Advances with In-Line Inspection Technology For Evaluating Pipeline Damage Including Dents

Pipeliners Association of Houston

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Taking on your toughest technical challenges.

Agenda

- Dent Terminology
- Regulations
- ILI Tools
- SCFs and Remaining Life Assessments
- SCF Validation
- Assessing Dents with Interactions
- An Example Test Project

Dent Terms

- **Depth:** The difference between the minimum diameter and the nominal diameter of the pipe, typically expressed as a % (A 6% dent in a 24-inch pipe has a depth of 1.44-inches)
- **Shallow Dents**: Typically refers to a dent with a depth less than 2%
- **Interaction:** A threat that occurs simultaneously with a dent resulting in increased concern. Examples may include dents in gouges, cracks, or welds.
- **Plain Dents:** Dents that are free from interactions
- **Constrained Dent:** A dent that is not free to flex – typically located on the bottom side of the pipe.

Dent Considerations

- Dents primarily represent a fatigue concern to operators
  - In general, liquid lines are more susceptible to fatigue than gas lines
  - Some gas lines do exhibit significant cycles
- In the absence of any mitigating factors such as metal loss or dents that have creased the pipe, burst pressure is typically not a concern
- For sharper dents or bottom side dents, coating disbondment may be an issue

Regulations

- **CFR 192**: Federal Safety Standards for Transportation of Natural and Other Gas by Pipeline
- **CFR 195**: Federal Safety standards for Transportation of Hazardous Liquids or Carbon Dioxide
- **ASME B31.8**: Gas Transmission and Distribution Piping Systems
- **ASME B31.4**: Pipeline Transportation Systems for Liquids and Slurries
- Regulations generally use depth, location, and interactions for guidelines.
- The CFR and ASME codes both permit engineering analysis for certain dents.

Regulations Matrix

	Topside Dent			Bottom Side Dent Depth > 6%	Dents with Metal Loss, Cracking, or Stress Riser		Interacting with a weld and Depth > 2%	Depth >6% and Corrosion
	Depth > 6 % OD	Depth > 3 % OD	Depth > 2 % OD		Topside	Bottom Side		
CFR 192	1 Year (1)	N/A	N/A	Monitor	Immediate	Immediate	1 Year (2)	Immediate
ASME B31.8	Injurious (3)	N/A	N/A	Injurious (3)	Injurious for Cracks and MD (6)	Injurious for Cracks and MD (6)	Injurious (4)	Injurious (5)
CFR 195	Immediate	60 Day	180 Day	180 Day	Immediate	60 Day	180 Day	Immediate
ASME B31.4	Remove / Repair	N/A	N/A	Remove / Repair	Remove / Repair for Cracks and MD	Remove / Repair for Cracks and MD	Remove / Repair (7)	Rem / Rep if WL > 12.5%

(1) Engineering analysis will permit this to be a monitored condition if critical strain levels are not exceeded

(2) If engineering analysis demonstrates critical strain levels are not exceeded, this can be a monitored condition. The analysis must consider weld properties.

(3) Unless strain levels do not exceed 6%

(4) May be shown to be safe by engineering analysis if the strains do not exceed 4%. Dents of any depth are not permitted in brittle welds.

(5) These dents are injurious if the corrosion exceeds what is permitted by ASME B31G

(6) In ASME B31.8, the statement only governs cracks. Mechanical damage is considered injurious. Metal loss is not included.

(7) No depth limit is specified in B31.4 for interaction with seam or girth welds

How do we Identify Dents?

- Bore measurement looks for changes in the pipe cross section due to any of the following (dents, buckles, ovality, bulges, etc.)
- Bore measurement tools come in different complexities (in order of increasing complexity)
  - Gage plate →These tools are not suitable for advanced assessments.
  - Clock Caliper → Analysis is possible, but with greater uncertainty
  - High Resolution Tools → These tools provide the best information for advanced assessments as they capture the full circumference of the pipe in the area adjacent to a dent.
  - *“High Resolution”* typically has a spacing of approximately 1-inch or less between sensors.
- ILI Resolution has progressed significantly in the last 5-10 years

High Resolution Geometry

- Usually have multiple circumferential rings with a tight circumferential spacing (1-inch)
- May have stand-off sensors to account for lift-off

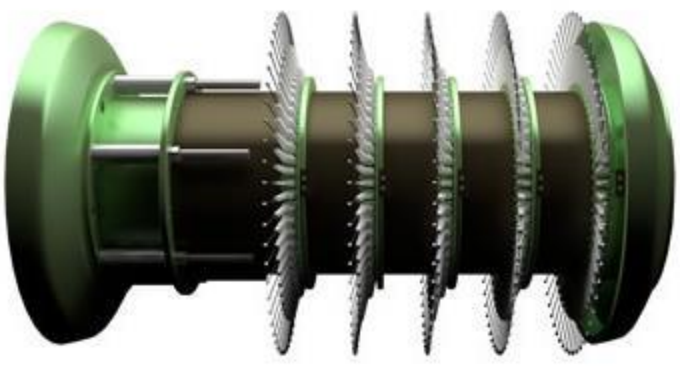


Image From Pipeway International

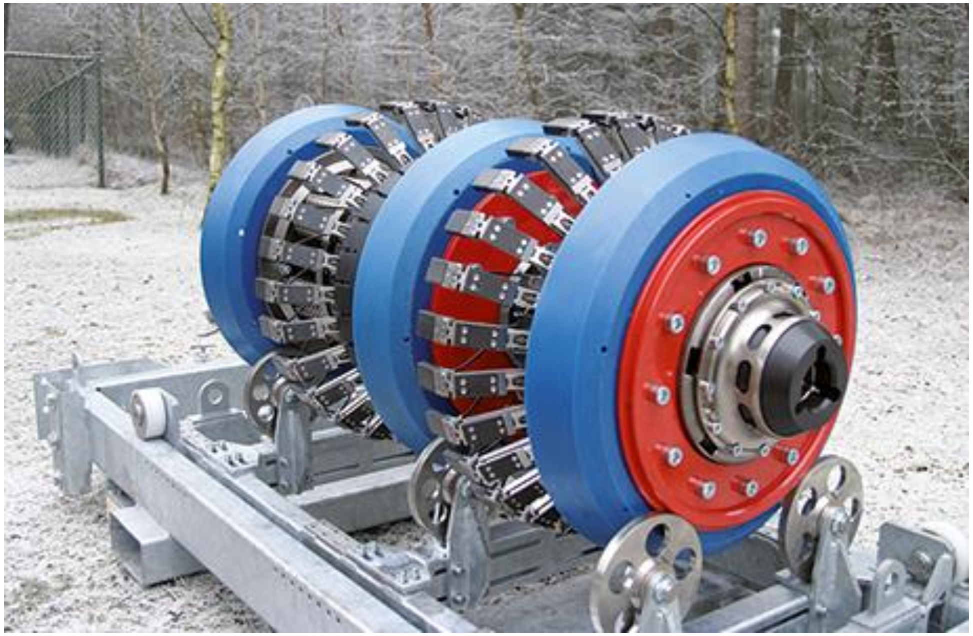
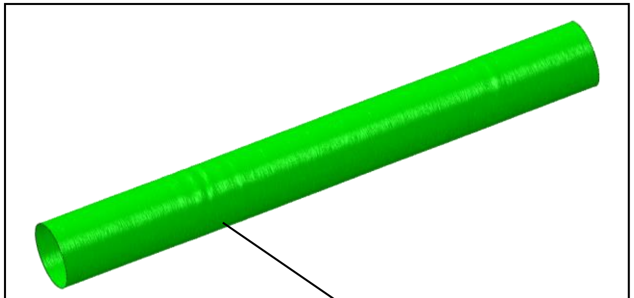


Image From ROSEN

Remaining Life Assessments

- A remaining life analysis address the fatigue performance of a dent by calculating its stress concentration factor (SCF)
- Remaining life analyses are useful for understanding how a dent behaves with respect to the actual operating conditions of the pipeline
- The SCF is useful for the operator to understand the ongoing threat and can be used for prioritization purposes
- There is some correlation between depth and SCF
- Remaining life assessments can also address constraint and interaction, depending on what is known about the pipeline materials and welding quality
- SCFs don't depend on a "classification"

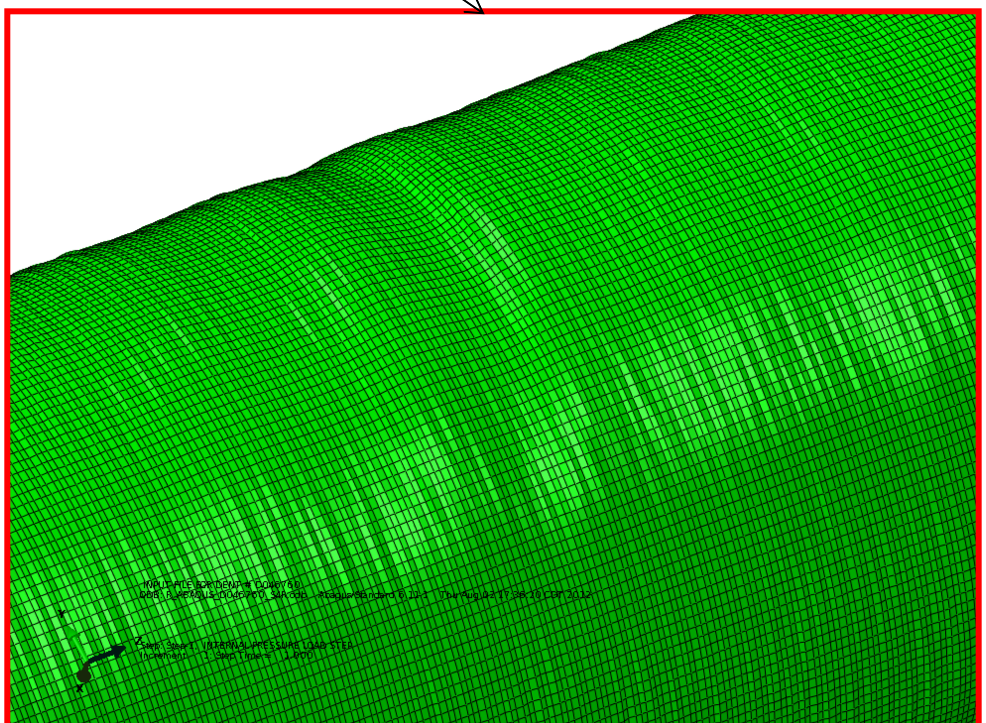
Advantages to RLA

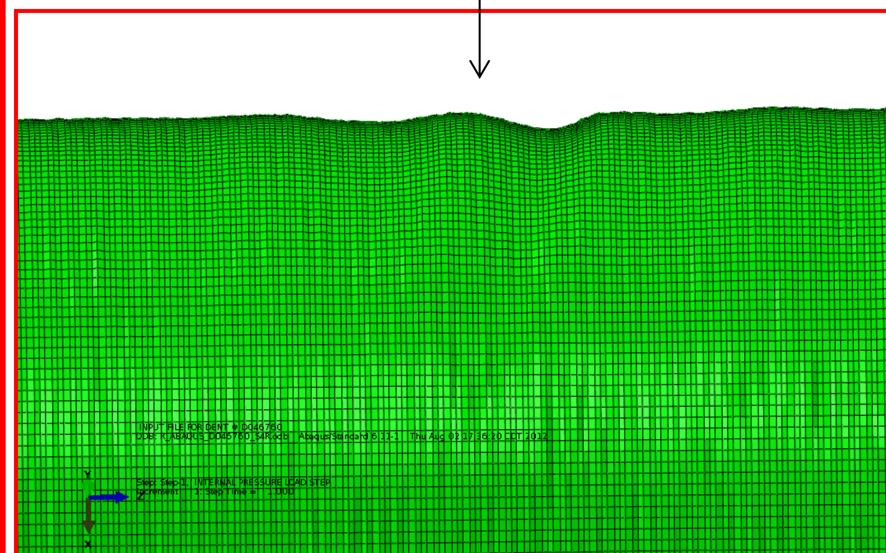


The Wrinkle-Dent

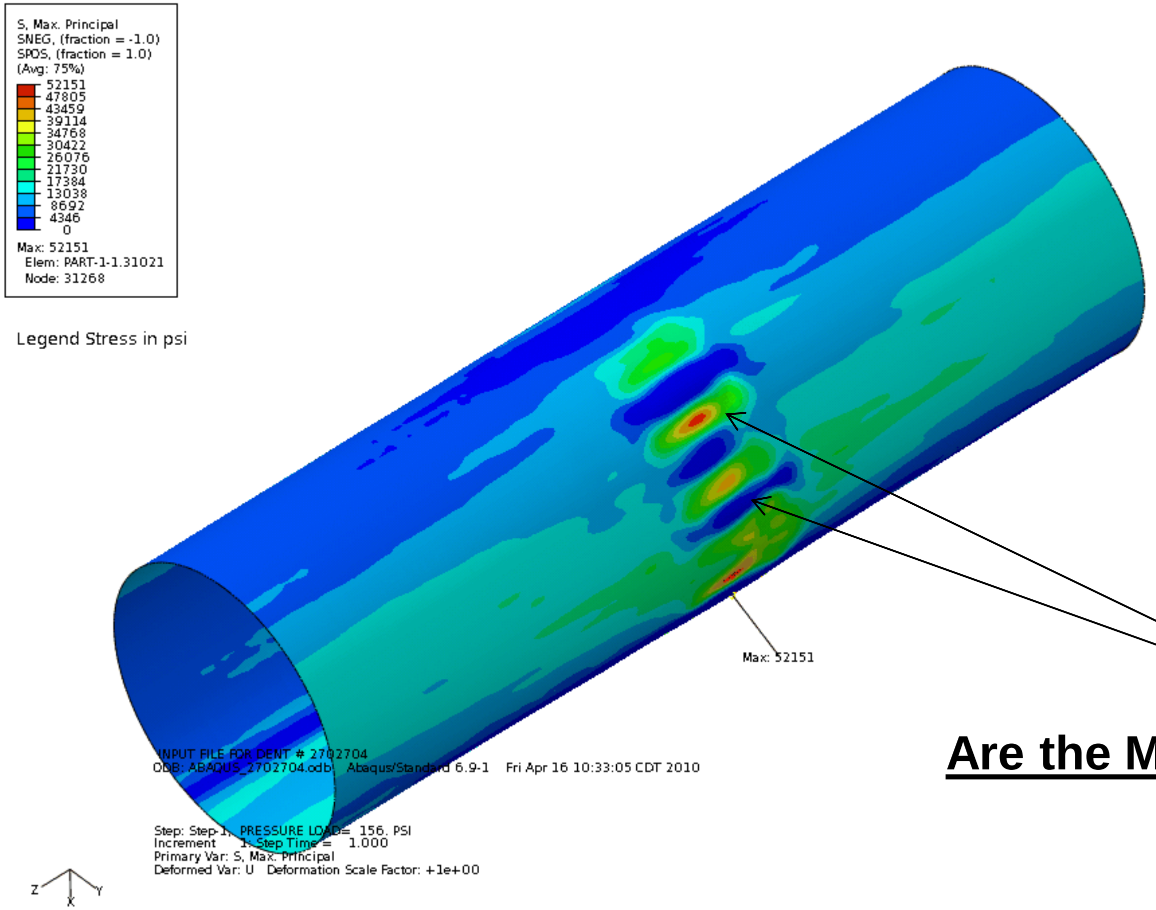
Treat it as a Wrinkle?

Treat it as a Dent?





Advantages to RLA



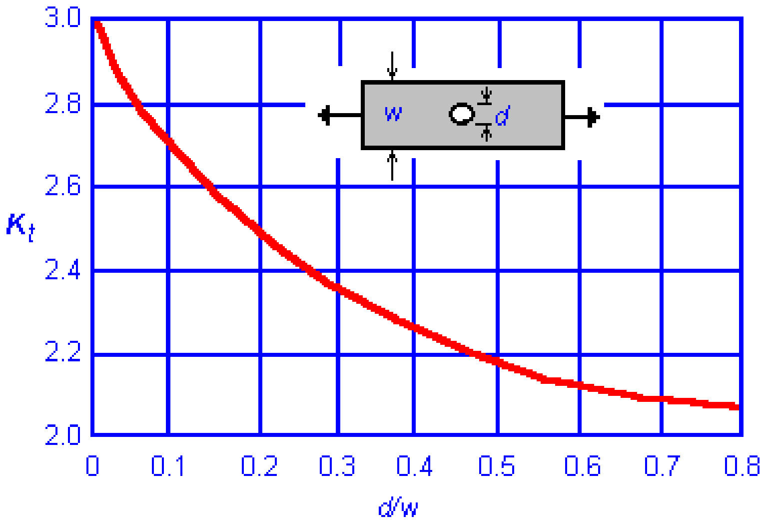
<u>Are the Multiple Dents Interacting?</u>

SCFs and Remaining Life Analysis

- Stress Concentration Factors (SCFs) are a widely recognized means for characterizing the severity of discontinuities
- By definition, an SCF represents the ratio of the peak stress in a body to the calculated nominal stress

$$SCF = \frac{\sigma_{peak}}{\sigma_{nom}}$$

SCFs and Remaining Life Analysis



- Analytical SCFs are available for simple shapes, and are typically shown in graphical form
- The SCF is useful because it permits the peak stress to be calculated and conveys the severity of a particular discontinuity

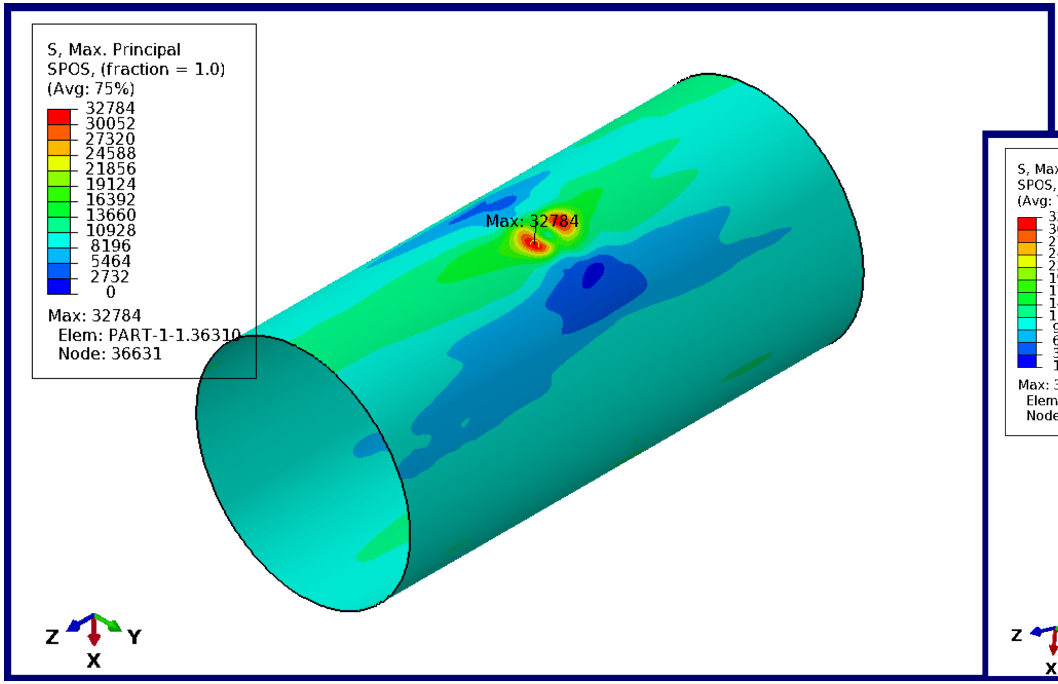
Remaining Life Analysis Procedure

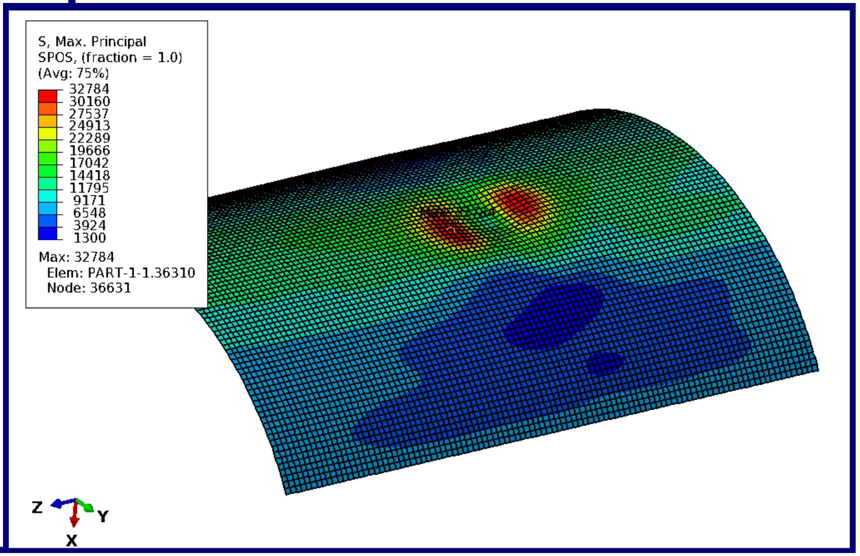
- It is straightforward to expand the methodology to dents
- First, a finite element model of the dent is constructed based on the ILI data
- Second, an internal pressure is applied to the model
- The magnitude of the maximum principal stresses from the analysis will depend on the dent shape, pipe diameter, and wall thickness
- Third, the nominal stress for the applied internal pressure is calculated according to Barlow's equation (i.e., $\sigma = P*D / 2*t$)

SCFs and Remaining Life Analysis

- After the analysis is complete the SCF can be computed as the ratio of the maximum principal stress to the nominal stress
- Next, a rainflow count is performed on a representative sample of the pressure history to determine the number of cycles for a given pressure range
- The SCF is then used to calculate the peak stress range for each set of cycles
- The damage from each peak range is calculated per a published fatigue curve and summed to get the damage per year and ultimately calculate the fatigue life.

Example SCF Analysis





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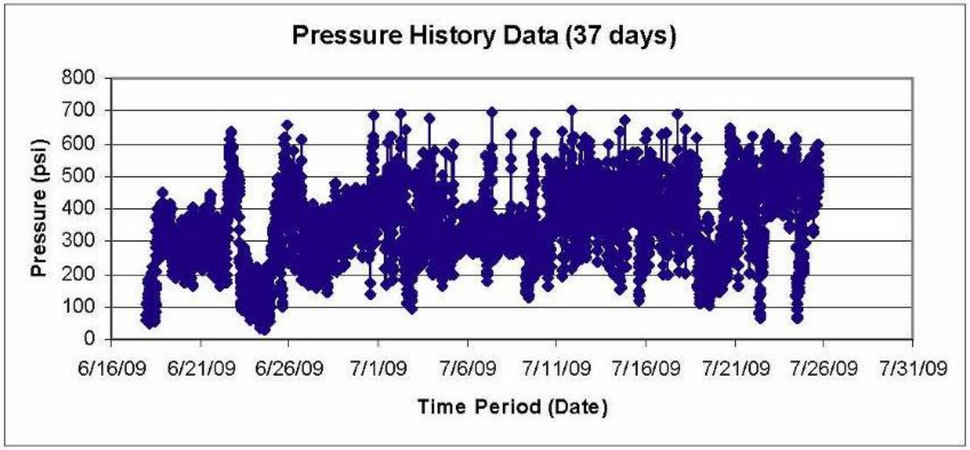
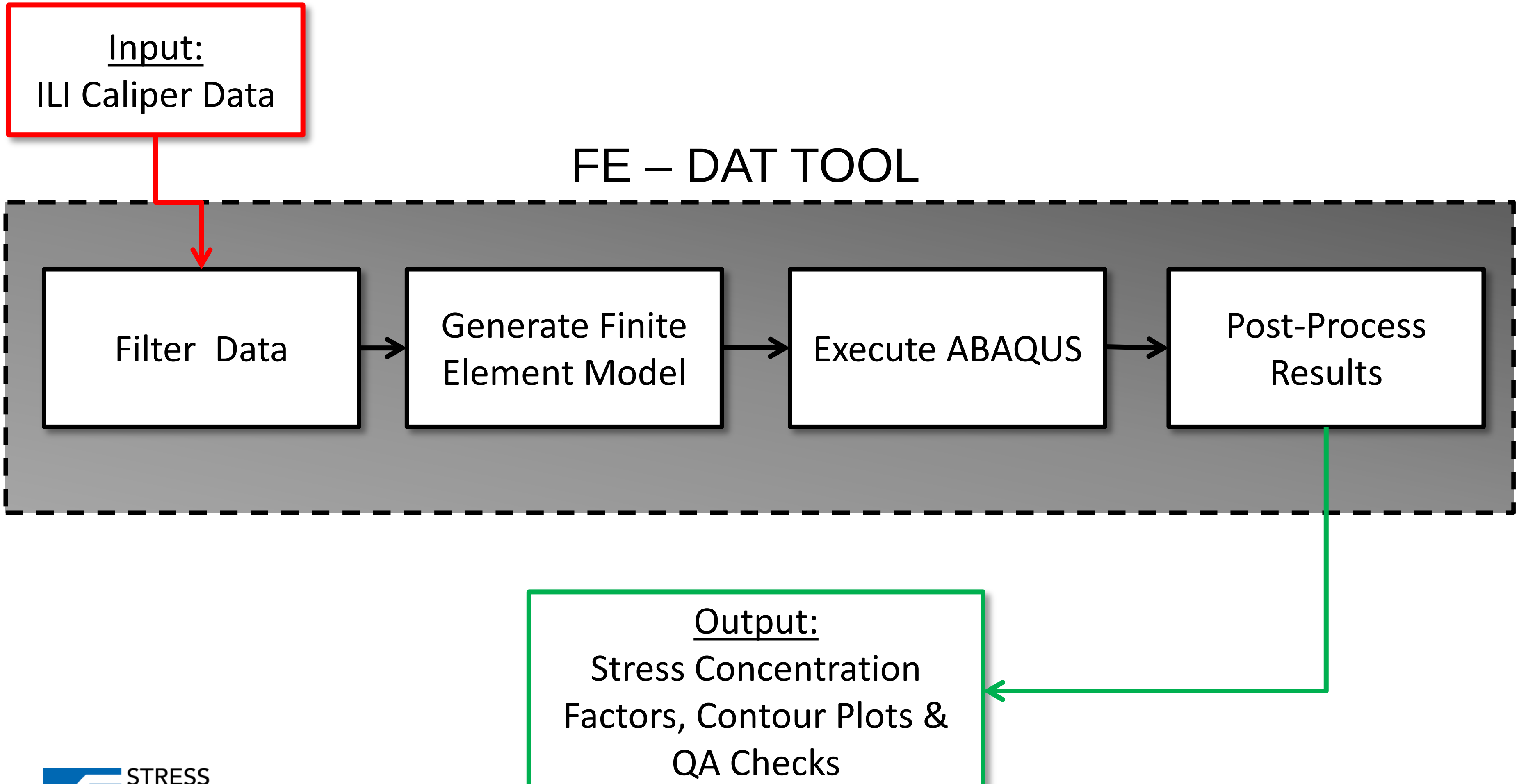
Example Remaining Life Analysis

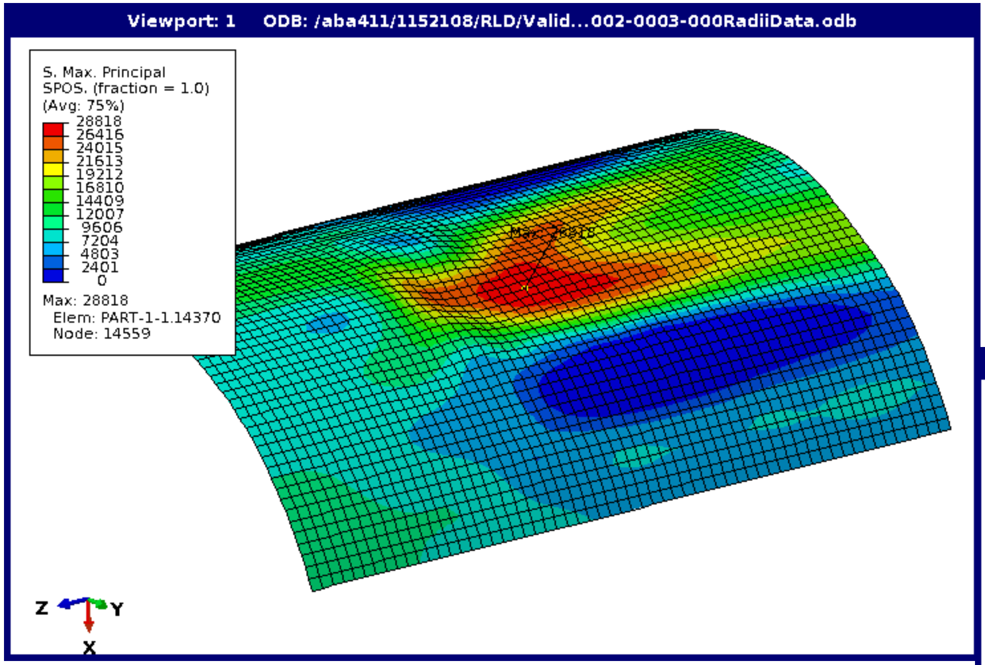


Pressure Range (psi)	# Cycles Per Year	Nominal Hoop Stress (psi)	Stess * SCF (ksi)	AWS C-Curve Parameters	
				# Cycles C-Curve	Damage Per Year C Curve
271	100	13000	42.64	97384	1.03E-03
379	50	18200	59.70	29994	1.67E-03
488	25	23400	76.75	12446	2.01E-03
596	0	28600	93.81	6166	0.00E+00
704	0	33800	110.86	3436	0.00E+00
780	0	37440	122.80	2402	0.00E+00
				TOTAL DAMAGE	**0.00470**
				Life	**212.7**
				Design Life	21.3

Finite Element Dent Analysis Tool (FE-DAT)

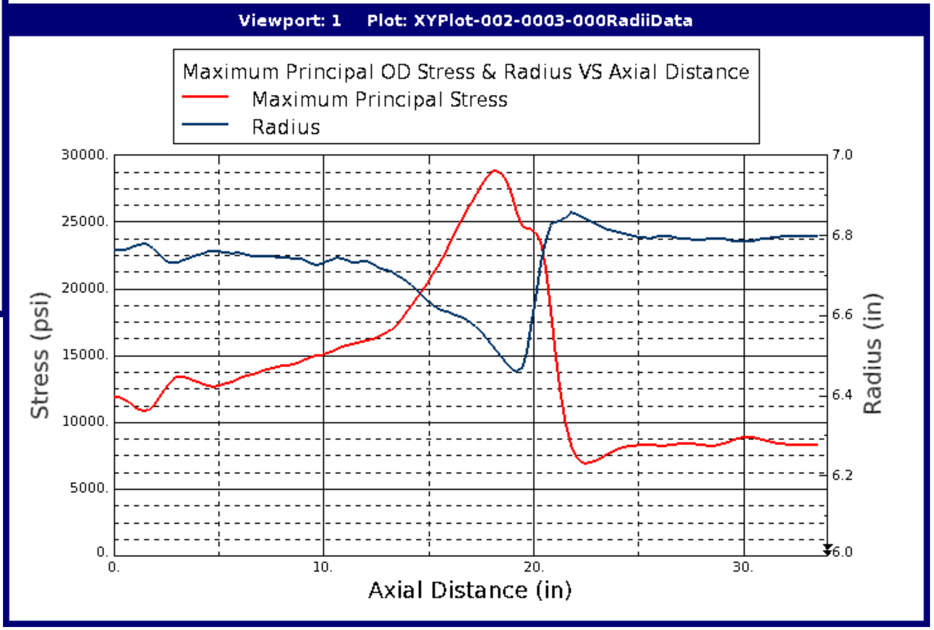


Sample Output



Stress Contour Plots

Data Plots Showing Stress Variation



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Finite Element Dent Analysis Tool (FE-DAT)

- Remaining life analyses have been greatly simplified for unconstrained plain dents.
- An analysis which used to take weeks can now be completed in a fraction of the time permitting rapid analysis of hundreds of dents.
- The phrase “You can’t analyze every dent” no longer applies to topside dents.
- The following example was performed for 113 plain dents.

Comparison of Depth, Strain, and SCF

Comparison of:

- Dent depth
- Curvature strain (B31.8)
- SCF (FE-DAT)

Based on:

- ROSEN RoGeo XT ILI data
- 14” diameter pipeline
- 0.375” wall thickness
- 113 dents
- Depths, strain and stress as per table:

	Dent Depth			Strain		SCF	
Statistic	**inch**	**mm**	**% OD**	**External**	**Internal**	**External**	**Internal**
Min	0.12	3.1	0.9	1.3%	1.3%	1.62	1.36
Max	0.45	11.5	3.2	4.9%	5.3%	4.39	3.39
Mean	0.23	5.8	1.6	2.6%	2.6%	2.38	1.88
Stdv	0.06	1.4	0.4	0.8%	0.8%	0.40	0.34

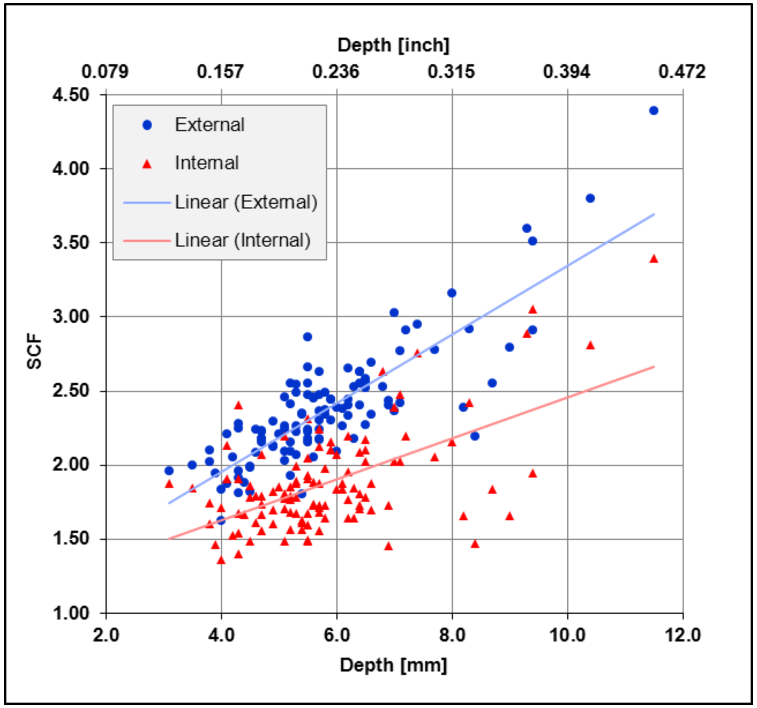
Comparison of Depth, Strain, and SCF

Correlation coefficients:

	OD Strain	ID Strain	OD SCF	ID SCF
Depth	0.48	0.47	**0.83**	0.58
OD Strain		0.99	**0.35**	0.31
ID Strain			0.31	0.27
OD SCF				0.73
Depth & OD strain			**0.84**	
Depth & ID strain				0.58

- High correlation between depth and SCF
- However, dents of same depth may have significantly different SCFs / remaining lives
- Strain has only slight influence on SCF

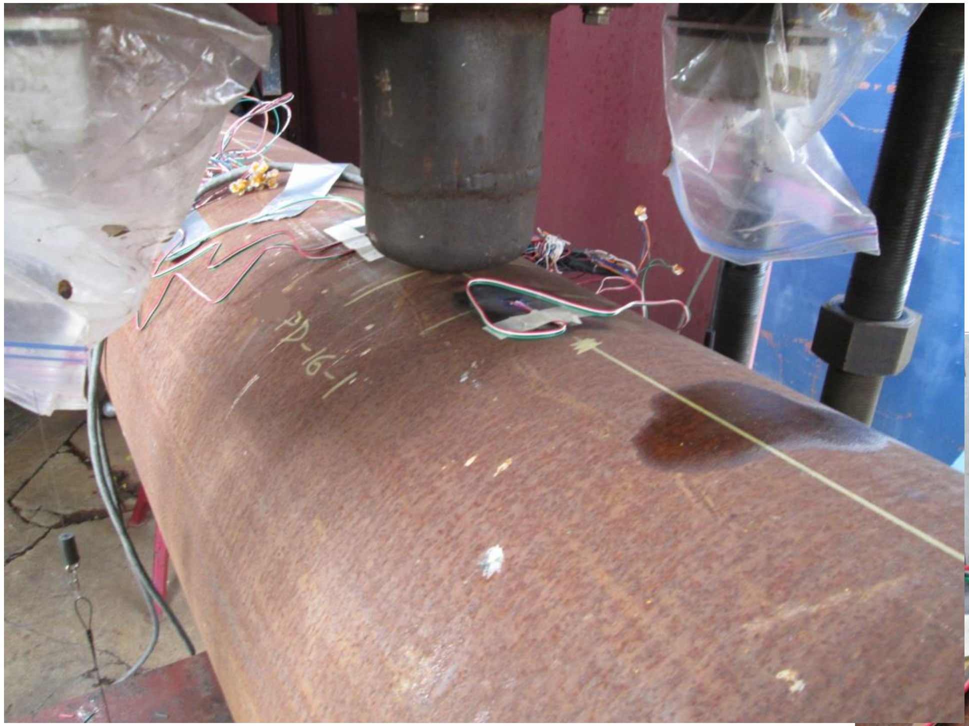
→ Neither depth nor curvature strain can accurately predict remaining life



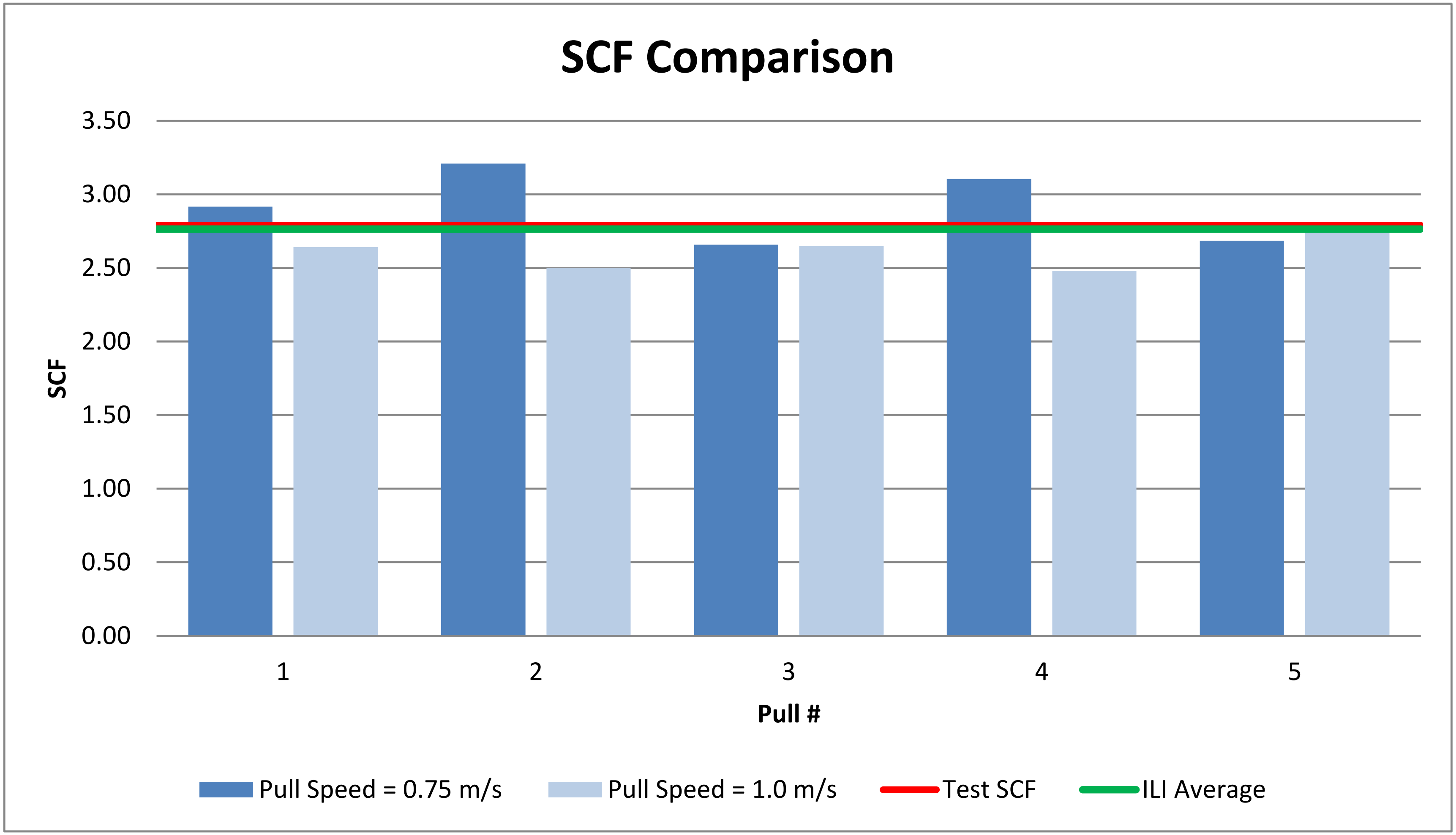
SCF Validation

- An unconstrained lab dent was generated in a pipe with a 16-inch OD and 0.25-inch WT
- The unconstrained dent had a depth of 0.206-inches (1.3%)
- The dent was pressure cycled to failure by running pressure cycles equivalent to a 72% SMYS range
- Ten repeat ILI pull runs were performed on the dent
- The SCF was calculated in three ways
  - By analysis using the ILI data from each of the 10 runs
  - By analysis using a laser scan (Creaform)
  - By testing using strain gages
- The remaining life was computed using the DOE and API Curves and compared to test data

Lab Generated Dent



SCF Comparisons



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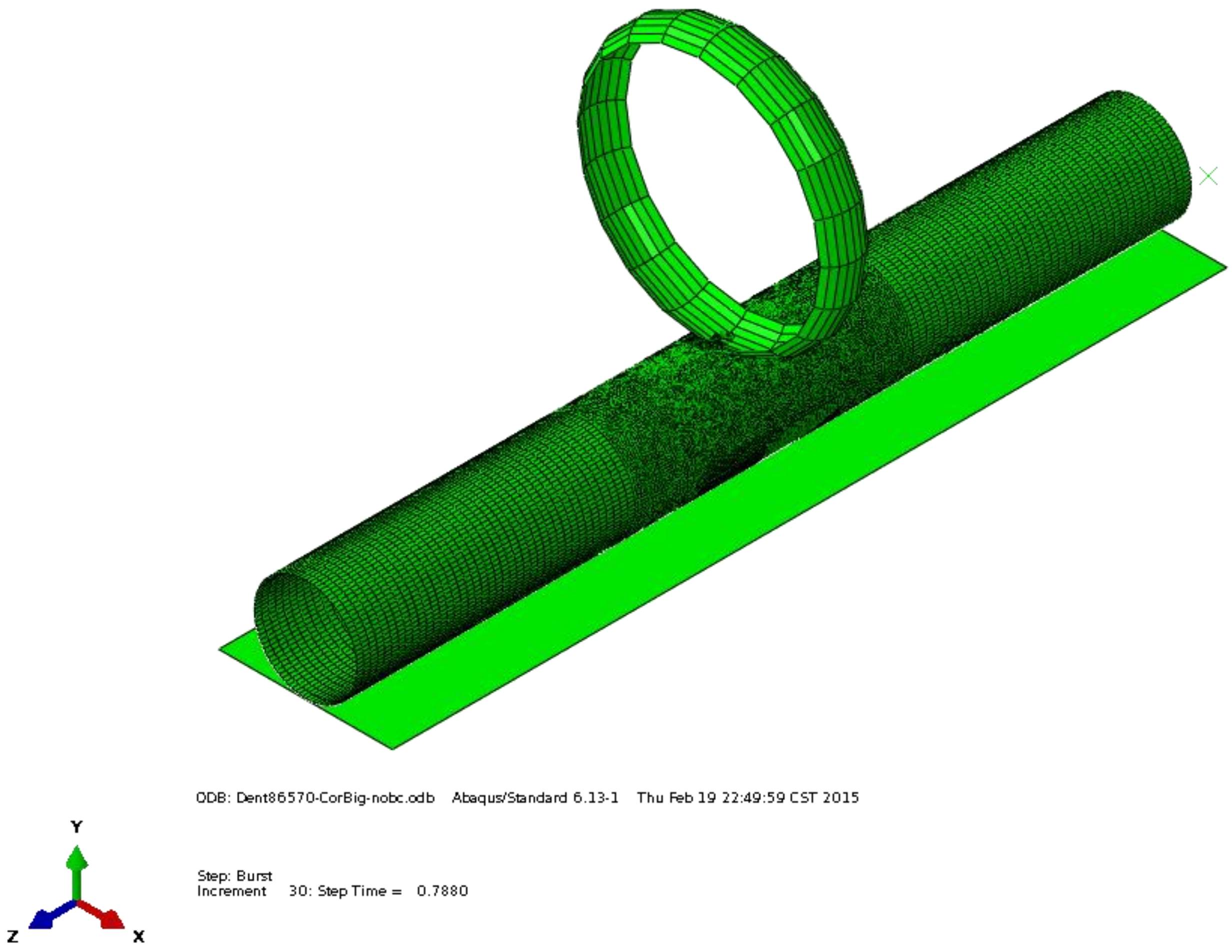
SCF Validation Results

- SCF Comparison
  - Testing: 2.79
  - ILI Average: 2.76 (st.dev of 0.23 over 10 runs)
  - Laser Scan: 2.76
- Remaining Life (Un-factored)
  - Actual Test Data: 32,876
  - Test SCF : 12,922 cycles
  - ILI: 8,950 – 17,730 cycles
  - Laser Scan: 13,298
- All of the predicted lives are well within the safety factors for fatigue, which can range from 3 – 10.

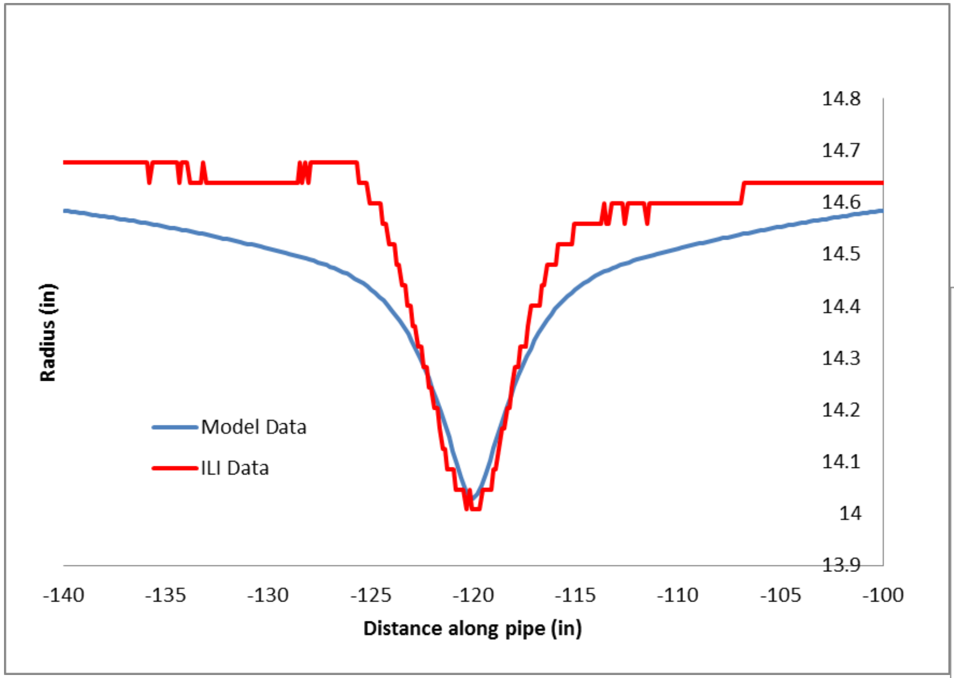
Assessments for Constrained Dents

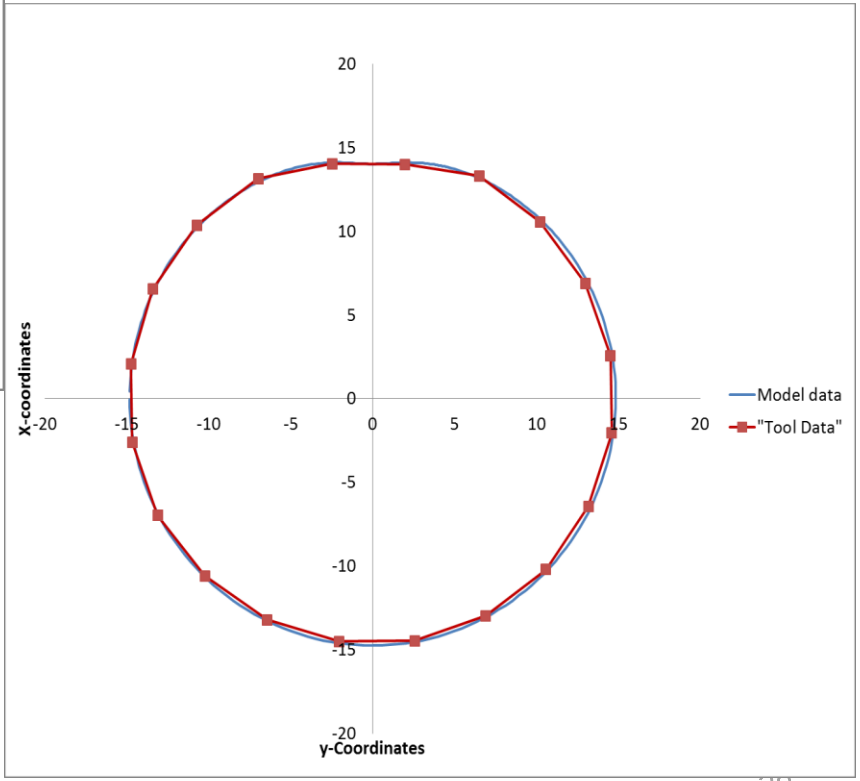
- Key Considerations
  - How much constraint exists?
    - Fully constrained may be unconservative
    - Assuming unconstrained conditions may be excessively conservative
  - Confidence in indenter shape is based on matching ILI profile in the axial and circumferential directions
  - Material plasticity must be accounted for
- More modelling and analysis time is required
- Solid element patch may be necessary in the area of constraint
- SCFs are calculated based on change in strain due to applied internal pressure

Constrained Dent Analyses



Constrained Dent Profiles





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Alternatives for Assessing Constrained Dents

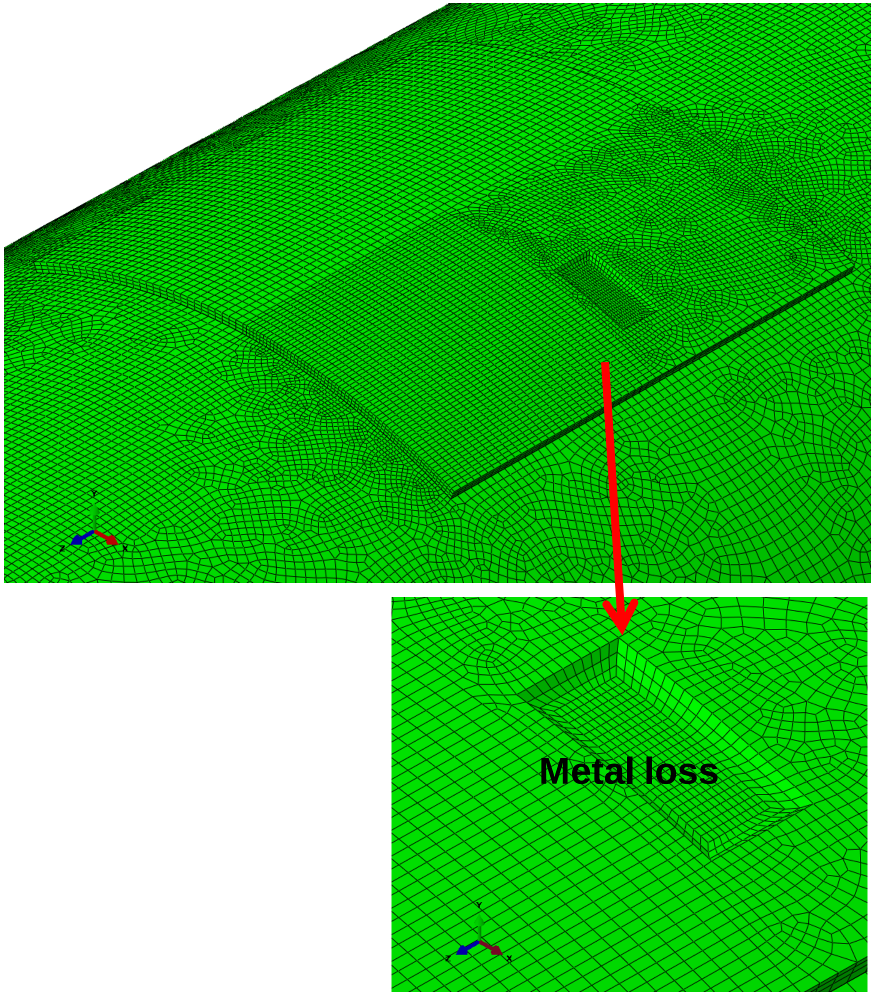
- Alternatively, the constrained dents can be analyzed as unconstrained recognizing that the results will be conservative and the remaining lives may be excessively conservative.
- The SCF can be used as a metric to prioritize the constrained dents under the assumption that although the actual SCF may not be accurate, the order of severity should be.

Dents with Metal Loss

- Key Considerations:
  - Is the metal loss associated with sharp features (i.e. cracks or gouges)?
  - Prior dig experience may provide confidence in assuming a smooth metal loss profile. Alternatively, buffing out any sharp features can eliminate this concern but requires excavation.
  - Corrosion typically has a significant impact on fatigue resistance requiring larger factors of safety than are appropriate for a plain dent
  - If a feature is not inspectable, it is difficult to confidently assess remaining life on the basis of analysis alone. This may change as inspection tools continue to improve
  - Analysis may be useful for demonstrating a feature is not interacting and/or not an immediate concern

Metal Loss Example

- When performing an assessment with metal loss the analysis must consider the confidence in metal loss sizing and location



Other Interactions

- Interactions with seam or girth welds are difficult based on numerical analysis alone unless the weld properties are known
  - Test data has shown that girth welds are generally less of a concern unless they are of a poor quality
  - Seam weld interaction remains a primary concern
- Seam or girth weld interaction can be confirmed with an analysis.
  - By demonstrating that the stresses associated with the dent do not affect the seam or girth weld, it can be shown that it is not “interacting”

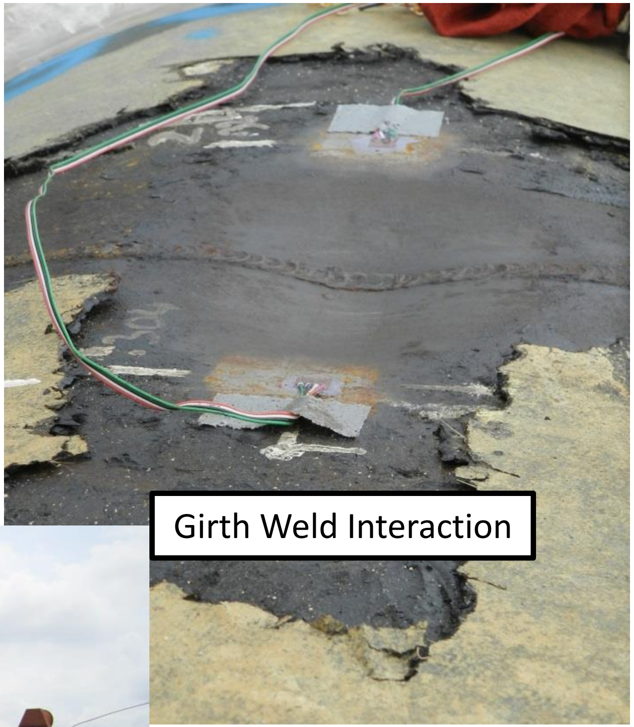
Using Test Data to Support Analysis

- If vintage pipe material is available, testing can be used to replicate ILI features incorporating any interactions present
  - Seam welds, girth welds, and metal loss
- Constraint can also be replicated in test conditions which eliminates some conservatism
- The result from physical testing are useful for demonstrating the performance and providing confidence in the analysis
- Test data can also be useful for demonstrating confidence in a repair method

Example Replication of a Defect

- A 1.5% dent in a 40-inch, 0.312-inch WT pipeline was recreated in the lab based on ILI data.
- The same dent was generated in four configurations
  - Unconstrained
  - Unconstrained in a girth weld
  - Unconstrained in the seam weld
  - Constrained
- The test data was compared to remaining life calculations based on the ILI data

Lab Simulation of Dents



Test Results

- The cycles to failure for each condition
  - Plain Dent: 18,325
  - Girth Weld: 31,799
  - Seam Weld: 6,245
  - Constrained: 27,664
- Predicted Life based on ILI data and DOE C Curve was 5,164
- The test data showed that the original calculations were significantly conservative in most cases, except for a seam weld interaction

Composite Repairs

- SES has been instrumental in the evaluation of composite repairs for reinforcing a variety of anomalies, including dents
- Composite reinforcement reduces the strains in the dented region of the pipe from internal pressure.
- The ability to reduce strain is related to two areas:
  - Composite stiffness (modulus and thickness)
  - Filler material
- Surface preparation and inspection is required before composites are installed.
- Future advancements may include the reinforcement of cracks and subsea repairs.

Conclusions

- ILI data has improved to the point where unconstrained plain dent assessments can rapidly be carried out and provide the remaining life of these features
- ILI data can also be used to replicate constrained dents and provide remaining life assessments
- Analysis can be useful for understanding the level of interaction in features such as metal loss or welds
- A confident analysis of dents with metal loss or interactions depends on the confidence of the assumptions (i.e., no sharp features and/or mechanical properties)

Thank You!

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