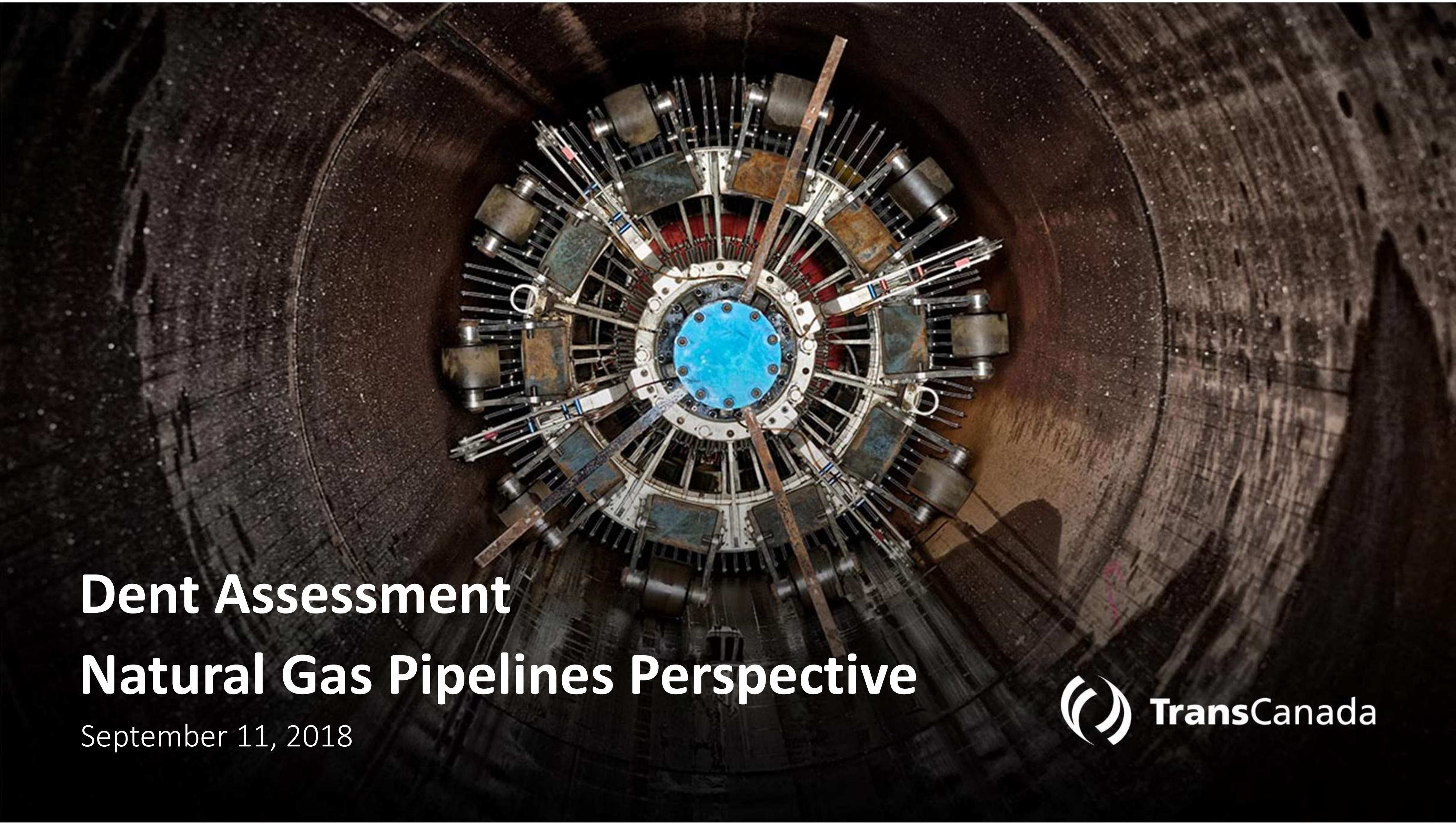


Dent Assessment
Natural Gas Pipelines Perspective

September 11, 2018

TransCanada

Agenda

- Background
- Screening Dents for Excavation and Further Assessment
- ECA for Dents with ML or at a GW
- Areas for Further R&D

TransCanada Dent Assessment Process

- Compliance with CSA Z662
- Due to limitation of ILI technology (ML in dents, cracks, gouges) introduced additional criteria for screening dents – a combined approach:
  - Strain calculated from both ASME B31.8 and modified equations (initiated 2007)
    - Screen dents based on plastic strain damage criterion
  - MFL signal characterization criterion (initiated in 2009)
- Issue with caliper tool and data resolved by high resolution caliper specification development

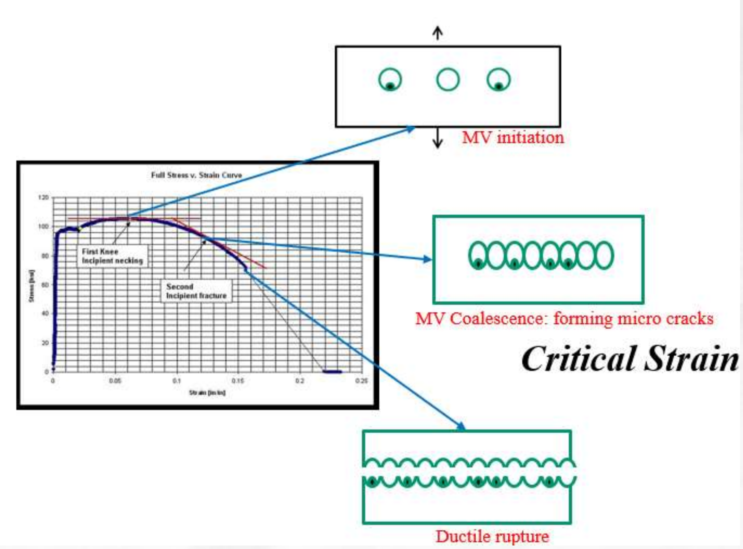
Screening Approach

- Dent is characterized by strain for all analyses
  - Geometric Strain Assessment (for screening purposes) – input is detailed caliper data or in ditch laser data
    - Circumferential & Longitudinal Bending Strain
    - Circumferential & Longitudinal Membrane Strain
- Dent can develop a crack during its formation –
  - Convert the strain into a plastic damage parameter DFDI (uses a material property called critical strain) plus MFL signal analysis
- Not a depth or a strain level criteria
- DFDI (for screening) is a ratio of total strain to critical strain (factored for stress)

	ASME B31.8	Modified Equation
Circumferential Bending Strain, ε_1	$\varepsilon_1 = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right)$	$\varepsilon_1 = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right)$
Circumferential Membrane Strain, ε_4	Assumed to be zero	Assumed to be zero for moderate dents, or modeled with changing the length in circuferential direction, or use FEA
Longitudinal Bending Strain, ε_2	$\varepsilon_2 = \frac{-t}{2R_2}$	$\varepsilon_2 = \frac{-t}{2R_2}$
Longitudinal Membrane Strain, ε_3	$\varepsilon_3 = \frac{1}{2}\left(\frac{d}{L}\right)^2$	$\varepsilon_3 = 2\left(\frac{d}{L}\right)^2$
Shear Strain, γ_{xy}	Assumed to be zero	Assumed to be zero or FEA
Effectve strain ε_{eff}	$\varepsilon_{eff} = \sqrt{\varepsilon_x^2 - \varepsilon_x\varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{max} = Max[\varepsilon_i, \varepsilon_o]$	$\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x\varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x\varepsilon_y + \varepsilon_y^2 + \gamma_{xy}^2/2}$ $\varepsilon_{max} = Max[\varepsilon_i, \varepsilon_o]$

Screening Criteria

- ASME B31.8 (2003 Edition) – Introduced **6% strain limit for plain dents** (empirical)
- Limitations of ASME B31.8 criterion
  - Plastic strain level of 12% for cracking is below the actual measured strain limit for cracking for most line pipe steels.
  - One strain limit for all steel grades is not appropriate.
- Critical-strain-based Ductile Failure Damage criterion
  - Quantify progressive damage limit for avoiding onset of failure in ductile materials.
  - Ductile Fracture Damage Index (DFDI) Criteria
  - DFDI >1 is onset of cracking
  - Conservative Screening criteria DFDI >0.6
  - DFDI = $\varepsilon_{eq}/(\varepsilon_0/1.65)$ --- simplified for screening

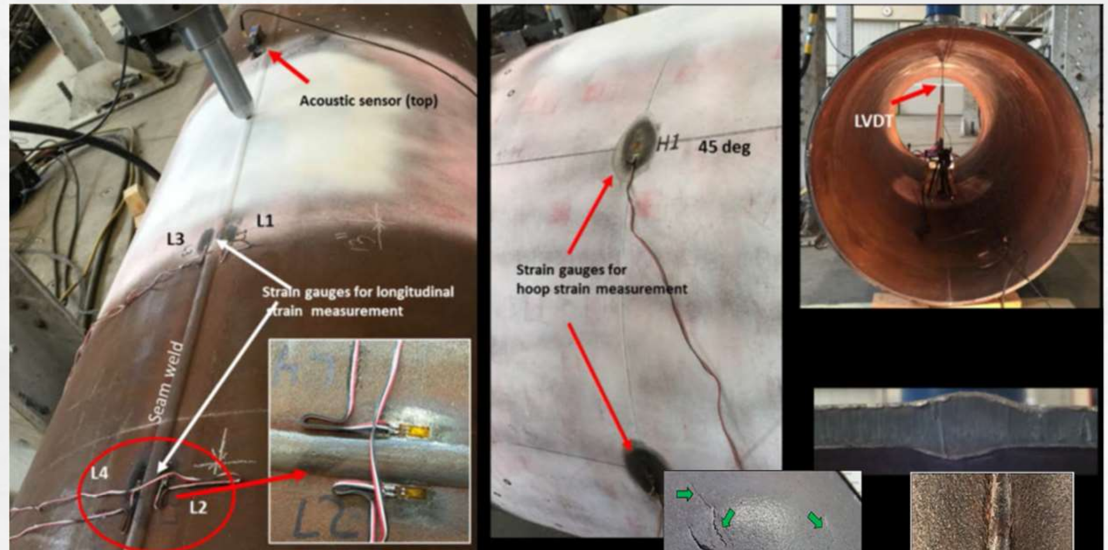


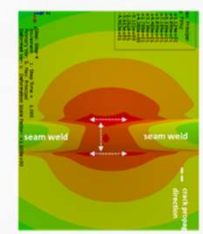
$$DFDI = \frac{1}{1.65\varepsilon_c}\int_0^{\varepsilon_{eq}} \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) d\varepsilon_{eq} \; or$$

Strain Criteria – Validated With Experiments

Denting (NPS 34, X52, 1.5"Dia. Indenter) – Pipe body and weld (seam/girth)Test Setup

- MTS Hydraulic Actuator with Indenter
- LVDT for displacement measurement (OD%)
- Strain gages for strain measurement
- Video camera for real time monitoring and recording
- In-situ Laserscan for real time strain measurement
- Acoustic sensor was mounted close to the dent deformation area to monitor the cracking sound if any during the test

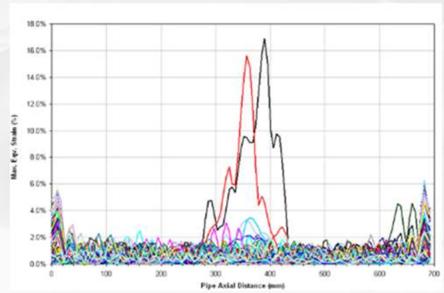


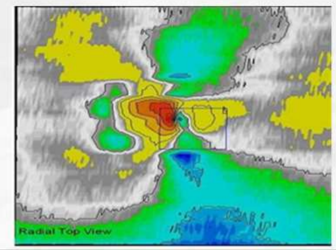


Test #	Pipe Specimen	Dent Location	Max. Eqv. Strain	Upper bound DFDI	DFDI ≥ 1 Criterion	Comments
1	NPS 34; X52 grade; 2.5"/1.5" indenter	Pipebody	30.1%	0.98	Yes. Validated	Several small cracks were found between 12% to 15% OD depth
2			37.5%	1.22	Yes. Validated	Wide-open transverse crack formed at 17.5%OD with several small cracks
3			34.9%	1.136	Yes. Validated	Several micro cracks were found
4	NPS 36; X65 grade; 1.5" indenter		31.2%	0.88	Not validated	Pipe was severely ovalized. Test abandoned & no crack found
5	NPS 34; X52 grade; 1.5" indenter	Seam weld	31.8%	1.05	Yes. Validated	Cracks formed in seam weld/HAZ region at 6%OD
6	NPS 36; X65 grade; 1.5"	Girth weld	31.5%	0.96	Yes.	Cracks formed in girth

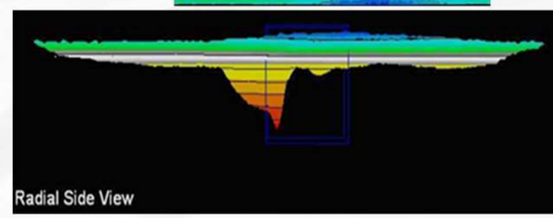
Screening Criteria – MFL Signal Assessment

- When characterizing the MFL signals in combination with the dent strain level, some new insight is gained into unique features of the signals that may be associated with ML in a dent:
  - Rule #1: A single strong MFL signal and located at the dent apex or highest strain spot in the dent, then the metal loss feature is most likely to be a crack.
  - Rule #2: Many general metal loss signals distributed within the dent area, then it is most likely to be corrosion.
  - Rule #3: A strong metal loss feature signal oriented circumferentially and located at dent apex or highest strain spot, then it is probably associated with gouge.
  - Rule #4: a strong metal loss feature signal located at dent apex or highest strain spot surrounded with general shallower metal loss features, then it is probably either a gouge or crack.





DFDI = 0.93

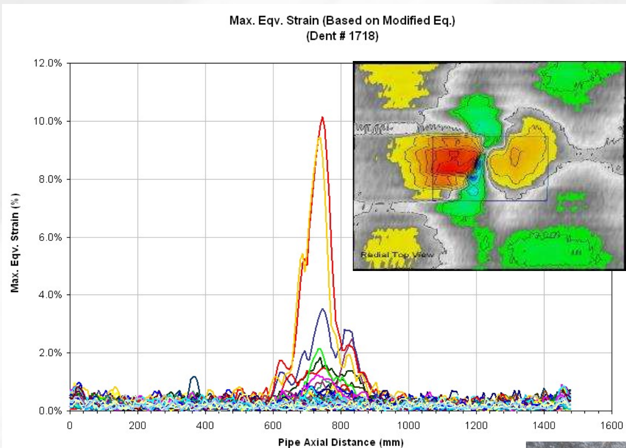


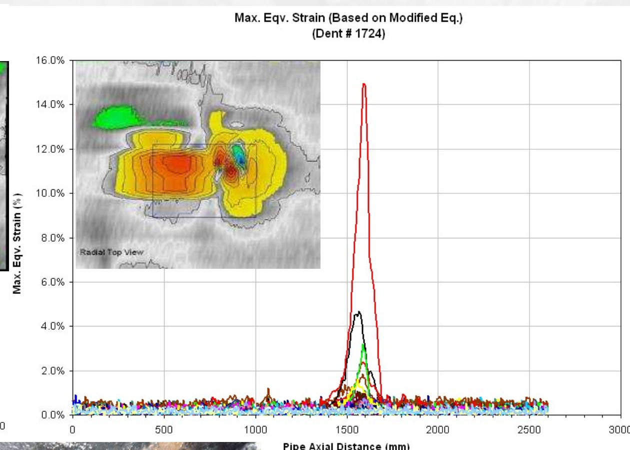
Examples Findings – 15 Cases

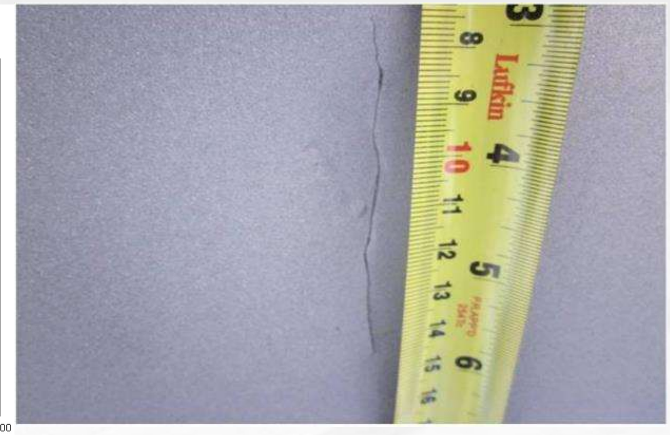
- Three pipeline segments with combo ILI reporting 6361 dents, 150 selected using screening method.
- Strain, DFDI and MFL analyses identified 15 dents for further validation.
  - Model prediction
    - 7 dents crack or gouges
    - 8 dents metal loss
- Excavation Results:
  - 7 dents with cracks or gouges.
  - 8 dents, corrosion or manufacturing defects (negative-negative)

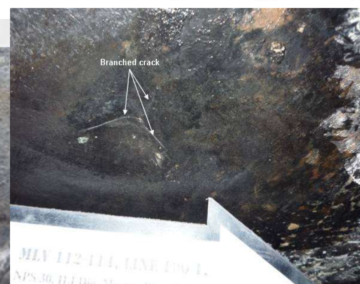
Case +S+ O6:T20	ε_{eq} (%)	Upper bound DFDI	Prediction	Excavation	Prediction-Excavation
1	10.20%	0.6	Possible crack	Through wall crack	Positive-positive
2	15.00%	0.8	Possible crack	Through wall crack	Positive-positive
3	16.90%	0.9	Possible crack and gouge	Gouge	Positive-positive
4	13.00%	0.7	Low confidence of possible crack	ID crack	Positive-positive
5	31.00%	1.7	Crack with gouge	Gouge	Positive-positive
6	17.60%	1	Possible crack	ID / OD crack	Positive-positive
7	11.50%	0.6	Possible crack	Through wall crack	Positive-positive
8	6.80%	0.4	no crack	6% ML dent on rock	Negative-negative
9	7.10%	0.4	no crack	16% ML dent on rock	Negative-negative
10	10.50%	0.6	no crack	12% ML dent on rock	Negative-negative
11	9.90%	0.5	no crack	16% ML dent on rock	Negative-negative
12	5.00%	0.3	no crack	36% OD corrosion	Negative-negative
13	9.00%	0.5	no crack	10% ML dent on rock	Negative-negative
14	7.80%	0.4	no crack	15% OD corrosion	Negative-negative
15	3.60%	0.2	no crack	37% OD corrosion	Negative-negative

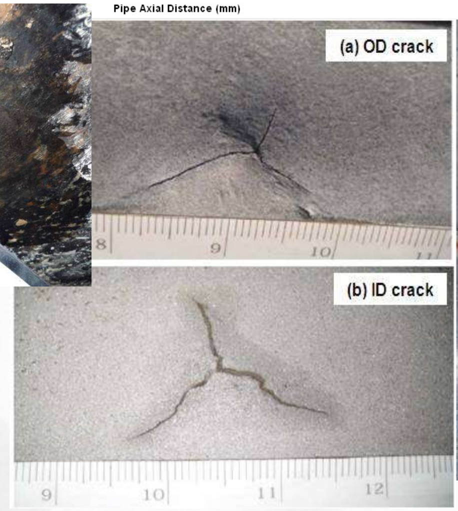
Examples of Findings – Further Validation

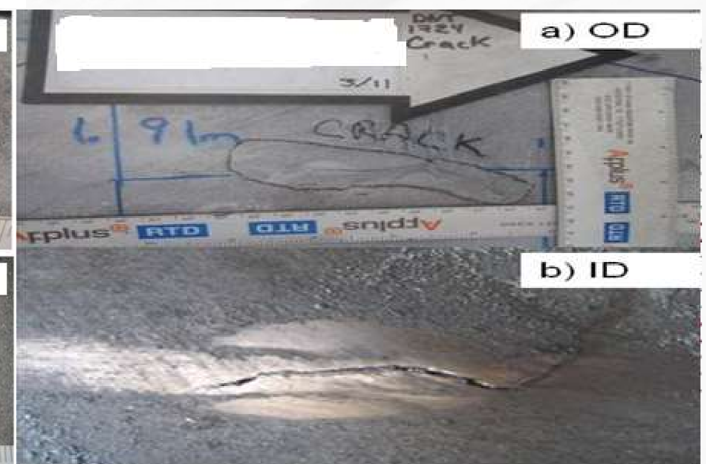






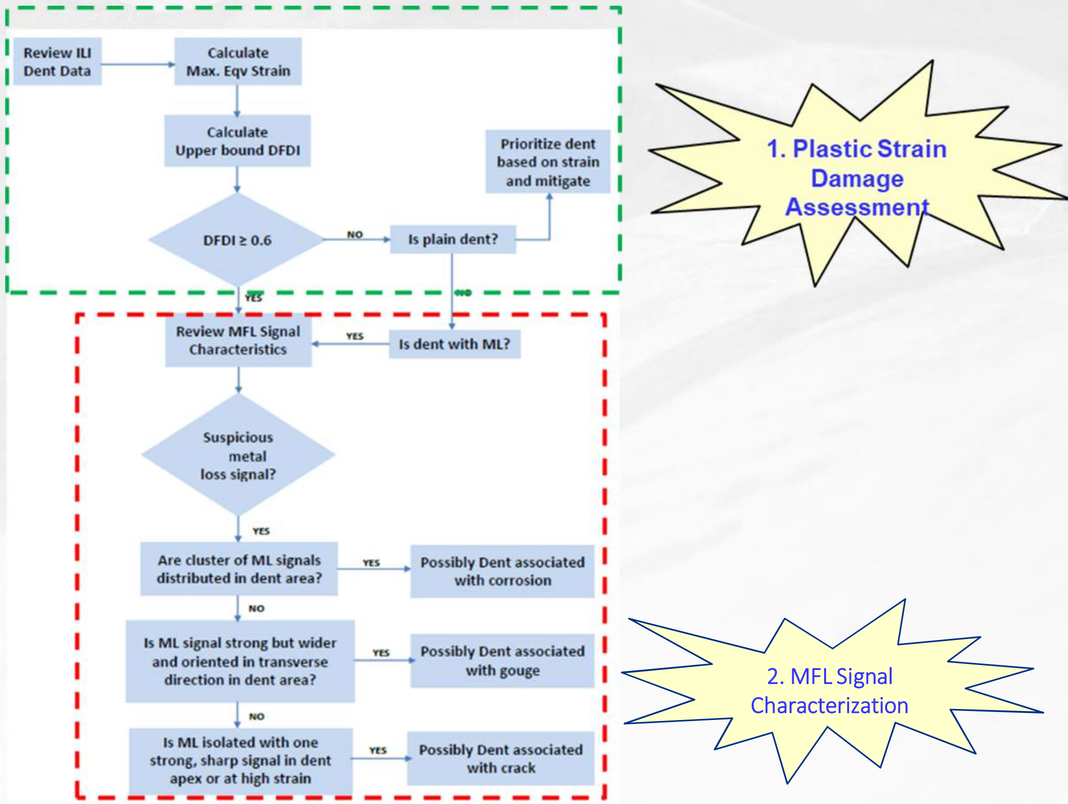






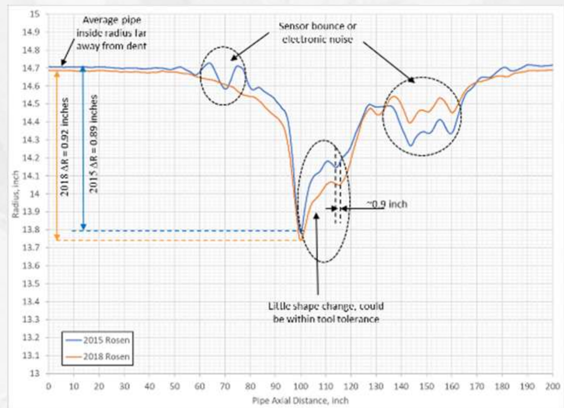
Screening Approach - Summary

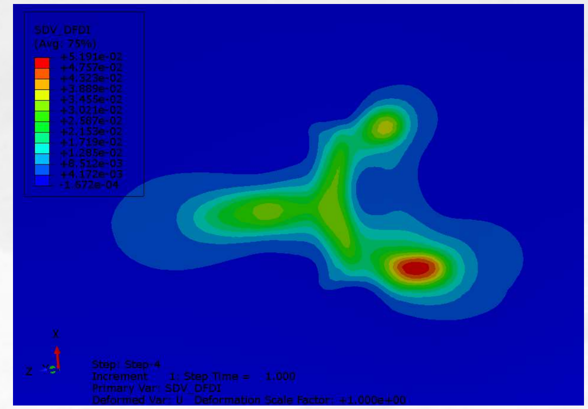
- Follow code requirements and complement with the combined approach to identify critical features:
  - DFDI assessment using geometric strain
  - Assess MFL data when DFDI greater than 0.6
- EPRG fatigue analyses check (no FEA strain required)
- If the above filtering identifies the dent then -Excavate to repair or perform an ECA

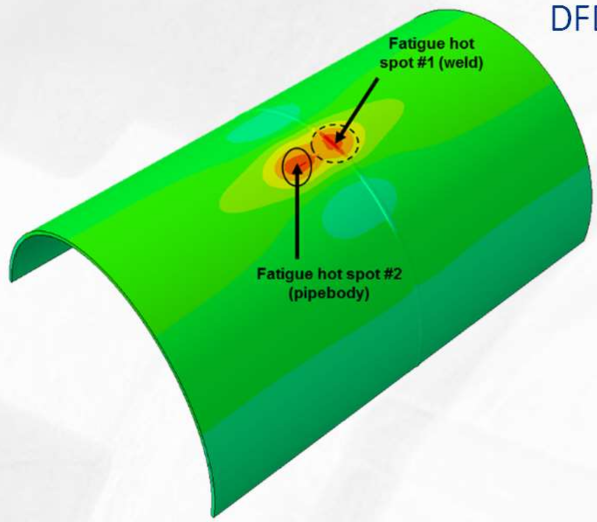


Approach for ECA for Dents with ML and/or on a GW

- Assess ILI data in detail + run comparison
- Identify all loads on the dent (welds, external and other local deformation)
- Geometric & FEA strain
- DFDI analyses
- If the above identifies dent then perform detailed fatigue analyses with FEA strain:
  - Apply the pressure differential
  - Obtain strain differential
  - Strain differential used for estimating fatigue life
  - Lowest fatigue life between Markl and SWT is used







DFDI = 0.18 to 0.19

API 1156 – 111,816 cycles

Markl – 19,921 to 2621 cycles

SWT – 66,740

GAPS & Opportunities – Mechanical Damage Assessment

- ILI delineation of dents (caliper and MFL)
  - Definition of high resolution caliper
  - Better identification and characterization of features interacting with dents
- Further validation of the DFDI
- Fatigue analyses model comparison to dents modeled with critical strain and other results