- Proposed a methodology to measure indentation strain for un-restrained dents based on the dent shape (@ pressure) during ILI run & maximum pressure seen by the dent

Un-restrained Dents Indentation Strain Prediction



Results - Dent Strain Criteria

- **ASME B31.8 Appendix R strain and DFDI methodology compared against full-scale tests**
- ASME B31.8 Appendix R
  - 6% strain for plain dents

- *Ductile Failure Damage Indicator (DFDI)*

$$DFDI_{Upper\ Bound} = \frac{1.65\varepsilon_{eq}}{\varepsilon_0}$$

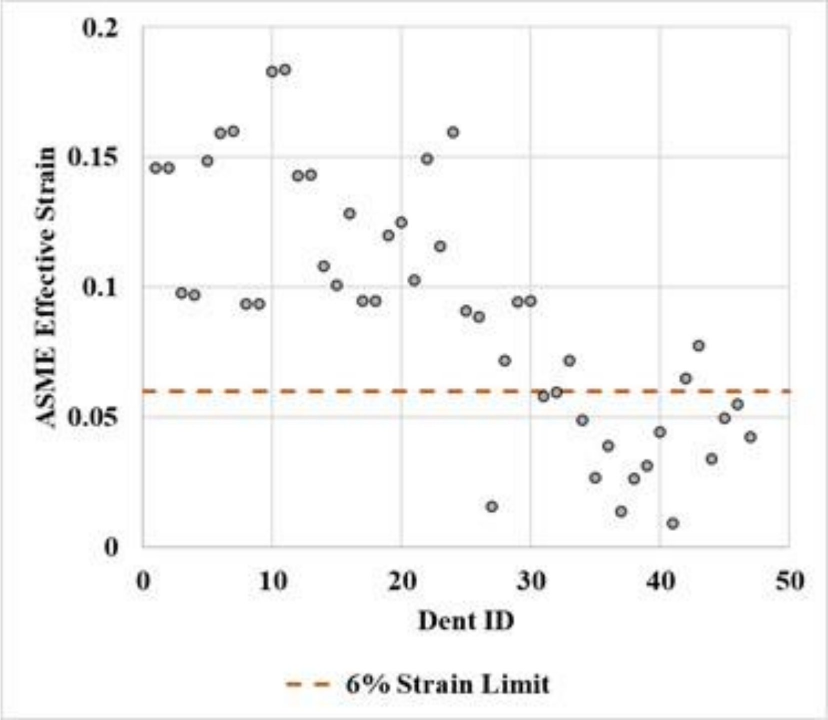
ε_{eq} is equivalent strain

ε_0 is critical strain (recommended values between 0.3-0.5)

- *DFDI = 1 (damaged state); 0.6 suggested as conservative option*

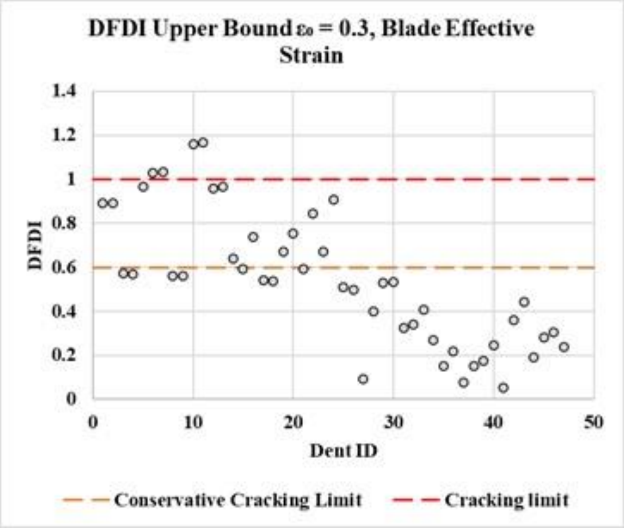
Results - Dent Strain Criteria – ASME B31.8 Appendix R

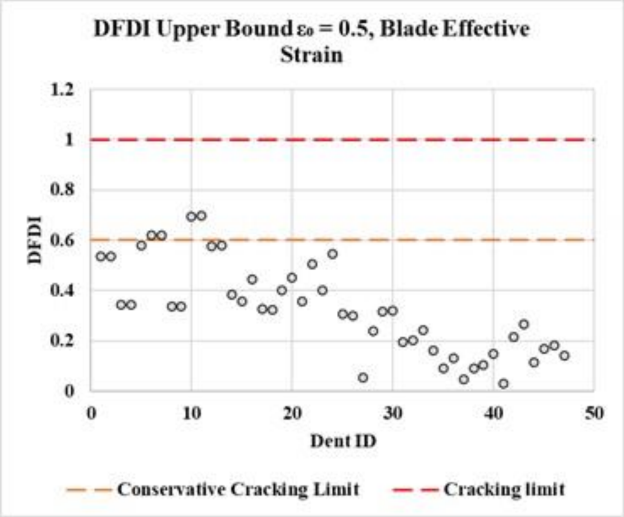
- **47 full-scale test on plain dents**
  - No cracks were observed during indentation
  - 32 out of 47> 6% strain



Results - Dent Strain Criteria - DFDI

- **47 full-scale test on plain dents**
  - No cracks were observed during indentation
- *For **0.3** critical strain value - 4 dents>DFDI =**1**; 16 dents>**0.6***
- *For **0.5** critical strain value - 0 dents>DFDI =**1**; 4 dents>**0.6***



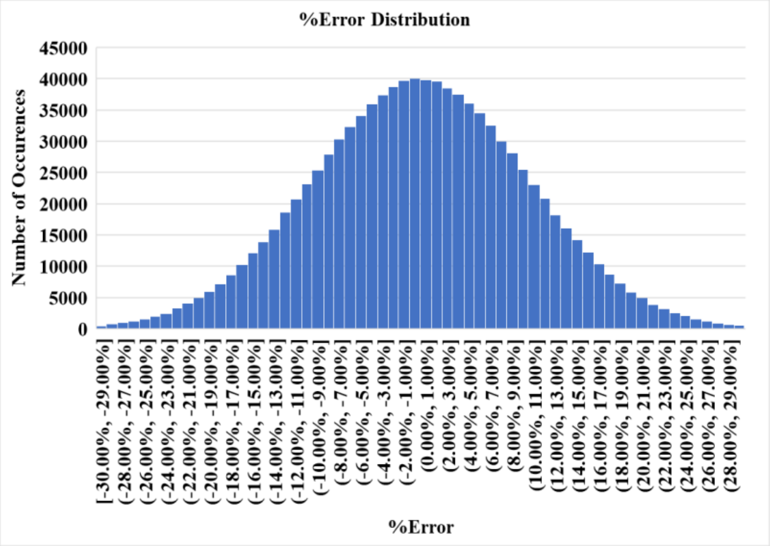


Results - Impact of ILI Dent Feature Sizing on Fatigue Life

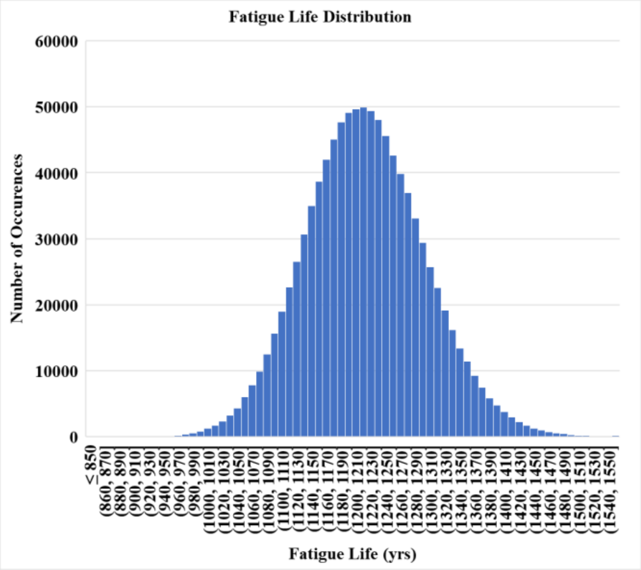
- **Monte Carlo simulations used where error distributions of the dent dimensions were applied to dent profiles and corresponding fatigue life estimated**
  - *ILI in-service dent data used for ~ 900 dents, 6 pipe OD (10.75”- 42” OD), dent depth range (0.25%-11%)*
  - *Six different variation schemes involving depth, length and width individually and coupled variation of these.*
  - *Three different standard deviation values were considered (10%, 15% & 20%)*
  - *For each distribution 1 million simulations (total 6 million/dent)*
- **Measurements from multiple ILI vendors measuring same dent set from ILI trials (NDE-4-18, PRCI only)**
  - *53 dents, duplicate pulls @ five different speeds, multiple ILI vendors*
  - *ILI results compared with reference laser scan data for these 53 dents*

Results - Impact of ILI Dent Feature Sizing on Fatigue Life

Input - Sample % error distribution

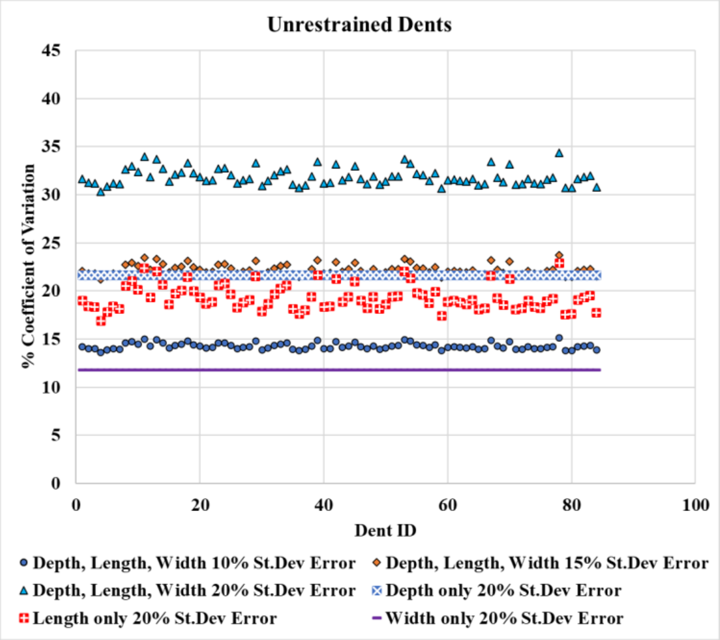


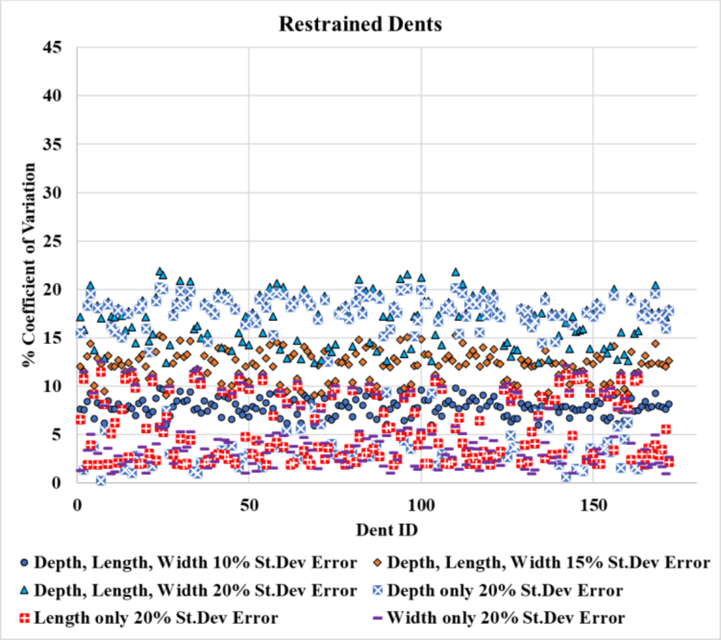
Output - Sample fatigue life distribution



Results - Impact of ILI Dent Feature Sizing on Fatigue Life

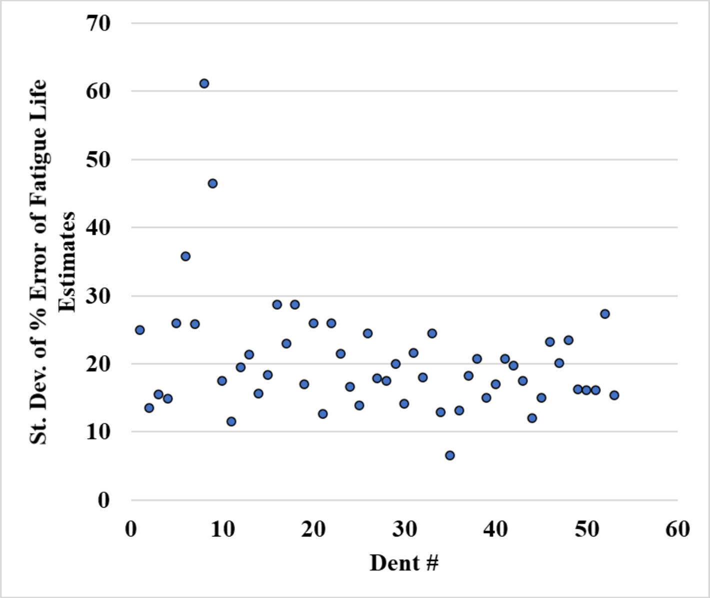
- **Average co-efficient of variation of fatigue life estimates varied between**
  ~ 12% - 35% for un-restrained dents & ~ 2% - 20% for restrained dents

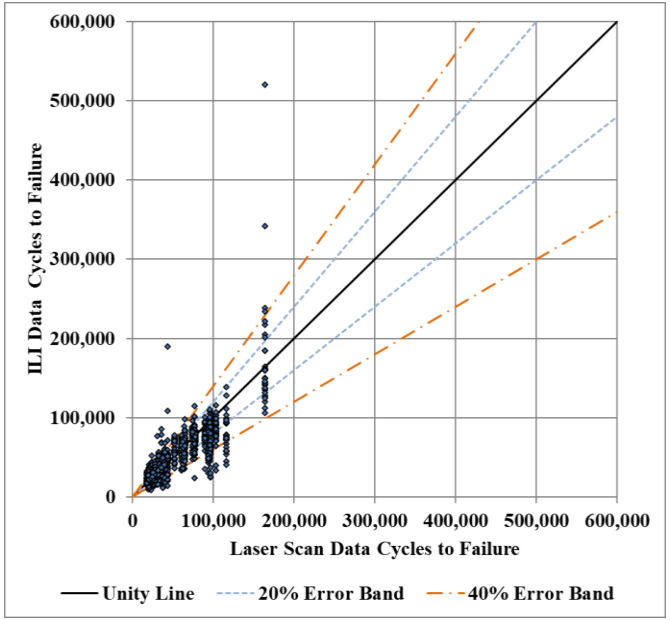




Results - Impact of ILI Dent Feature Sizing on Fatigue Life

- **Fatigue Life estimates for dents in the ILI trial data**
  - Fatigue life estimates are within 40% std dev. for majority of the dents.
  - Results comparable to Monte Carlo simulation results.

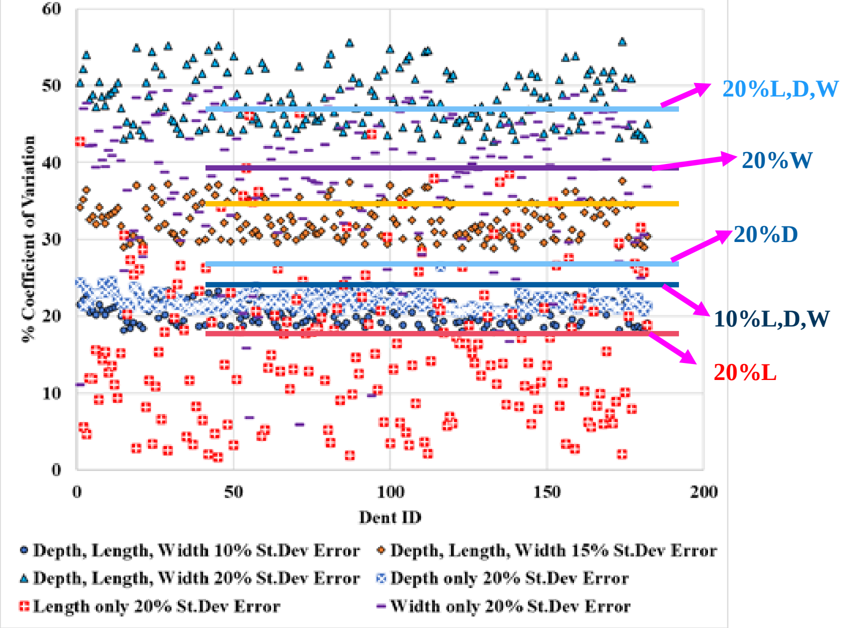




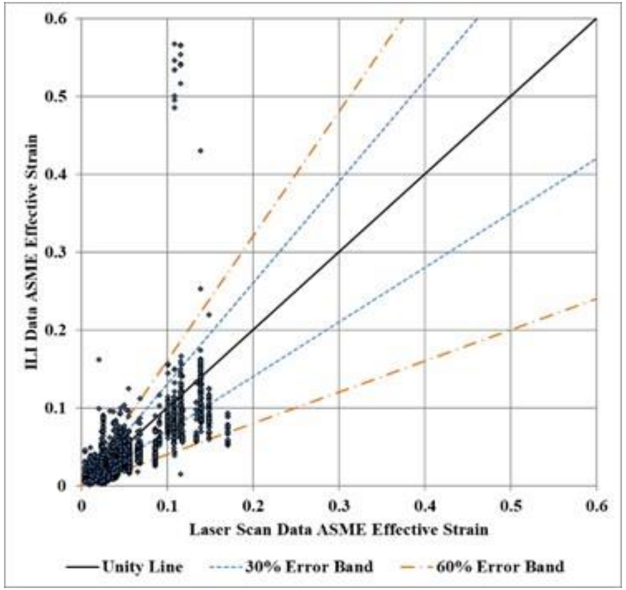
Results - Impact of ILI Dent Feature Sizing on Dent Strain

- **Same data set was used for ASME dent effective strain evaluation**
  - *Similar results for other dent strain definitions*

Field Dents ILI



Dent ILI Trials



Results - Dent Fatigue Life Assessment Safety Factor Quantification

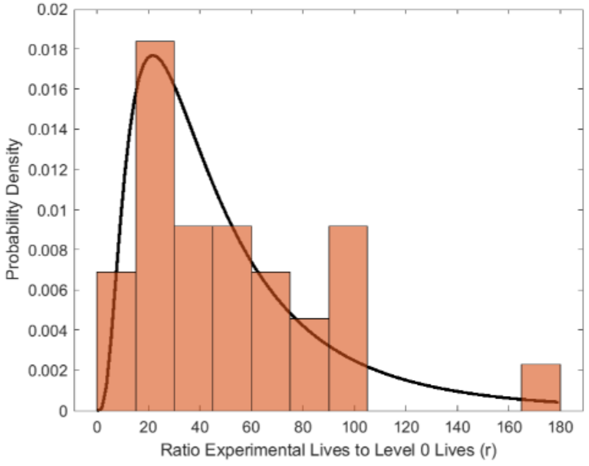
- Objective - Define the conservatism incorporated in the dent fatigue assessment tools, define appropriate safety factors
- Approach - Full Scale dent fatigue test experimental fatigue lives were compared with fatigue life predictions based on
  - CEPA Level 0 and Level 0.5 dent screening approaches and
  - PRCI Level 2 fatigue life assessment
- The above two approaches are incorporated in API 1183
- Experimental Data Available
  - Plain Dents
  - Dents Interacting with weld and metal loss
  - Field dents

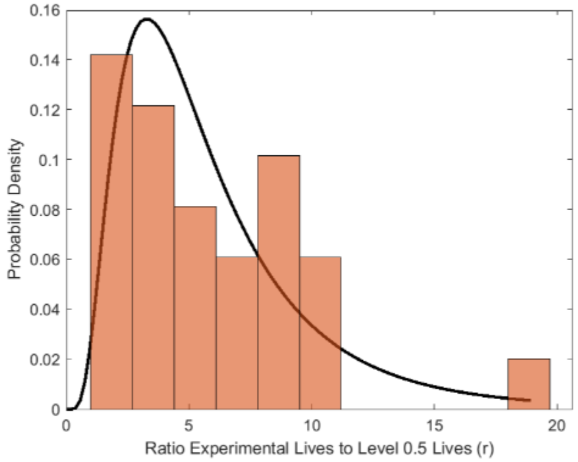
Results - Dent Fatigue Life Assessment Safety Factor Quantification

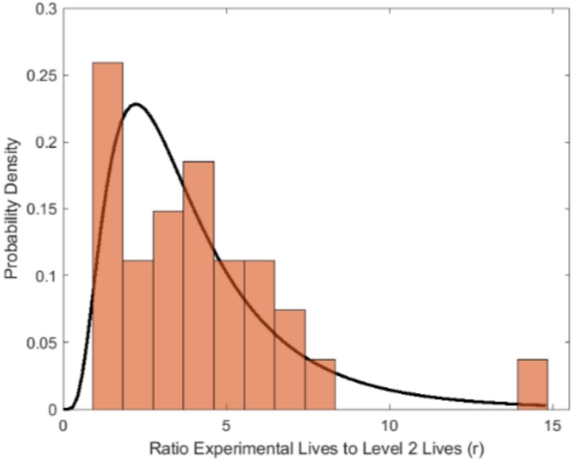
- **Safety factors established for different fatigue life assessment approaches for plain dents and dents interacting with secondary features (corrosion and weld)**
  - *Histograms of ratios of experimental to predicted fatigue lives (safety factor) were developed and probability distribution functions were fitted onto these*
  - *Defined scale factors (s) that can be applied to the calculated fatigue lives to return life estimates that have minimum factors of safety (R) with a specified certainty (α)*
  - *Scale factors were evaluated from the comparison of full-scale dent fatigue life data with the estimates from fatigue life assessment methodology (API RP 1183)*
  - *These fitted probability density functions were scaled so that a minimum factor of safety, with a specified certainty, could be achieved and the factor by which these functions were scaled are the scaling factors*

Results - Dent Fatigue Life Assessment Safety Factor Quantification

- **Distribution of full-scale fatigue life to predicted fatigue life based on different assessment approaches incorporated in API RP 1183**
  - Levels 0, 0.5 and 2







Results - Safety Factors – Plain Dents

- **Safety factors inherent/ to be used for target confidence level in different fatigue assessment approaches**
  - Level 0: @ 80% confidence SF>10
  - Level 0.5: @ 80% confidence predicted life needs to be divided by 1.3 to get a safety factor of 2
  - Level 2: @ 80% confidence predicted life needs to be divided by 1.4 to get a safety factor of 2

Level 0, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
SafetyFactor (Target Ratio R)	10	1	1

Level 0.5, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
SafetyFactor (Target Ratio R)	1	1	1
	2	1.7	1.3

Level 2, Mean - 1sd			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
SafetyFactor (Target Ratio R)	1	N/A	1
	2	1.9	1.4

Results - Safety Factors – Dents Interacting with Metal Loss (Corrosion)

- Level 0: @ 80% confidence SF>15
- Level 0.5: @ 80% confidence SF=3
- Level 2: @ 80% confidence SF=2

Level 0, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	15	1	1
Level 0.5, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	2	1	1
	3	1.4	1.0
Level 2, Mean-1sd			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	2	1.4	1.0

Results - Safety Factors – Dents Interacting with Weld

With Fatigue Life Reduction Factor of 10X as per API RP 1183

Level 0, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	25	1	1
Level 0.5, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	9	1.0676	1
Level 2, Mean-1sd			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	6	1.1026	1

With Fatigue Life Reduction Factor of 5X

Level 0, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	25	1	1
Level 0.5, Mean			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	5	1.1862	1
Level 2, Mean-1sd			
Scaling Factor Matrix		Probability of Exceedance of Target Ratio α	
		0.9	0.8
Safety Factor (Target Ratio R)	4	1.1026	1

Concluding Remarks

- **Dent Strain**
- ASME B31.8 dent strain compares well with FE dent strain for smooth shallow restrained dents
- ASME dent strain diverges for deep/sharp restrained dents for dents greater than 6% deep with radius of curvature less than 200 mm (8 inch)
- ASME dent strain is not indicative of indentation strain for unrestrained dents
- Modified ASME strain model developed in this project works well across all restrained dents including deep &sharper dents
- Prediction model developed to predict indentation strain for unrestrained dents
- Strain limit criterion of 6% in ASME B31.8 Appendix R is very conservative. Full scale indentation strain data was compared against ASME B31.8 Appendix R strain limit criterion and predicted 32 out of 47 tests exceeded the 6% strain limit

Concluding Remarks

- **ILI Dent Shape Variation**
- Impact of dent shape variations (due to ILI measurement variability) were assessed on dent fatigue life assessment approaches incorporated in API RP 1183
  - *Fatigue life estimates varied between 15% - 35% for restrained and unrestrained dents respectively due to variability in ILI measurements considered in the current project*
  - *Dent strain measurements for majority of the dents were within 60% error band due to variability in ILI measurements considered in the project.*
- **Fatigue Life Safety Factors**
  - *Safety factors and associated confidence levels were evaluated for fatigue life assessment approaches (Level 0, Level 0.5 and Level 2) incorporated in API RP 1183 for plain dents and dents interacting with secondary features (weld and corrosion)*

Recommendation

- Further work is required to define the critical strain values for pipeline steels and address the conservatism in ASME B31.8 Appendix R 6% strain limit criteria.
- Improvement in Dent Weld Interaction Criteria - Fatigue life reduction factor of 10, as recommended in API RP 1183, in dent weld interaction leads to very conservative fatigue life estimates and further work is required to address the conservatism.
- Improvements in Safety factor calculations - In the current project were carried out for plain dents using combined experimental data for restrained dents and unrestrained dents. Further work is required to explore the differences between the two dent restraint conditions as experimental data suggests restrained dents have much longer fatigue lives as compared to unrestrained dents.

Technology Transfer

- **Presented the work in**
  - PRCI Research Exchange March 2022
  - EPRG-PRCI-APGA 23rd Joint Technical Meeting May 2022
- **Paper accepted for IPC 2022, " Enhancement of Mechanical Damage Crack Evaluation" IPC 2022-87345**
- **Incorporation of findings in API RP 1183**

More Information

- **Department of Transportation**
  - Pipeline and Hazardous Materials Safety Administration
  - Pipeline Safety Research Program
    - *Improve Dent/ Cracking Assessment Methods*
    - *Final report and this presentation available on the PHMSA project page :*

    https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=855

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