Assessment Methods Issues/Challenges

Dents

Cracks

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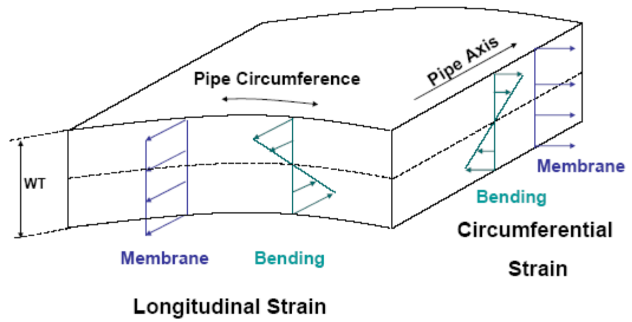
Dent Assessments

- Strain drives failure probability
- Strain components to be considered
  - Axial membrane
  - Axial Bending
  - Circumferential membrane (usually un
  - Circumferential Bending
- Total or Equivalent Strain



Criteria: Dent size less than 6% OD

ASME guideline: Strain less than 6% (either single strain or equivalent)

ASME B31.8 provides non-mandatory strain calculation formulas but allows to use other formulas developed by qualified professionals

Current Equations in B31.8

	ASME B31.8
Circumferential Bending Strain, ε_1	$\varepsilon_1 = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right)$
Circumferential Membrane Strain, ε_4	Assumed to be zero
Longitudinal Bending Strain, ε_2	$\varepsilon_2 = \frac{-t}{2R_2}$
Longitudinal Membrane Strain, ε_3	$\varepsilon_3 = \frac{1}{2}\left(\frac{d}{L}\right)^2$
Shear Strain, γ_{xy}	Assumed to be zero
Effectve strain ε_{eff}	$\varepsilon_{eff} = \sqrt{\varepsilon_x^2 - \varepsilon_x \varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{max} = Max[\varepsilon_i, \varepsilon_o]$

- Six parameters
  - R_o = Initial pipe surface radius
  - R_1= Radius of dent curvature in transverse plane, negative for reentrant dents
  - R_2 = Radius of dent curvature in longitudinal plane, negative for reentrant dents
  - d = Dent depth
  - L = Dent length
  - t = wall thickness

Possible Modifications of B31.8 (2007) Strain Based Method

	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 use FEA or same order of longitudinal membrane strain for sharp dents
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}	$\varepsilon_{eff} = \sqrt{\varepsilon_x^2 - \varepsilon_x \varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{\max} = Max\left[\varepsilon_i, \varepsilon_o\right]$	$\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x \varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x \varepsilon_y + \varepsilon_y^2 + \gamma_{xy}^2 / 2}$ $\varepsilon_{\max} = Max\left[\varepsilon_i, \varepsilon_o\right]$

Lukasiewicz et al; IPC 2006, Paper 10101

Gao et al: IPC 2008

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Impact of the Modification on the Total Effective Strain - Illustrations

- Using the three cases provided in the Baker Dent Study Report(2004)
- B31.8 under-estimates the effective strain by a factor of about 3
- Consistent with L-C's findings

Strain component		Case 1	Case 2	Case 3
Circumferetial Bending Strain ε_1		2.3%	2.3%	2.3%
Longitudinal Beding Strain, ε_2		1.1%	1.5%	2.2%
Longitudinal Membrane Strain, ε_3		0.6%	0.8%	1.0%
Modified Longitudinal Membrane Strain, ε_3		2.4%	3.1%	4.2%
Effective Strain ID	ASME B31.8 2007	2.1%	2.3%	2.9%
	Proposed Method	5.9%	7.0%	9.0%
B31.8 Under Estimate Factor		2.8	3.1	3.1
Effective Strain OD	ASME B31.8 2007	2.1%	2.1%	2.0%
	Proposed Method	2.3%	2.4%	2.5%
B31.8 Under Estimate Factor		1.1	1.2	1.2

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Illustrations (Cont'd)

- An example from the actual pipeline ILI data
  - One fails to meet B31.8 strain criterion (6 %) when assessed using B31.8 2007
  - Nine fail to meet B31.8 strain criterion (6%) when assessed using the modified method
  - One shallow (1.04 wt%, number 14 in depth ranking) shows quite high total strain (8.46 wt% number 3 in strain ranking)

Weld Number	Dent ID	Absolute Distance (ft)	Depth %OD	Depth Based Priority	Dent Length (inch)	Dent Width (inch)	B31.8 200 7 Max. Total Strain (%)	B31.8 Based Priority	Propose d Method Max. Total Strain	Propos ed Method Priority
31160	530	96294.7	4.61%	1	5	14	5.58	2	23.0	1
75770	465	188158.1	4.19%	2	7	8	7.76	1	18.3	2
64300	402	160431.9	3.96%	3	6	14	4.10	3	8.5	3
75670	463	187957.9	3.67%	4	15	17	3.47	6	7.2	4
155120	693	366795.6	2.73%	5	16	17	3.48	5	7.0	5
155310	697	367502.2	2.50%	6	21	11	3.51	4	6.9	6
155420	700	367949.8	2.46%	7	11	17	3.16	7	6.7	7
155310	696	367500.1	2.40%	8	14	28	3.07	9	6.4	8
157710	727	376749.4	2.19%	9	21	39	3.08	8	6.1	9
155400	698	367844.2	2.07%	10	13	12	2.63	11	5.4	10
155400	699	367848.3	2.07%	11	25	12	2.81	10	5.3	11
14740	229	51853.2	2.07%	12	18	17	2.48	12	4.7	12
23620	182	55213.4	2.05%	13	8	8	2.34	13	4.5	13
58770		181282.5	1.04%	14	13	17	1.69	14	3.4	14

Still single point strain calculation; assumption that strain is highest at deepest point

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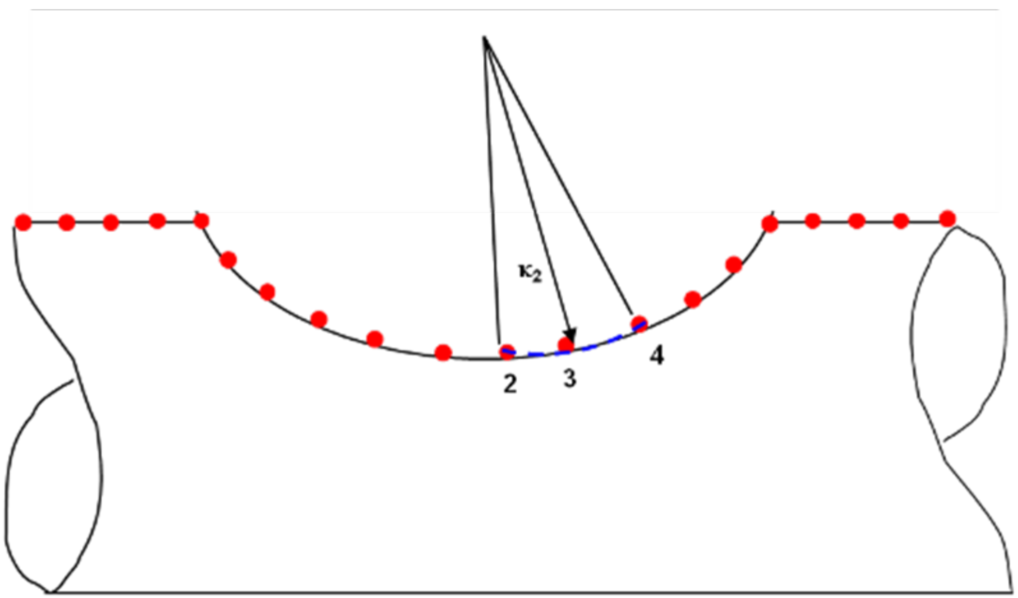
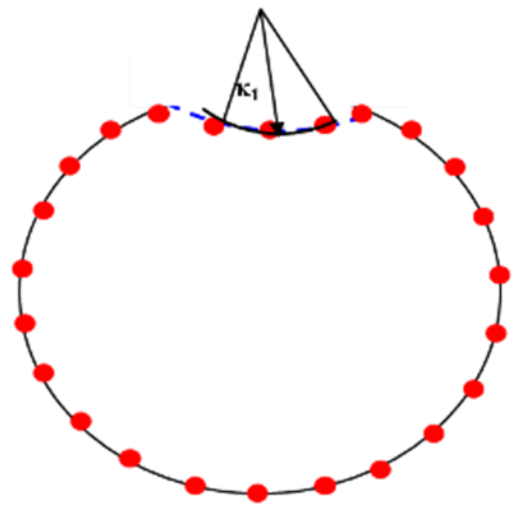
Point to Point Strain Calculation

- **Input data & processing:**
  - Uses HR ILI data – both axial & circumferential displacement profile data.
  - Data input format – Cartesian co-ordinate (not necessary) & independent of ILI vendors data format.
  - Filters the noises and smoothens the profile data .
  - Uses piecewise quadratic equation with 3 or 5 points and calculates curvature at mid point (B-spline optional)

- **Output:**
  - Evaluates point-to-point based strains with improved axial/circum. membrane and equivalent strain calculation method.
  - Reports 6 strains at any point in the dent area (e1, e2, e3, eeqv_in, eeqv_out and eeqv-max)





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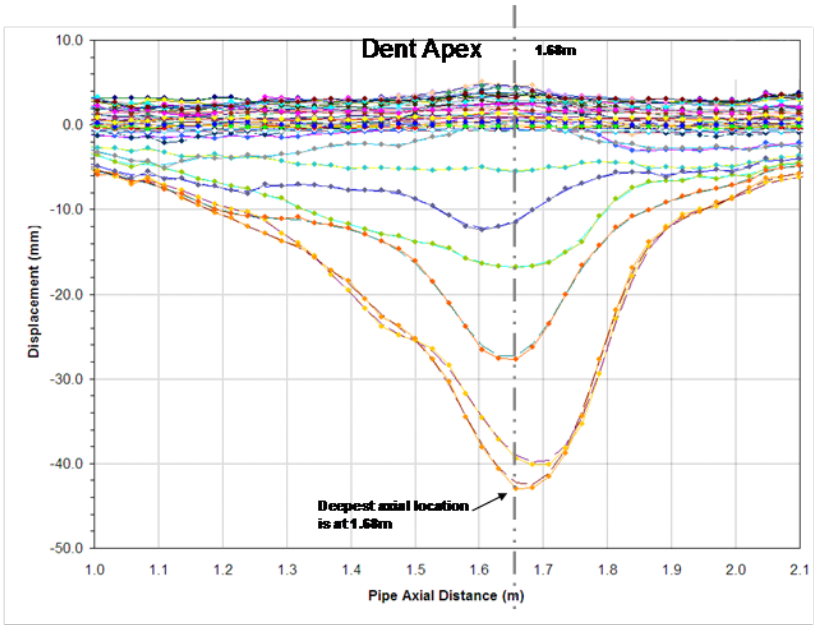
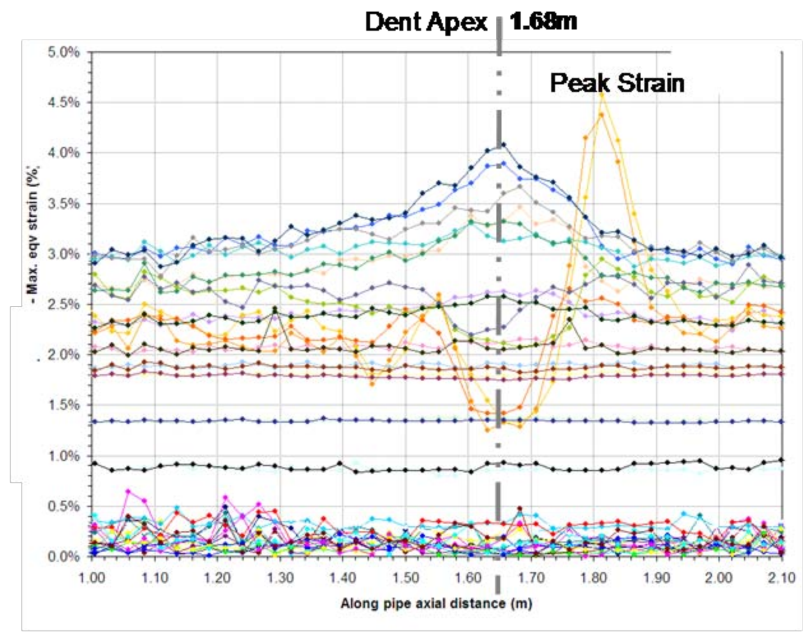
Summary of all options

	ASME B31.8	Modified Equation	Point to Point Strain Calculation
Circumferential Bending Strain, ε_1	$\varepsilon_1 = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right)$	$\varepsilon_1 = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right)$	$\varepsilon_1 = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right)$
Circumferential Membrane Strain, ε_4	Assumed to be zero	Assumed to be zero for moderate dents or use FEA or same order of longitudinal membrane strain for sharp dents	Utilizing actual measurements of curvature
Longitudinal Bending Strain, ε_2	$\varepsilon_2 = \frac{-t}{2R_2}$	$\varepsilon_2 = \frac{-t}{2R_2}$	$\varepsilon_2 = \frac{-t}{2R_2}$
Longitudinal Membrane Strain, ε_3	$\varepsilon_3 = \frac{1}{2}\left(\frac{d}{L}\right)^2$	$\varepsilon_3 = 2\left(\frac{d}{L}\right)^2$	$\varepsilon_3 = \frac{(L_s - \Delta z)}{\Delta z}$ $L_s = R\theta$
Effectve strain ε_{eff}	$\varepsilon_{eff} = \sqrt{\varepsilon_x^2 - \varepsilon_x\varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{max} = Max[\varepsilon_i, \varepsilon_o]$	$\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x\varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x\varepsilon_y + \varepsilon_y^2 + \gamma_{xy}^2/2}$ $\varepsilon_{max} = Max[\varepsilon_i, \varepsilon_o]$	$\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x\varepsilon_y + \varepsilon_y^2}$ $\varepsilon_{eq} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \varepsilon_x\varepsilon_y + \varepsilon_y^2 + \gamma_{xy}^2/2}$ $\varepsilon_{max} = Max[\varepsilon_i, \varepsilon_o]$

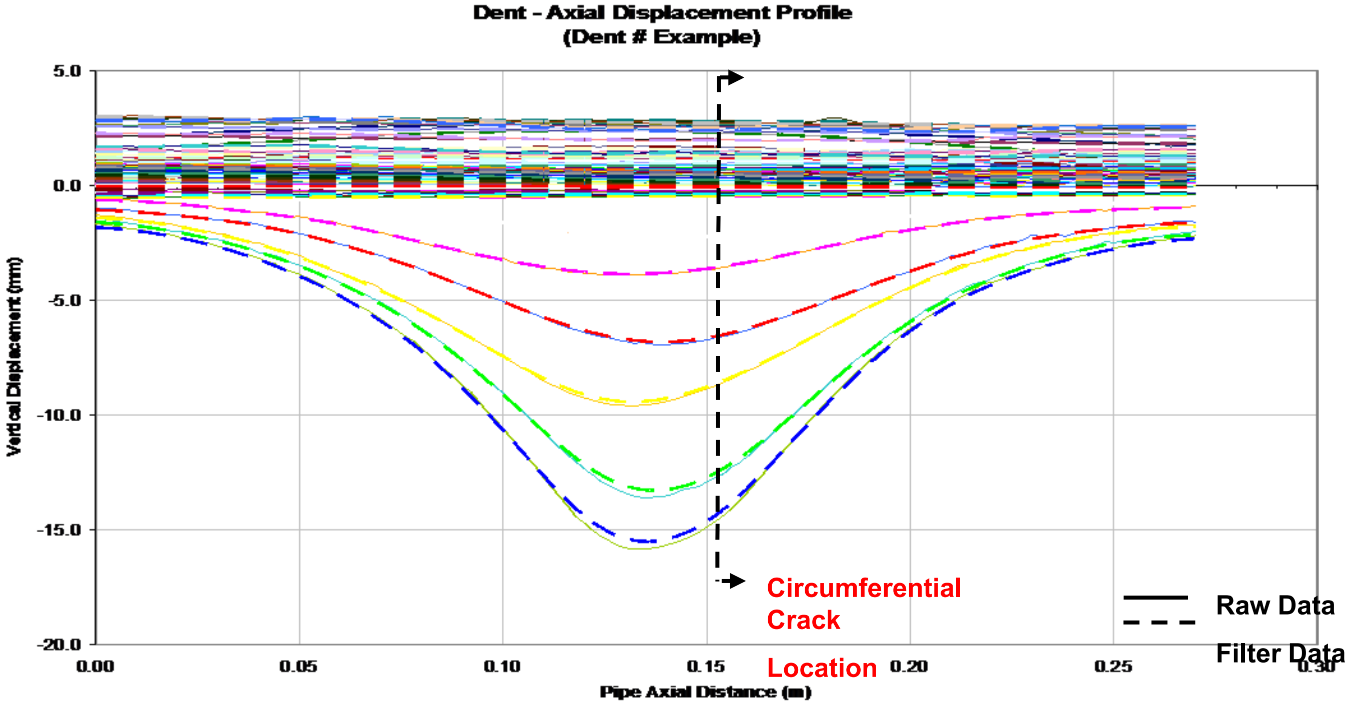
Point to Point provides a distribution of strain across entire dent utilizing all the components

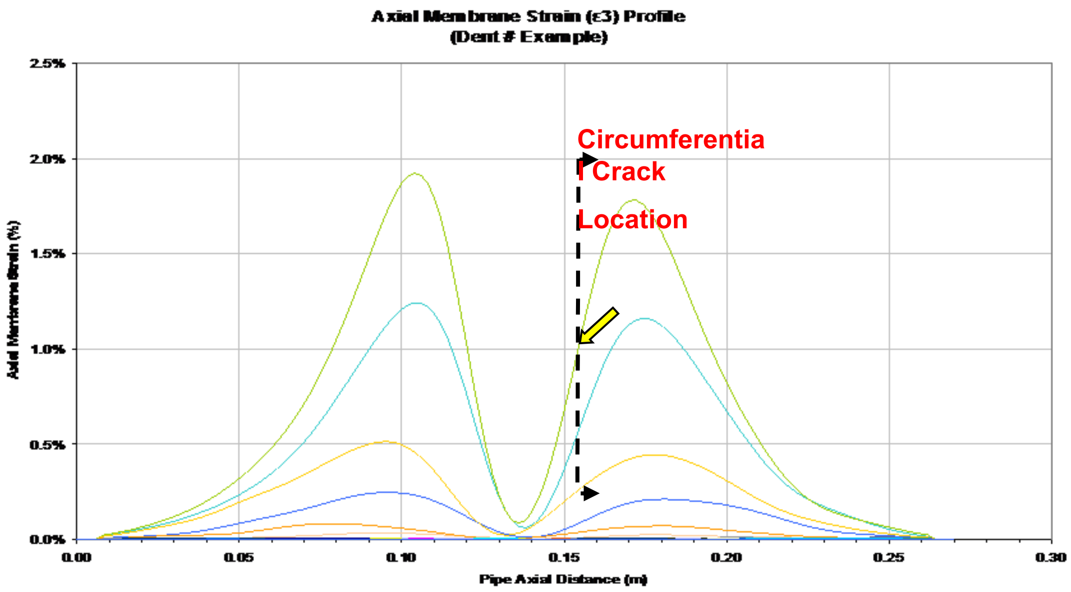
Strain distribution across a dent

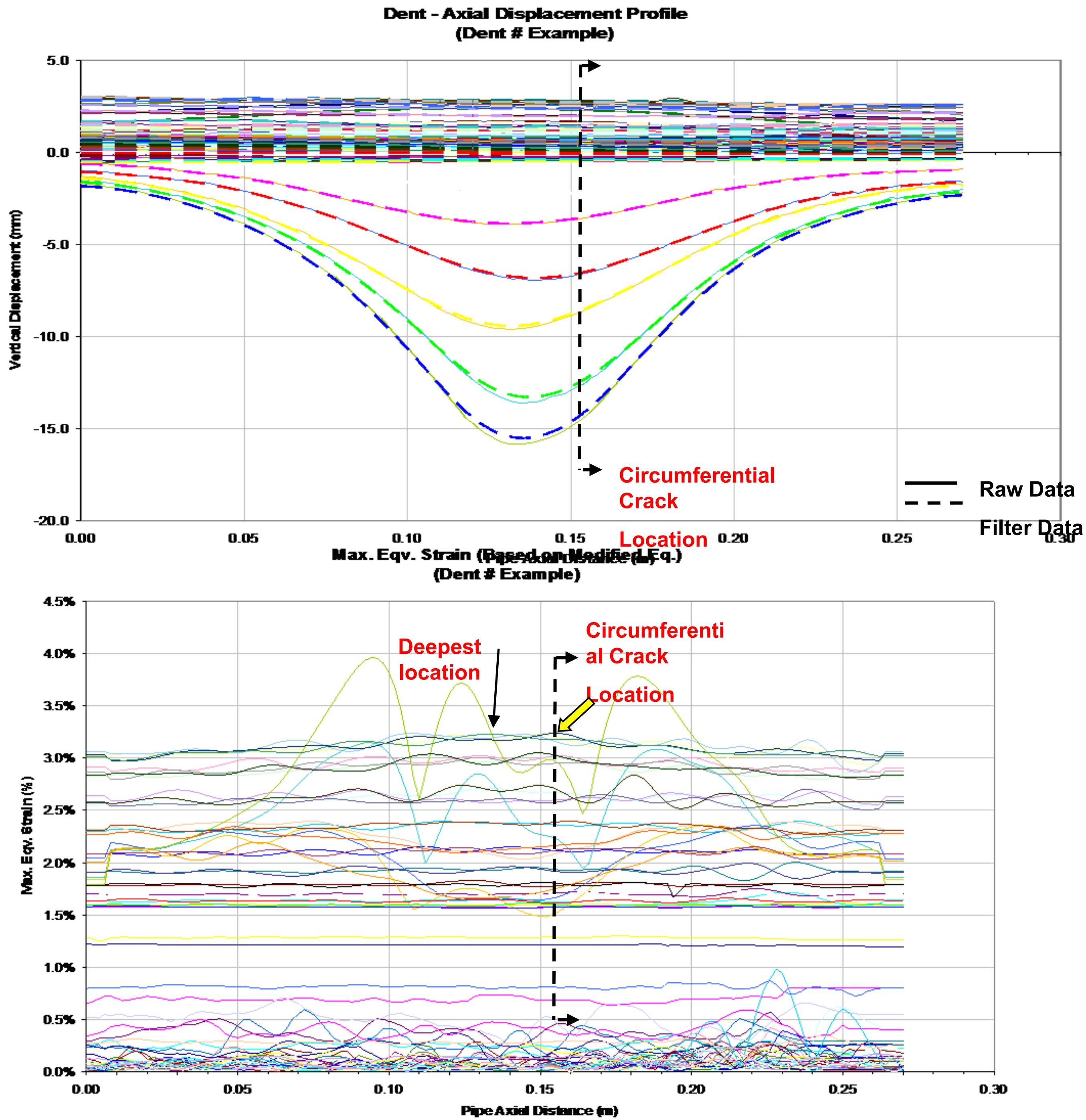




- Maximum strain not at the deepest point
- Critical to calculate across the entire dent; dependent on tool resolution (ILI or in ditch)


Dent - Axial Displacement Profile
(Dent # Example)
5.0
0.0
-5.0
-10.0
-15.0
-20.0
Vertical Displacement (mm)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Pipe Axial Distance (m)
Circumferential Crack
Location
Raw Data
Filter Data


Axial Membrane Strain (ε3) Profile
(Dent # Example)
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
Axial Membrane Strain (%)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Pipe Axial Distance (m)
Circumferentia
l Crack
Location

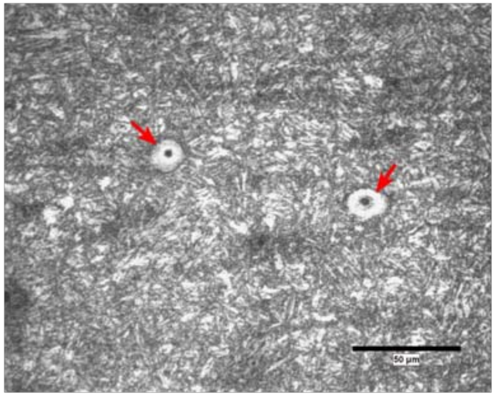

Dent - Axial Displacement Profile
(Dent # Example)
Vertical Displacement (mm)
Pipe Axial Distance (m)
Circumferential Crack Location
Raw Data
Filter Data
Max. Eqv. Strain (Based on Modified Eq.)
(Dent # Example)
Max. Eqv. Strain (%)
Deepest location
Circumferential Crack Location
Pipe Axial Distance (m)

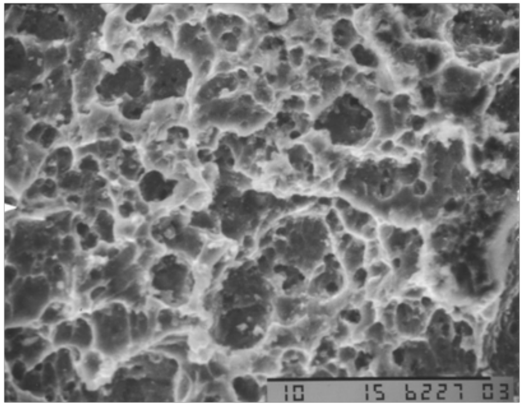
Key Issues / Challenges

- Comprehensive strain calculation
  - Maximum strain not necessarily at the deepest point of the dent
  - Maximum strain may/may not (appear to) coincide with the presence of a crack (more analyses and data is being collected)
- Is 6% Strain criteria appropriate / adequate?
  - Many dents were accepted but now fail to meet the 6% strain criterion using the modified strain calculation methods
  - Most of the “fail-to-meet” dents still remain in the pipeline probably without cracking
- Should there be a criteria that is material/pipeline/loading specific?
- Can a more generalized strain criteria be identified?

Potential solutions

- Expandables and high plastic strain applications
  - Critical strain / ductile failure damage indicator
    - Material ductile failure by micro void initiation and coalescence
    - Critical strain – limit state for strain-dominated failure
    - Micromechanics model by Hancock et. Al. using Rice and Tracey
    - Severity of ductile damage can be quantified with Ductile Failure Damage Indicator (DFDI)
      - Degree of ductile damage with respect to failure





Failure Model

- **Combines stress triaxiality, equivalent strain and critical strain to quantify ductile damage**
  - Driving Force
    - Stresses: triaxiality of stress (σ_m/σ_{mises}), and magnitude $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$
    - Strain: equivalent plastic strain – PEEQ
  - Material resistance: critical strain for rupture ε_c –to failure
- **Failure (cracking or rupture) occurs when DFDI ≥1**
  - Failure driving force: equivalent strain and stress triaxiality
  - Failure resistance: critical strain
- Ductile Failure model developed by Hancock et. Al. using Rice and Tracey micromechanics model

$$DFDI = \frac{1}{1.65\varepsilon_c} \int_0^{\varepsilon_{eq}^p} \exp\left\{ \frac{3\sigma_m}{2\sigma_y} \right\} d\varepsilon_{eq}^p$$

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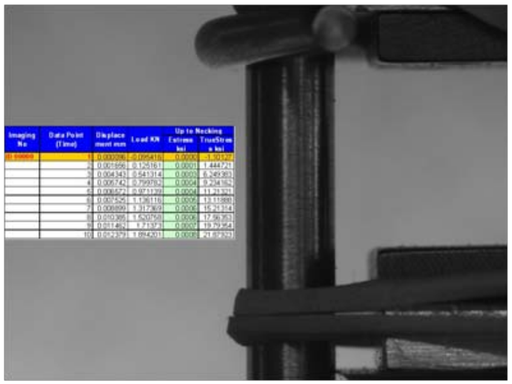
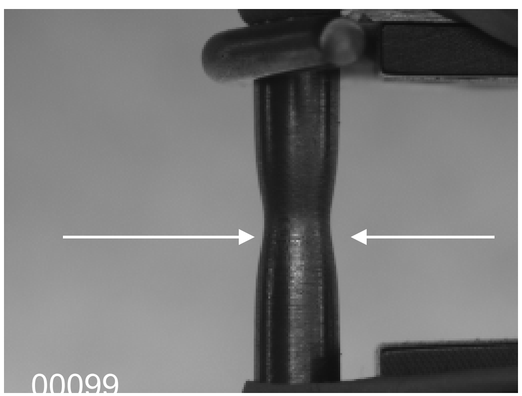
Critical Strain Testing





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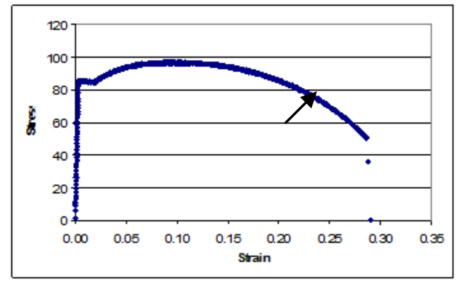

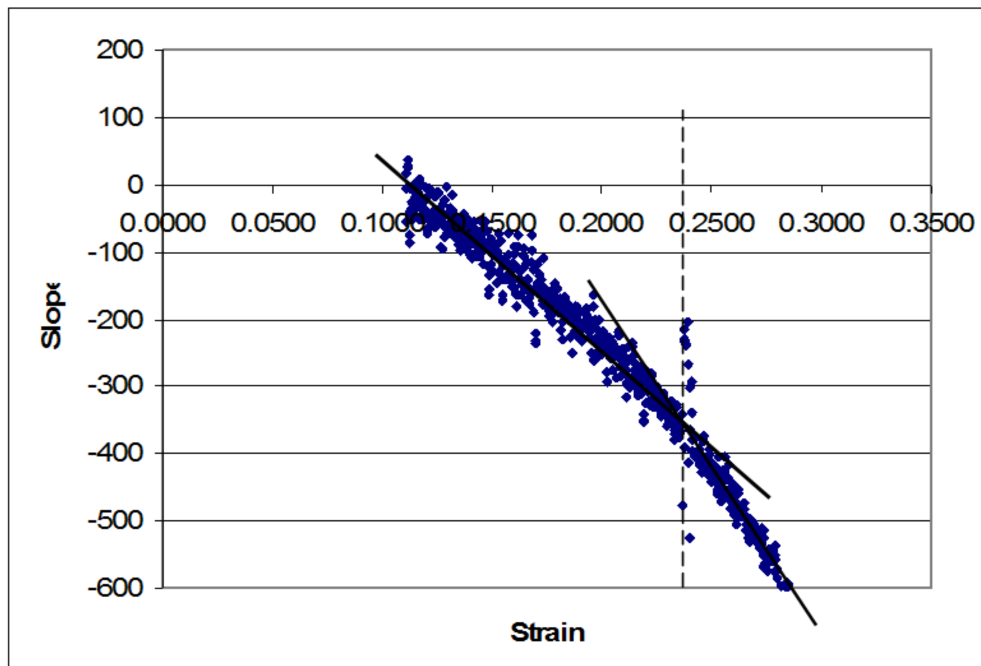

Possible Research Direction

- Further validate & refine the Point to Point Strain estimates against FEA
- Continue to compare the presence of defects (cracks) versus the strain output from these dents
- Review possible dent criteria that considers
  - Critical strain as a material property for a series of pipeline material
  - Evaluate the possibility of using Critical strain and / or DFDI parameter
    - Conduct 2-D/3-D FEA and evaluate the failure criteria
- Adopt Ductile Failure model developed by Hancock et. Al. using Rice and Tracey micromechanics model
- Material testing to determine $\varepsilon_{critical}$ for a series of steel grades and vantage
- FEA and analytical work to establish strain limit for dent for a series o steel grades
    - Utilize 2-D or 3D FEA model
    - Strain-Stress analysis
- SCC susceptibility and fatigue analyses

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Fundamental Questions

- What do we have?
    - **Generic methods: API 579-2000, BS7910:1999**
    - **Pipeline specific methods: NG-18, PFC40, CorLas**
- How do we select?
    - **Reliable, conservative and cost-effective**
    - **Advantages and limitations**
    - **Consistency**
- What do we need?
    - **A consistent guidance**
    - **Standard code or a standard procedure**
- Are we ready?
    - **To develop a standard**
    - **To adopt a method as the standard**
    - **Critical Review can help**

Crack Assessment Requires An Appropriate Tool

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What Do We Have?

– Generic Methods

- **BS 7910:1999**
  - **British Standard**
  - **Two failure mechanisms: brittle fracture and plastic collapse**
  - **Failure Assessment Diagram (FAD) depicts the interaction between fracture and plastic collapse.**
- **API Recommended Practice 579 -2000**
  - **API 579 is the US equivalent of BS 7910**
  - **Similarity and Differences**
- **Either one can be used**
  - **The choice of the methods solely depends on user's preference and regional regulations**
- **The earliest application of FAD method to pipeline integrity Assessment: 1995**

Failure Assessment Diagram (FAD) Methods

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What Do We Have

– Pipeline Specific Methods (Non FAD methods)

- **NG-18 (LnSecant) Method (1972-)**
  - Two failure criteria:
    - » Toughness dependent failure
    - » Flow stress dependent failure
    - » Assessment separately
  - Based on Dugdale Yield Strip Model
  - Widely used and has been Included in recent M. Baker's report

- **PAFFC (pipe axial flaw failure criteria)**
  - Developed Under PRCI research program
  - Non-linear fracture mechanics based failure model (PAFFC, PCORR, DYNAFRAC)

- **CorLas**
  - Developed by CC Technologies
  - Two failure criteria
  - Inelastic fracture mechanics (J-integral)

Two Failure Criteria – Non-FAD Methods (FAD)

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Possible Research/Development

- Currently ongoing with one operator funding
  - Undertaking burst testing to compare and contrast all these methodologies
- Additional testing and more evaluation will be necessary