Strain-Based Design and Assessment in Critical Areas of Pipeline Systems with Realistic Anomalies

DTPH56-14-H-00003

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Final Project Closeout Meeting

8/29/2017

Overview of the Presentation

- Overview of strain-based design and assessment (SBDA)
- Overview of guidelines and guidelines for material specifications
- Guidelines for strain-based assessment of corrosion anomalies
- Guidelines for SBDA of girth welds
- Guidelines for strain-based assessment of dents

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Overview of Strain-Based Design and Assessment

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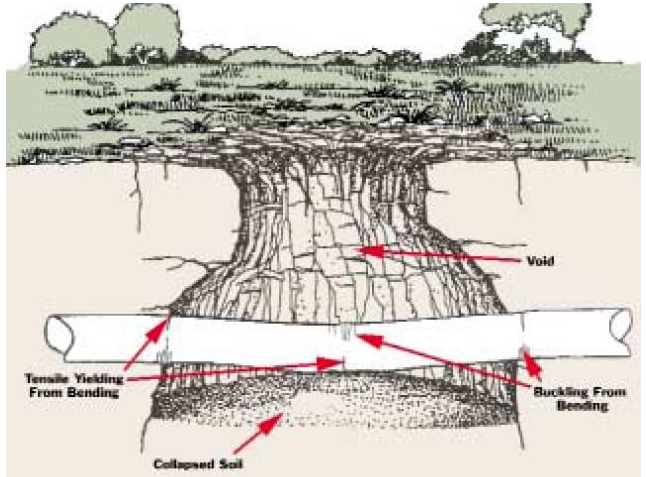
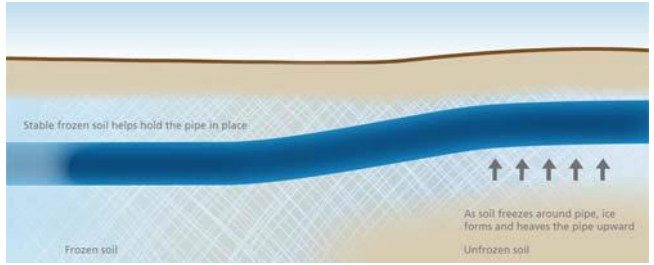
Part I Overview of Strain-Based Design and Assessment

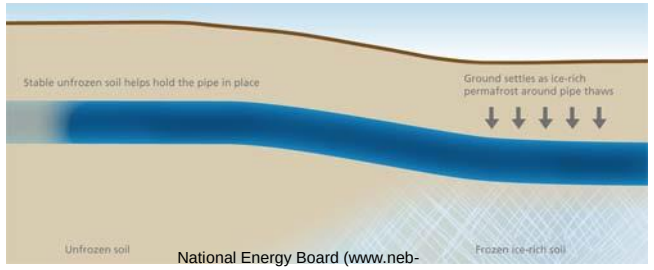
- For general conceptual understanding
- No time to get into the depth at this meeting
- References are available.

SBDA vs. Pipeline Service Life

- SBDA focuses on pipeline integrity under potentially high longitudinal stresses/strains.



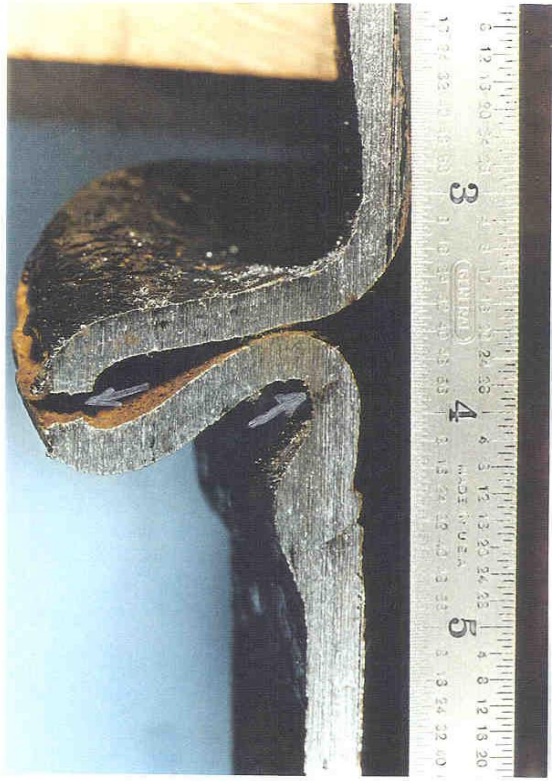




National Energy Board (www.neb-one.gc.ca)

Failure Modes Associated with SBDA – Immediate Concern

- Tensile rupture at girth welds
- At severe wrinkles
  - Circumferential crack due to overstraining in the longitudinal direction
  - Seam weld integrity due to high hoop strain



Failure Modes Associated with SBDA – Delayed Failures

- Fatigue at wrinkles
- Corrosion under high longitudinal strain
  - Spiral corrosion on tape-coated pipes
  - Corrosion at girth welds

A Few General Concepts

- Stress-based design
  - Puts focus on the control of internal pressure
  - Hoop stress is usually higher than longitudinal stress in most cases
  - There are design criteria limiting longitudinal stress (ASME B31.4 and B31.8). However, these limits are not enforced at the same rigorous level as internal pressure limit.
- Strain-based design
  - Focuses on the impact of high longitudinal stresses/strains.
  - Strain-based design is often an addition to the stress-based design, not a replacement for stress-based design.
  - Strain-based “design” is meant for new pipelines.
- Strain-based assessment
  - Assess the integrity of in-service pipelines under high longitudinal strains.

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Applications of SBDA

- Strain-based design and strain-based assessment employ the same underlining principles and procedures.
- Strain-based design
  - Hazards are considered in the design phase.
  - More knobs to turn
    - ►Selection of pipes (grade, wall thickness, etc.)
    - ►Material specifications
    - ►Welding and NDT
  - Initial conditions are better known than in-service pipelines.
    - ►Pipeline centerline, imperfections
    - ►Records are available.
- Strain-based assessment
  - Hazards may be identified in service.
  - Material property and other records may not be readily available or insufficient.
  - Prior strain history may not be available.

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Strain-Based Design – PHMSA Special Permit Conditions

- Design and Materials
  - Pre-production qualification of plate/coil mills and pipe manufacturers
  - Material specifications and associated testing (including the needs to specify non-standardized tests)
  - Separation of strain demand and strain capacity (safety factor)
  - Considerations for hoop strain from local buckles and wrinkles
- Construction and Commissioning
  - Girth weld procedure qualification
  - ECA and associated testing and tensile strain models
  - Construction quality monitoring and quality assurance
  - Initial run of deformation tool

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Strain-Based Design – PHMSA Special Permit Conditions

- Grounding and cathodic protection
- Right-of-way monitoring
- Operation and Maintenance (O&M)
  - O&M procedure document
  - Geospatial mapping including the frequency of runs and reporting requirements
  - Coating disbondment and cathodic protection
  - Interference currents control
  - Data integration
  - Remediation, including varying levels of response time
  - Report to regulators, depending on the strain level

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Design and Assessment Framework

- ε_d(strain demand) ≤ ε_d^L (strain demand limit)
  - ε_d^L (strain demand limit) = f (safety factor) ×ε_c (strain capacity)
  - Strain capacity
    - ►Tensile strain capacity (TSC)
    - ►Compressive strain capacity (CSC)
- Integrity can be achieved by (1) increasing capacity, (2) reducing demand, (3) or both
- Tensile strain models
  - Targeting new construction, relatively high strain demand
    - ►PRCI-CRES (PHMSA), ExxonMobil, SINTEF, JFE, University of Gent, TWI
  - Assessment of vintage pipelines
    - ►PRCI projects by CRES: (1) assessment models, (2) material properties, (3) flaw characteristics
- Compressive strain models
  - Existing codes: CSA Z662, API RP 1111, DNV OS F101
  - Other existing models: University of Alberta, JFE, C-FER, CRES (PHMSA)

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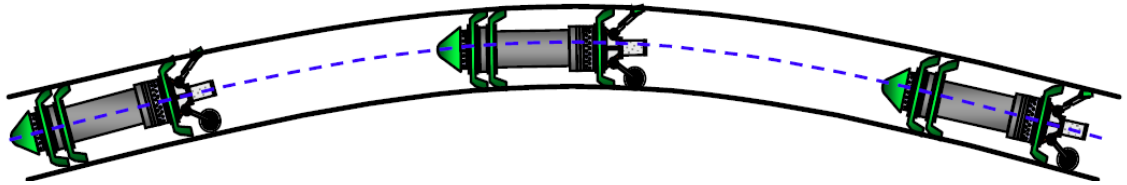
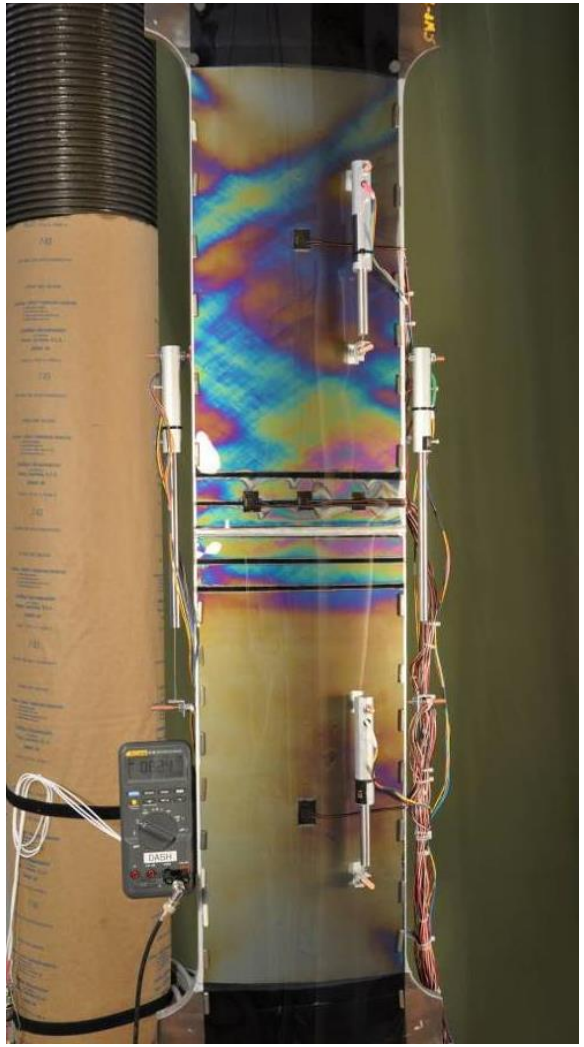
Gaps and Area for Improvement

- Inconsistent measures of strain demand and strain capacity
  - Strain demand
    - ►IMU: bending strain, gage length, initial state, tie-down points
    - ►Strain gage: local measurement

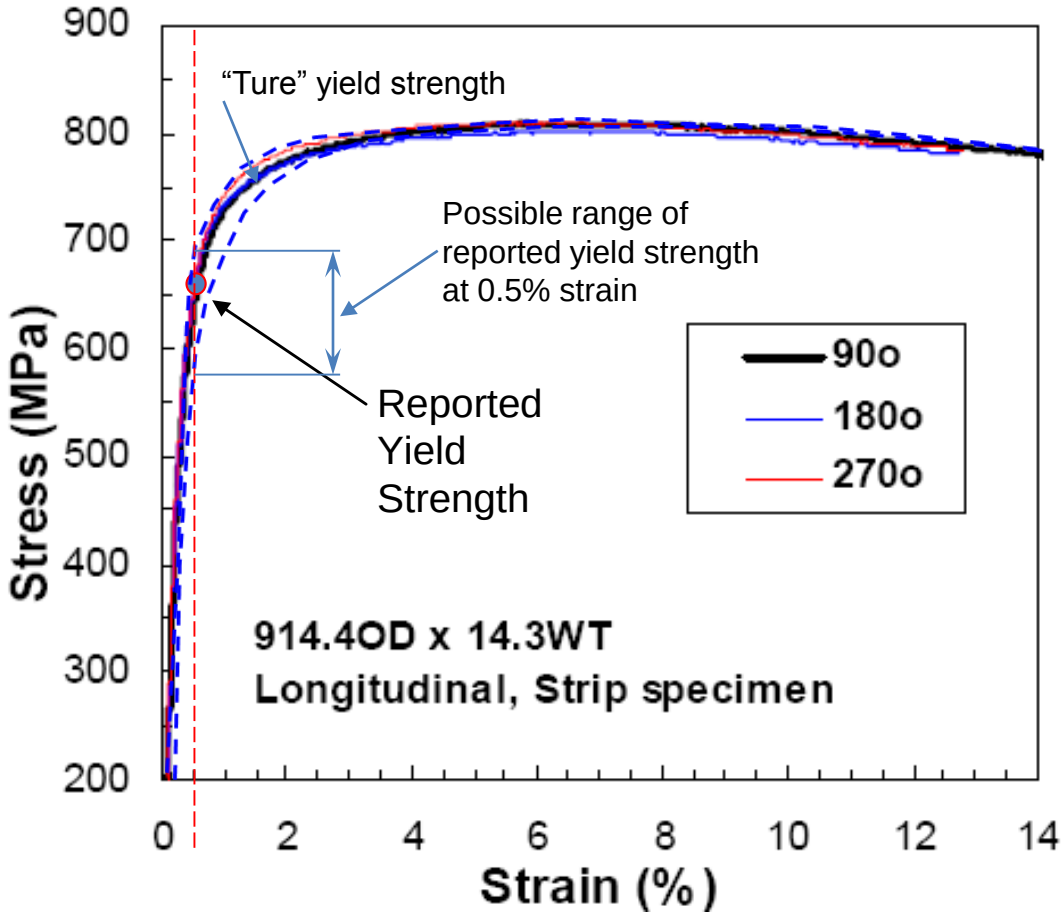


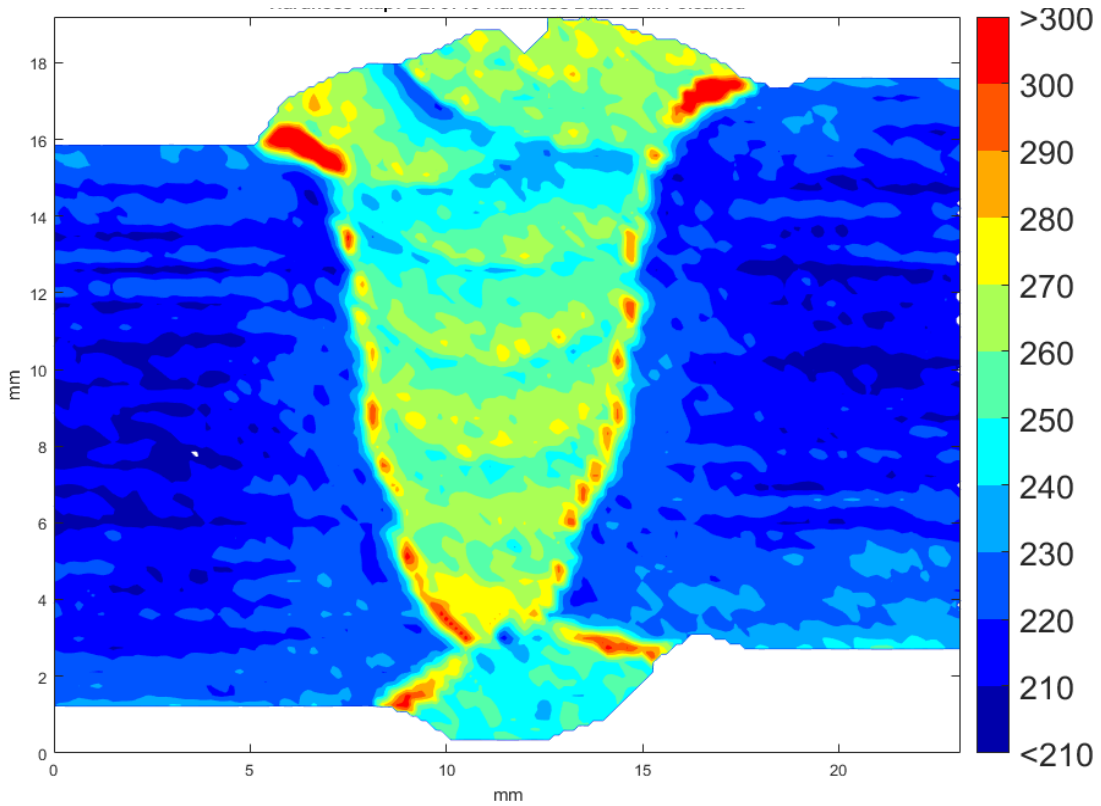


  - Strain capacity: TSC and CSC
    - ►Loading mode of test specimen
      - Uniform tension/compression vs. bending
      - With or without internal pressure
    - ►Scale and size of the specimen
    - ►Location of strain measurement
    - ►Gage length of the measurement

Gaps and Area for Improvement

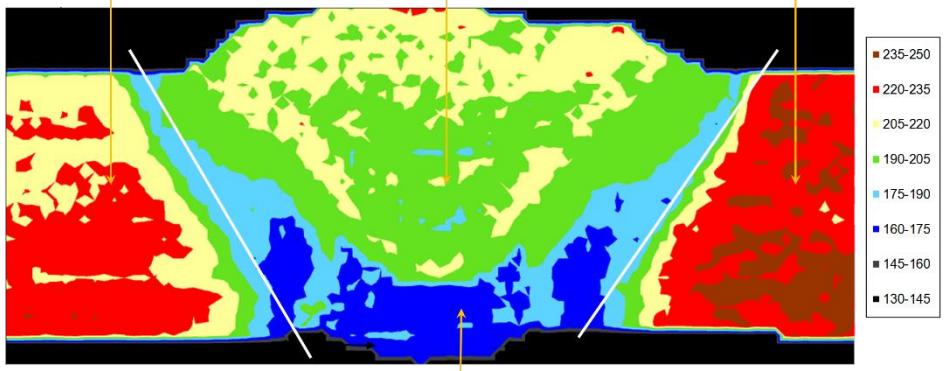
- Linepipe specifications
  - What to specify and how
  - Test methods to support the specifications, e.g., weld strength mismatch



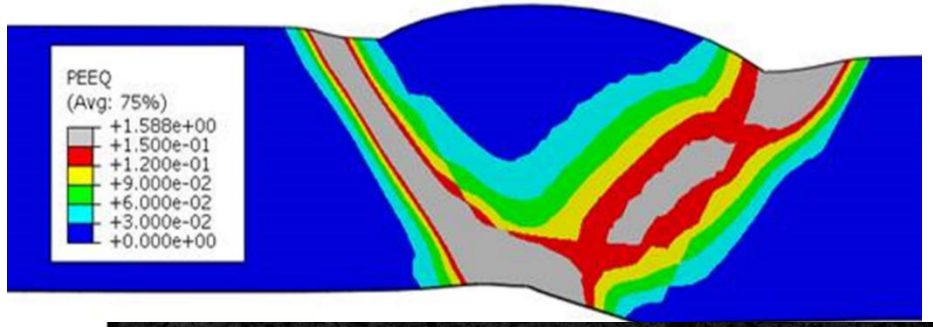


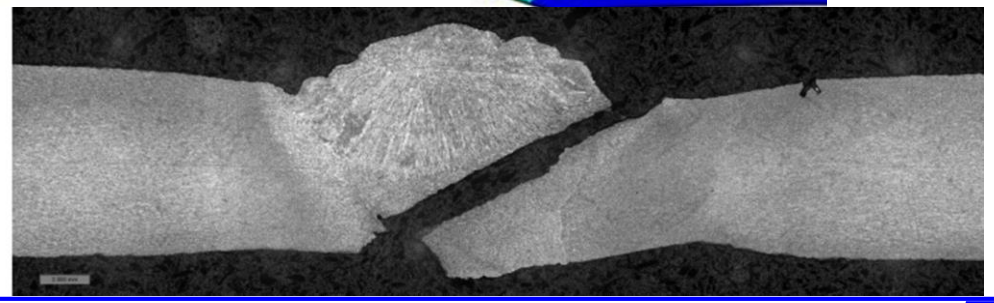
Gaps and Area for Improvement

- Girth welding practice
  - Mechanized GMAW has been the focus of TSC work.
  - Manual welds are more likely to be problematic.
    - ►At high stress locations
    - ►Limited selection of welding processes and high strength and tough consumables
    - ►HAZ properties
    - ►Potentially poor fit-up
    - ►Requirements in codes and standards are insufficient for high-strain applications



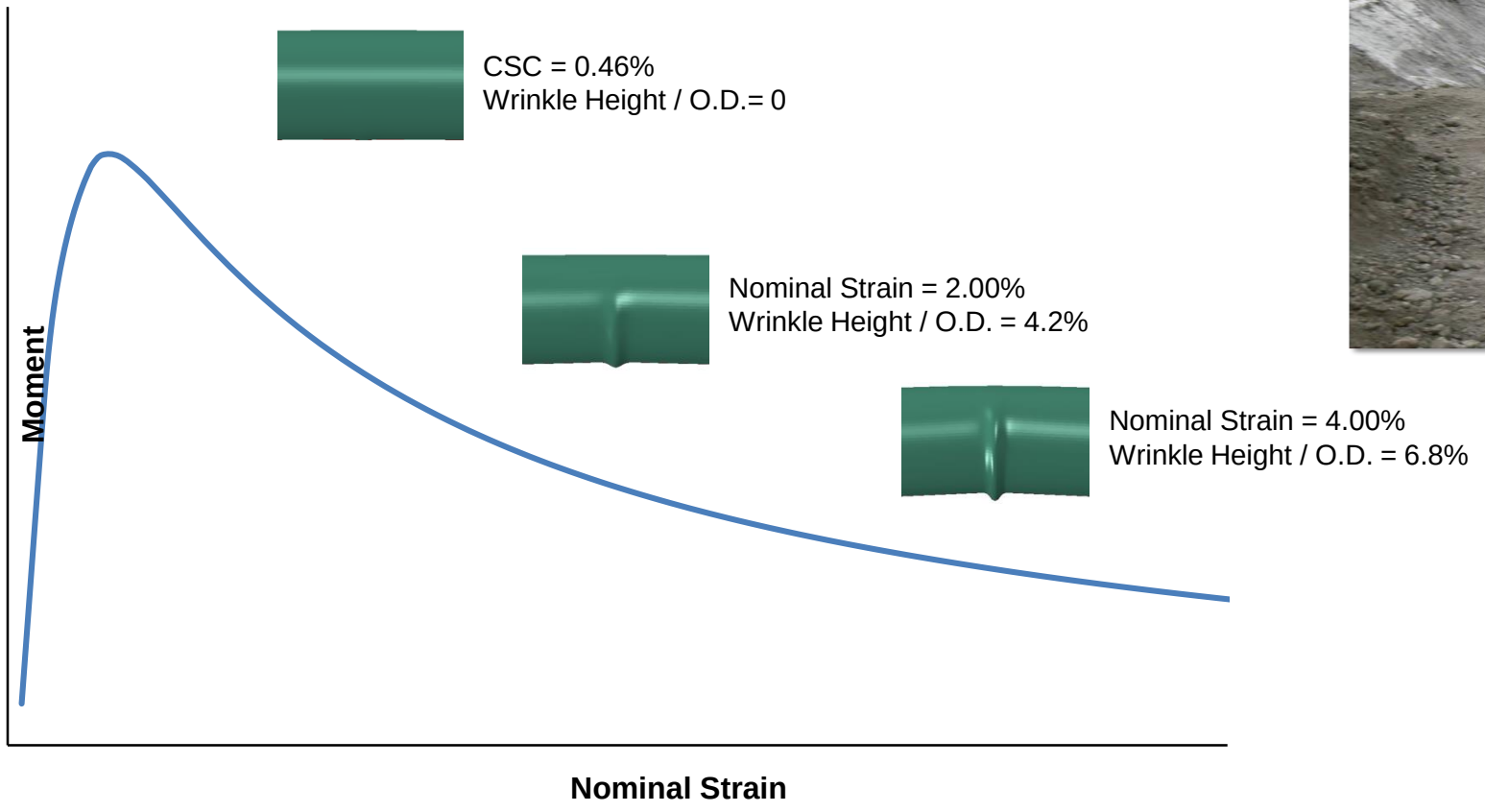
- **X70, early 2010's**
- **GW: Manual SMAW**





Gaps and Area for Improvement

- Significance of wrinkles and CSC



Gaps and Area for Improvement

- Interaction of high longitudinal strain and anomalies from corrosion or mechanical damage
  - Present assessment methodology on those anomalies was established
    - ►under the condition of small longitudinal strain
    - ►Hoop stress level is higher than longitudinal stress level
  - Would the behavior of those anomalies change under high longitudinal strain?
    - ►Strain capacity
    - ►Burst pressure
  - Depth and spatial precision of ILI and in-ditch tools
- SBDA with transition welds of fittings (bends, elbows, tees, etc.), i.e., transition welds
  - Mechanics
    - ►Prevention of strain concentration
    - ►Strain capacity
  - Welding/inspection
    - ►Qualification, flaw detection, and monitoring of field practice
  - Code requirements falling behind, e.g., post weld heat treatment when WT>1.25 inch

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Overview of Guidelines and Guidelines for Material Specifications

List of Guidelines

- Material specifications for strain-based design
- Corrosion anomalies
  - Assessment of tensile rupture – tensile strain capacity (TSC)
  - Assessment of compressive buckling – compressive strain capacity (CSC)
  - Assessment of burst – burst pressure
- Girth welds
  - Assessment of tensile rupture – TSC
  - Assessment of compressive buckling – CSC
- Plain dents
  - Assessment of compressive buckling – CSC
- Assessment levels:
  - Level 1: assessment diagrams and/or equations
  - Level 2: finite element analyses

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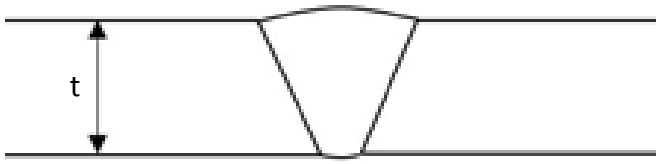
Guidelines for Material Specifications

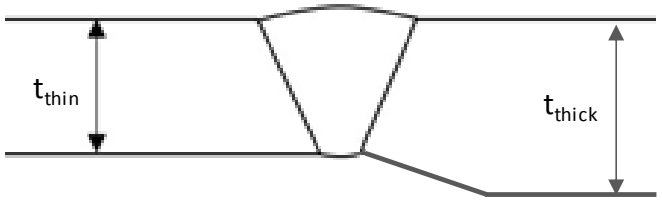
- General guidelines for material specifications
  - Upper and lower bound pipe longitudinal properties including yield strength, tensile strength, uniform strain, and pipe Y/T ratio;
    - ►*Note: it is recommended to request pipe longitudinal properties including yield strength, ultimate tensile strength, uniform strain, and Y/T ratio in mill certificates (MTRs).*
  - Upper and lower bound full pipe stress-strain curves in longitudinal and circumferential directions; and
    - ►*Note: it is recommended to request full pipe stress-strain curves in both longitudinal and circumferential directions in mill certificates (MTRs).*
  - The effects of pipe coating (such as preparation and application temperatures and times) on pipe properties should be considered.

Transition Girth Welds

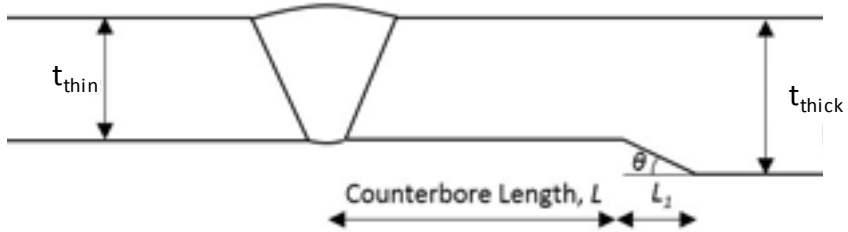
- Transition welds: joining two pipes of different wall thicknesses



Regular



Back-Beveled



Counterbore-Tapered

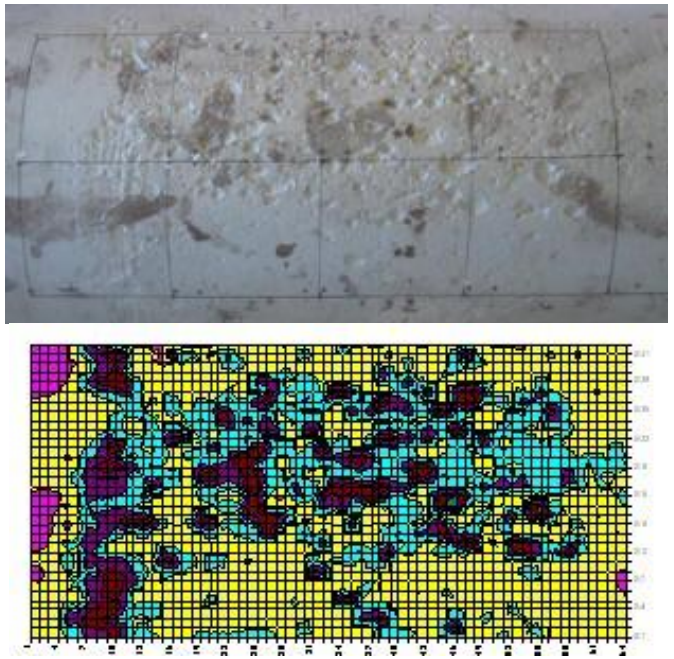
Guidelines for Material/Thickness Specifications for Transition Welds

- Counterbore-tapered welds:
  - The longitudinal yield and ultimate tensile strengths of the thick-wall pipe should not be less than those of the thin-wall pipe.
  - The (circumferential) specified minimum yield strength (SMYS) of the thick-wall pipe should not be less than the SMYS of the thin-wall pipe.
  - If the wall thickness ratio is greater than 1.50, the wall thickness ratio should be treated as a maximum of 1.50 for design and assessment.
- Back-beveled welds:
  - The longitudinal ultimate tensile strength of the thick-wall pipe should not be less than the longitudinal flow strength of the thin-wall pipe, where the flow strength of the thin-wall pipe is the average of the yield strength and ultimate tensile strength of the thin-wall pipe.
  - $R_t \geq \max(R_G, R_y, R_u)$, where R_t is the ratio between the thickness of thick-wall pipe and that of the thin-wall pipe; R_G is the ratio between the (circumferential) SMYS of thin-wall pipe and that of the thick-wall pipe; R_y is the ratio between the longitudinal yield strength of thin-wall pipe and that of the thick-wall pipe; R_u is the ratio between the longitudinal ultimate tensile strength of the thin-wall pipe and that of the thick-wall pipe.
  - If the wall thickness ratio (R_t) is greater than 1.50, the wall thickness ratio should be treated as a maximum of 1.50 for design and assessment.

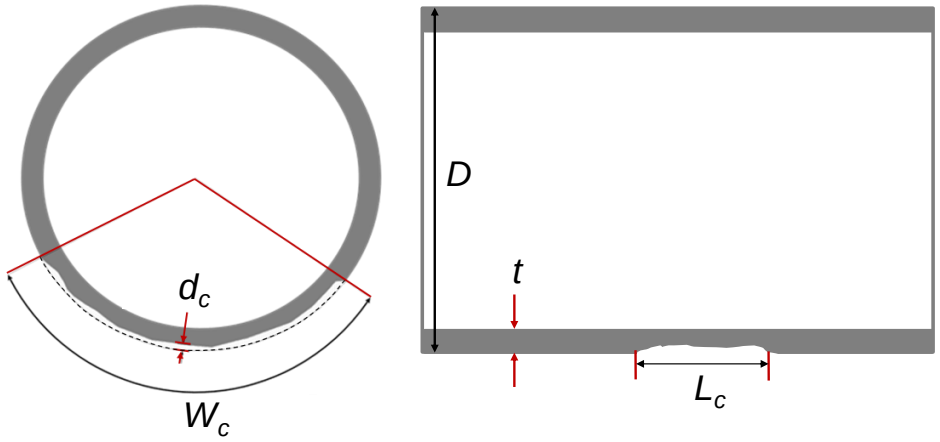
Guidelines for Strain-Based Assessment of Corrosion Anomalies

Corrosion Anomalies

- Corrosion and dimensions needed for strain-based assessment
  - Depth (d_c)
  - Longitudinal length (L_c)
  - Circumferential width (W_c)



(www.swri.org)



Acceptable Applications

- Acceptable Applications
  - Metal loss type of corrosion anomalies on pipe inside or outside surface, including general corrosion, longitudinal and circumferential grooves that are not too sharp (see Exclusions in the next section), and pitting; and
  - Pipe segments subjected to displacement-controlled longitudinal loading, e.g., stable slope movement.
- Exclusions
  - Crack-like planar anomalies such as stress corrosion cracks;
  - Slotting/groove corrosion with the short dimension in the pipe longitudinal or circumferential direction smaller than one pipe wall thickness;
  - Corrosion anomalies interacting with other anomalies (e.g., gouge, dent, etc.) or girth/seam welds;
  - Interacting corrosion anomalies;
  - Pipe materials showing creep behaviors under operating conditions; and
  - Pipe segments subjected to load-controlled longitudinal loading, e.g., free span.
- Failure modes
  - Burst, tensile rupture, and compressive buckling

ASME Burst Pressure Equations for Corroded Pipes

❑ ASME B31G Equation

❖

$$P_b = \begin{cases} \dfrac{2t}{D} S_{flow} \left[\dfrac{1 - \frac{2}{3}(d_c/t)}{1 - \frac{2}{3}(d_c/t)/M} \right], & \dfrac{L_c^2}{Dt} \le 20 \\ \dfrac{2t}{D} S_{flow} \left(1 - (d_c/t)\right), & \dfrac{L_c^2}{Dt} > 20 \end{cases}$$

❖ Folias factor

$$M = \left[1 + 0.8\, L_c^2 / Dt\right]^{1/2}$$

❖ S_{flow}

- ►1.1 × SMYS
- ►Not exceed SMTS

❑ Modified ASME B31G Equation

❖

$$P_b = \frac{2t}{D} S_{flow} \left[\frac{1 - 0.85(d_c/t)}{1 - 0.85(d_c/t)/M} \right]$$

❖ Folias factor

$$M = \begin{cases} \left[1 + 0.6275\, L_c^2/Dt, -0.003375\, \left(L_c^2/Dt\right)^2\right]^{1/2}, & \dfrac{L_c^2}{Dt} \le 50 \\ 0.032\, L_c^2/Dt + 3.3, & \dfrac{L_c^2}{Dt} > 50 \end{cases}$$

❖ S_{flow}

- ►SMYS+10 ksi, SMYS ≤ 70 ksi
- ►(SMYS + SMTS)/2, SMYS ≤ 80 ksi
- ►Not exceed SMTS

Assessment of Burst Pressure with Longitudinal Compressive Strain

- Step 1: Determine the burst pressure (P_b) of the pipe segment for no longitudinal load from existing standards, e.g., ASME B31G
- Step 2: Determine the burst pressure ($P_b^{\varepsilon_c}$) of the segment subjected to the longitudinal compressive strain using the following equation:

$$P_b^{\varepsilon_c} = \gamma_b P_b \cdot \left(1.00 - 5.76\left|\varepsilon_c^{dem}\right| \cdot \gamma_{sd}\right)$$

γ_b : safety factor applied to burst pressure (≤ 0.80 if no safety factor applied to P_b, otherwise 1.0)

$\left|\varepsilon_c^{dem}\right|$: magnitude of longitudinal compressive strain demand (unit mm/mm or in/in)

γ_{sd} : safety factor applied to strain demand (> 1.0)

- Applicable ranges
  - Corrosion Dimensions: $L_c/\sqrt{Dt} \leq 1.3$, $W_c/\sqrt{Dt} \leq 1.3$, $d_c/t \leq 0.4$, $L_c > t$, $W_c > t$
  - Longitudinal Compression Strain: $0 \leq \left|\varepsilon_c^{dem}\right| \cdot \gamma_{sd} \leq 0.02$

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Determine the Required Parameters

- The strain demand should be the average compressive strain within a 2D gauge length centered at the location of the corrosion (D is the pipe outside diameter).
- The strain demand should be obtained at the operational state of interest (during operations). It can be obtained through IMU strain measurements or from strain demand numerical simulations (e.g., pipe-soil interaction simulations).
- It should be noted that IMU tools measure only bending strain. The membrane compressive strain due to other effects such as the temperature effect should be estimated and added to the measured bending strain.
- For the strain demand numerical simulations, the corrosion anomaly should be built in the simulation models.

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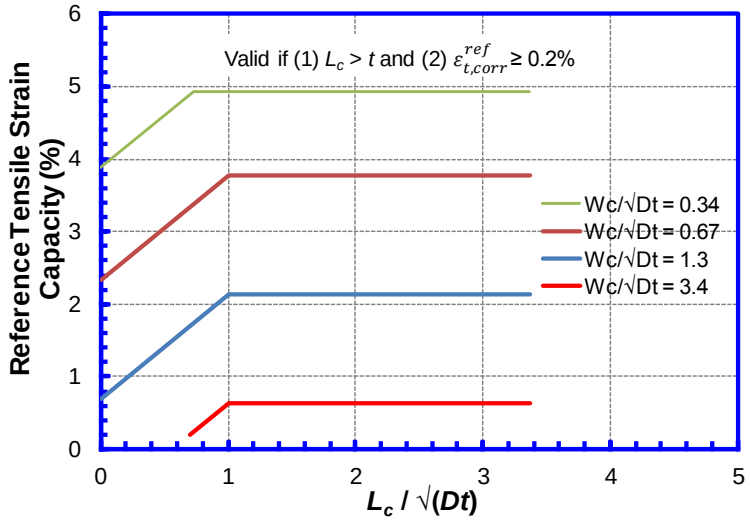
About Tensile Strain Capacity

- Definition of tensile strain capacity (TSC)
  - The maximum tensile strain before leak or rupture
  - The capacity to accommodate global/nominal longitudinal tensile strain induced by tension or bending
  - Should not reflect the local strain concentration in/near the corrosion area.
- Application of TSC
  - For tension and bending dominant deformation
  - Proper measure of strain demand
    - ►Avoid the effect of the strain concentration in the corrosion area on the strain demand measurement
    - ►Strain demand measured from IMU
      - Gauge length for strain demand calculation vs. anomaly size
      - Bending and membrane strain component
    - ►Strain demand calculated with FEA (pipe-soil interaction)

Assessment of Tensile Strain Capacity

- Step 1 – Calculate reference tensile strain capacity of a pipe with corrosion



$d_c/t \leq 0.25$

D	Pipe outside diameter
t	Pipe nominal wall thickness
L_c	Length of a corrosion anomaly in pipe longitudinal direction
W_c	Length of a corrosion anomaly in pipe circumferential direction
d_c	Depth of corrosion anomaly
$\varepsilon_{t,corr}^{crit}$	Tensile strain capacity of a pipe with corrosion anomaly
$\varepsilon_{t,corr}^{ref}$	Reference tensile strain capacity of a pipe with corrosion anomaly
f_p	Pressure factor
R_{YT}	Yield to tensile strength ratio, or Y/T ratio

- Step 2 – Determine the tensile strain capacity using the following equation

$$\varepsilon_{t,corr}^{crit} = \begin{cases} \gamma_t \varepsilon_{t,corr}^{ref}, & R_{YT} \leq 0.83 \\ \gamma_t \varepsilon_{t,corr}^{ref}\left(-7.14 R_{YT} + 6.92\right), & R_{YT} > 0.83 \end{cases}. \qquad \gamma_t \leq 0.60$$

- Application range
  - Corrosion Dimensions: $L_c/\sqrt{Dt} \leq 3.4$, $W_c/\sqrt{Dt} \leq 3.4$, $d_c/t \leq 0.25$, $L_c > t$, $W_c > t$
  - Pipe Material Properties: $R_{YT} \leq 0.92$
  - Internal Pressure: $f_p \leq 0.80$
  - Reference Tensile Strain: $\varepsilon_{t,corr}^{ref} \geq 0.2\%$

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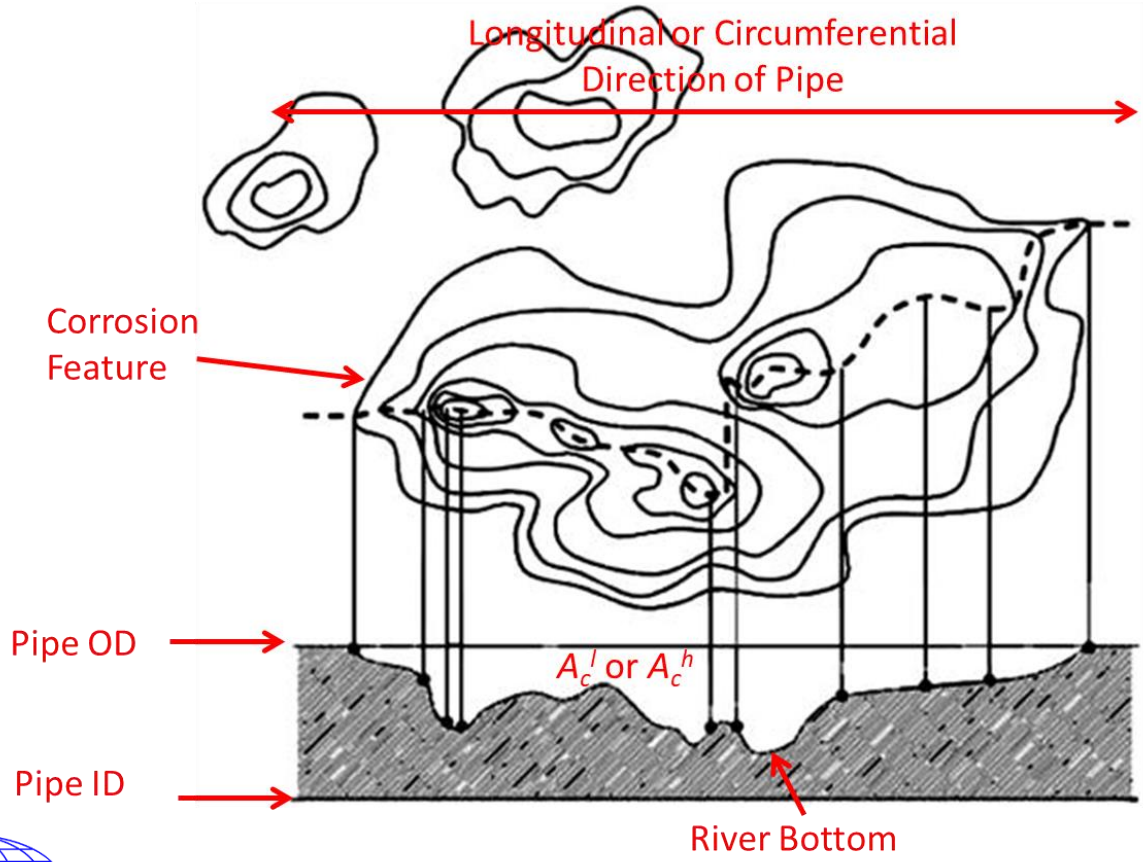
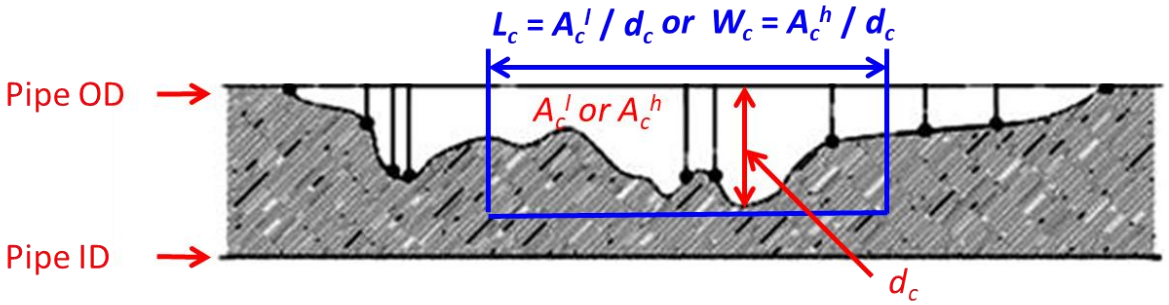
Determine the Required Parameters

- Determine the depth (d_c), circumferential width (W_c), and longitudinal length (L_c) of the corrosion anomalies.
  - Option I:
    - The depth (d_c) is the maximum depth in the metal loss area.
    - The width (W_c) and length (L_c) should be determined using the procedures in Section 5.3.3 of API 579.
    - If there are circumferential grooves inside a general corrosion, the smallest L_c of all the circumferential grooves should be used as the longitudinal length (L_c) of the anomaly.

Determine the Required Parameters

- Determine the depth (d_c), circumferential width (W_c), and longitudinal length (L_c) of the corrosion anomalies.
  - Option II: Determine the above parameters using river bottom profiles and equivalent area methods (not applicable for general corrosion containing circumferential grooves inside).





Determine the Required Parameters

- Pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T
  - Use the upper-bound Y/T ratio in the longitudinal direction
    - ►Use the Y/T ratio of the actual pipe joint if it's available
    - ►If the actual pipe Y/T ratio is not available, the upper-bound Y/T ratio should be estimated by considering the pipe grade, vintage, chemical composition, type (e.g., UOE, ERW, etc.), strength range (e.g., in project specifications, relevant pipe standards (e.g., API 5L), or mill certificates), properties of similar pipes on the same pipeline, and/or pipe coating conditions. For modern micro-alloyed linepipe steels, if proper pipe coating procedures are followed to avoid the change of pipe properties, the following can be used as a starting point.

$$R_{YT} = \max\left(0.84, \frac{1}{1+2\left(21.75/\sigma_{SMYS}\right)^{2.30}}\right).$$

Grade	X52	X56	X60	X65	X70	X80
API 5L Upper-bound Y/T ratio	0.93	0.93	0.93	0.93	0.93	0.93
Equation Estimation	0.84	0.84	0.84	0.86	0.88	0.91

►*Note: If the pipe Y/T ratio in the circumferential direction is significantly higher than that in the longitudinal direction, using the Y/T ratio of the longitudinal direction can overestimate the strain capacity. For such circumstances, it is recommended to use the average of the Y/T ratios in the longitudinal and circumferential directions to calculate the strain capacity.*

Determine the Required Parameters

- Pipe yield strength (σ_y)
  - Use the lower-bound pipe yield strength in the longitudinal and circumferential directions
    - ►Use the strength of the actual pipe joint if it's available
    - ►If the actual pipe strength is not available, the lower-bound strength should be estimated by considering the pipe grade, vintage, chemical composition, type (e.g., UOE, ERW, etc.), strength range (e.g., in project specifications, relevant pipe standards (e.g., API 5L), or mill certificates), properties of similar pipes on the same pipeline, and/or pipe coating conditions.

About Compressive Strain Capacity

- Definition of compressive strain capacity (CSC)
  - The compressive strain corresponding to the maximum bending moment the corroded pipe can withstand
  - The capacity of the pipe to accommodate global/nominal longitudinal bending deformation
  - Should not reflect the local strain concentration in/near the corrosion area.
- Application of CSC
  - For bending dominant deformation
  - Measure of strain demand
    - ►Avoid the effect of the strain concentration in the corrosion area on the strain demand measurement
    - ►Strain demand measured from IMU
      - Gauge length for strain demand calculation vs. anomaly size
      - Bending and membrane strain component
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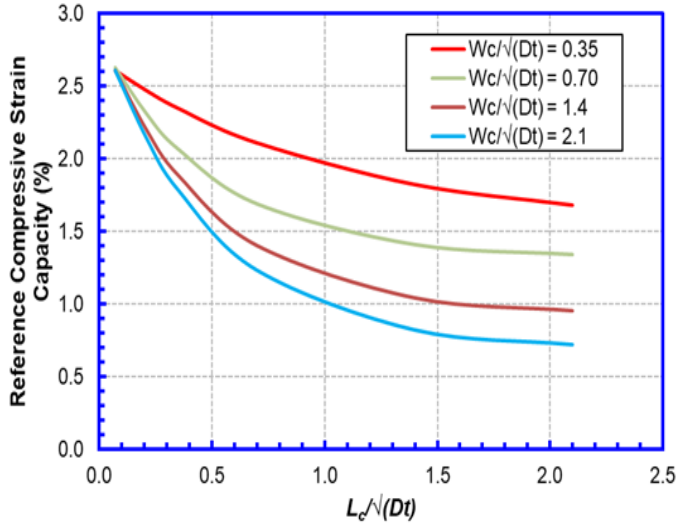
Assessment of Compressive Strain Capacity

- Step 1 – Calculate reference compressive strain capacity of a pipe with corrosion



$d_c/t \leq 0.25$

D	Pipe outside diameter
t	Pipe nominal wall thickness
L_c	Length of a corrosion anomaly in pipe longitudinal direction
W_c	Length of a corrosion anomaly in pipe circumferential direction
d_c	Depth of corrosion anomaly
$\varepsilon_{c,corr}^{crit}$	Compressive strain capacity of a pipe with corrosion anomaly
$\varepsilon_{c,corr}^{ref}$	Reference compressive strain capacity of a pipe with corrosion anomaly
f_p	Pressure factor
R_{YT}	Yield to tensile strength ratio, or Y/T ratio

- Step 2 – Determine the compressive strain capacity using the following equation

$$\varepsilon_{c,corr}^{crit} = \gamma_c \varepsilon_{c,corr}^{ref} F_{DP}, \quad F_{DP} = 539.3 \cdot (2.87 - 2.13 R_{YT}) \left(\frac{D}{t}\right)^{-1.6}.$$

$$\gamma_c \leq 0.80$$

- Application range
  - Pipe Dimensions: $20 \leq D/t \leq 51$
  - Corrosion Dimensions: $L_c/\sqrt{Dt} \leq 2.1$, $W_c/\sqrt{Dt} \leq 2.1$, $d_c/t \leq 0.25$, $L_c > t$, $W_c > t$
  - Pipe Material Properties: $0.84 \leq R_{YT} \leq 0.88$
  - Internal Pressure: $f_p \geq 0.72$

Determine the Required Parameters

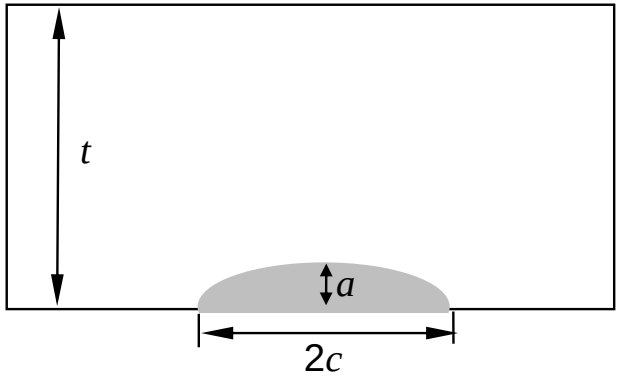
- Determine the depth (d_c), circumferential width (W_c), and longitudinal length (L_c) of the corrosion anomalies.
  - The depth (d_c) is the maximum depth in the metal loss area.
  - The width (W_c) and length (L_c) should be determined using the procedures in Section 5.3.3 of API 579.
- Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T
  - The upper-bound Y/T ratio in the longitudinal direction should be used.
- Determine the pipe yield strength (σ_y).
  - The upper-bound pipe yield strength in the longitudinal and circumferential directions should be used.

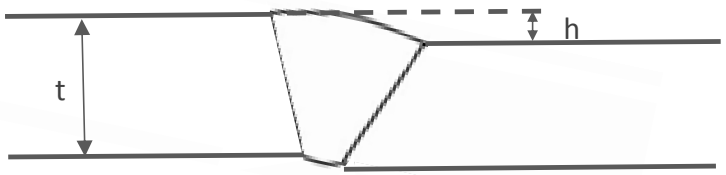
Guidelines for Strain-Based Design and Assessment of Girth Welds

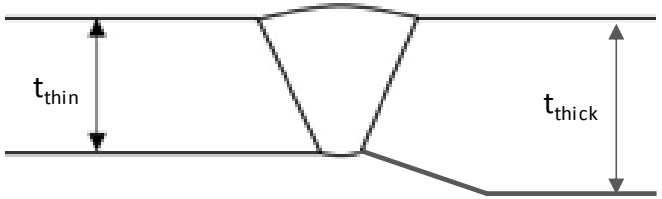
Girth Welds

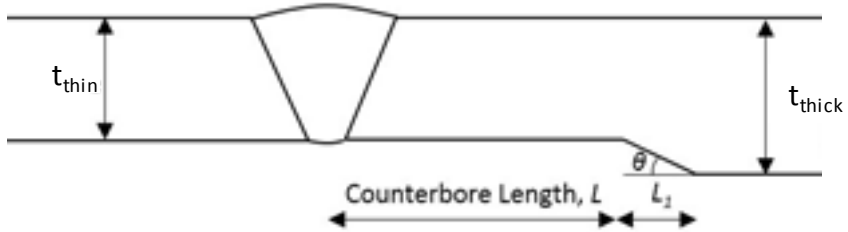
- Weld anomalies and geometry discontinuities

Surface Anomaly









Acceptable Applications

- Acceptable Applications
  - Girth welds containing crack-like surface-breaking planar anomalies;
    - Regular girth welds jointing pipes with equal wall thickness; and
    - Transition girth welds jointing pipes with unequal wall thickness including back-beveled joints and counterbore-tapered joints.
  - Pipe segments subjected to displacement-controlled longitudinal loading, e.g., stable slope movement.
- Exclusions
  - Girth welds interacting with other anomalies (e.g., corrosion, gouge, dent, etc.);
  - Pipe materials showing creep behaviors under operating conditions; and
  - Pipe segments subjected to load-controlled longitudinal loading, e.g., free span
- Failure modes
  - Tensile rupture and compressive buckling

About Tensile Strain Capacity

- Definition of tensile strain capacity (TSC)
  - The maximum tensile strain before leak or rupture
  - The capacity to accommodate global/nominal longitudinal tensile strain induced by tension or bending
  - Should not reflect the local strain concentration in/near the girth weld.
- Application of TSC
  - For tension and bending dominant deformation
  - Measure of strain demand
    - ►Avoid the effect of the strain concentration in the weld defect area on the strain demand measurement
    - ►Strain demand measured from IMU
      - Gauge length for strain demand calculation
      - Bending and membrane strain component
    - ►Strain demand calculated with FEA (pipe-soil interaction)

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Assessment of TSC for Regular and Counterbore Tapered Welds

- The TSC of the regular and counterbore-tapered girth welds can be determined as

$$\varepsilon_{t,gw}^{crit} = \gamma_{t,gw}\varepsilon_t^{crit} \qquad \varepsilon_t^{crit} = \min\left(\varepsilon_u, P(f_p)G(t)\varepsilon_{t,f_p}^{crit}\right) \qquad \gamma_{t,gw} \le 0.60$$

- $P(f_p)$ accounts for the effect of operating pressure on TSC

$$P(f_p) = \begin{cases} P_{max} - \frac{5f_p}{3}(P_{max} - 1) & if\ \ 0 < f_p < 0.6 \\ 1 & if\ \ 0.6 \le f_p < 0.8 \end{cases} \qquad P_{max} = 2.25 - 2\frac{a}{t}$$

- $G(t)$ accounts for the effect of pipe wall thickness on TSC

$$G(t) = \left(\frac{15.9}{t}\right)^{0.8096\left[1+1.503\left(\frac{h}{t}\right)^{1.229}\right]}$$

The unit of *t* must be mm.

- and $\varepsilon_{t,f_p}^{crit} = A\frac{f(\delta_A)}{1+f(\delta_A)}$, $f(\delta_A) = (C\delta_A)^{B(\delta_A)^D}$

A, B, C, and D are functions of flaw size, weld high-low misalignment, pipe Y/T ratio, and weld strength mismatch

ε_t^{crit} unit: mm/mm or in/in

Input parameters and applicable ranges

$0.05 \le R_a \le 0.50$,

$1.0 \le R_c \le 20$,

$R_h \le 0.2$,

$f_p \le 0.8$,

$0.2\ \text{mm}\ (0.0079\ in) \le \delta_A \le 2.5\ \text{mm}\ (0.10\ \text{in})$,

$12.7\ \text{mm}\ (0.5\ \text{in}) \le t \le 25.4\ \text{mm}\ (1.0\ \text{in})$,

$0.75 \le R_{YT} \le 0.94$, and

$1.0 \le R_M \le 1.3$.

Material and thickness specifications for counterbore tapered welds.

Assessment of TSC for Back-Beveled Welds

- The tensile strain capacity of the back-beveled transition girth weld with a safety factor can be determined as

$$\varepsilon_{t,tw}^{crit} = \gamma_{t,tw}\varepsilon_t^{crit}\left(1 - F_{tw}\right) \qquad \gamma_{t,tw} \le 0.60$$

$$F_{tw} = 0.1443 \cdot \left[\max\left(1.0, R_y\right) - 1\right]^{0.4241}\left(100 \cdot \varepsilon_t^{ref} + 3.053\right) \qquad \varepsilon_t^{ref} = \varepsilon_t^{crit}\big|_{\delta_A = 0.8\,mm}.$$

R_y is the yield strength ratio between the thin-wall pipe and thick-wall pipe.

Additional input parameters and parameters with reduced applicable ranges

$0.75 \le R_{YT} \le 0.92$,

$1.00 \le R_M \le 1.15$,

$1.00 \le R_y \le 1.25$,

Material and thickness specifications for back-beveled welds.

Determine the Required Parameters for TSC

- Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T
  - The upper-bound Y/T ratio in the longitudinal direction of the actual pipe joint
  - For transition welds, the R_{YT} of the thin-wall pipe should be used.
- Determine the pipe yield strength and ultimate tensile strengths
  - For regular girth welds, determine the upper-bound pipe yield strength and ultimate tensile strength in the longitudinal direction.
  - For transition welds, determine strengths in the longitudinal direction
    - ►the lower-bound pipe yield strength and ultimate tensile strengths of the thick-wall pipe
    - ►the upper-bound pipe yield strength and ultimate tensile strength of the thin-wall pipe
- Determine the weld ultimate tensile strength
  - The lower bound ultimate tensile strength of the weld should be used.
  - For transition welds, the weld strength mismatching should be calculated based on the thin-pipe strength.

Determine the Required Parameters for TSC

- Determine the normalized depth, normalized length of the planar anomaly and normalized high-low misalignment
  - The depth (*a*) and length (2*c*) should be determined using the procedures in Section 9.3.6 of API 579.
  - For the high-low misalignment (*h*) of the girth weld, the maximum high-low misalignment along the length of the anomaly should be used.
  - Calculate the normalized depth, normalized length of the planar anomaly and normalized high-low misalignment as
    - ►Regular Weld: a/t, $2c/t$, and h/t
    - ►Transition Weld: a/t_{thin}, $2c/t_{thin}$, and h/t_{thin}

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About Compressive Strain Capacity

- Definition of compressive strain capacity (CSC)
  - The compressive strain corresponding to the maximum bending moment the pipe can withstand
  - Two methods are used to measure the compressive strain capacity (CSC).
    - 2D CSC: follows the traditional definition of the CSC used for plain pipes, i.e., the average compressive strain within a 2D (D is the pipe outside diameter) gauge length centered at the wrinkle location. The 2D CSC is affected by the strain localization at the wrinkle.
    - CSC by extrapolation: is the strain determined in such a way that the reported CSC is not affected by the strain localization at the wrinkle. The CSC by extrapolation is designated to capture the overall capacity of the pipe to accommodate global/nominal longitudinal bending deformation.
- Application of CSC
  - For bending dominant deformation
  - Measure of strain demand
    - Strain demand measured from IMU
      - Gauge length for strain demand calculation
      - Bending and membrane strain component
    - Strain demand calculated with FEA (pipe-soil interaction)

CSC Assessment – Equations for Plain Pipes

- CSC Equations for Plain Pipes
  - 2D CSC

$$\varepsilon_c^{crit,2D} = \min(\varepsilon_u, F_{LD} * \varepsilon_r)$$

$$F_{LD} = \begin{cases} 1 - 0.50 * (1 - 0.75\varepsilon_r{}^{-0.23})\left[1 + \tanh\left(8.0\frac{\varepsilon_e}{\varepsilon_r} - 8.2\right)\right] & \text{(With Lüder's Strain)} \\ 1 & \text{(No Lüder's Strain)} \end{cases}$$

$$\varepsilon_r = F_{DP} * F_{YT} * F_{GI} * F_{NF}$$

$$F_{DP} = \begin{cases} 980 * \left[0.5\left(\frac{D}{t}\right)^{-1.6} + 1.9 * 10^{-4}\right] & if\ f_p < f_{pc} \\ 980 * (1.06f_p + 0.5)\left(\frac{D}{t}\right)^{-1.6} & if\ f_p \geq f_{pc} \end{cases}$$

$$f_{pc} = 1.8 * 10^{-4} * \left(\frac{D}{t}\right)^{-1.6}$$

$$F_{YT} = 2.7 - 2.0R_{YT}$$

$$F_{GI} = 1.84 - 1.6\left(\frac{h_g}{t}\right)^{0.2}$$

$$F_{NF} = 1.2f_n^2 + 1$$

  - CSC by extrapolation

$$\varepsilon_c^{crit,ex} = 1.03 * \varepsilon_c^{crit,2D} - 0.20$$

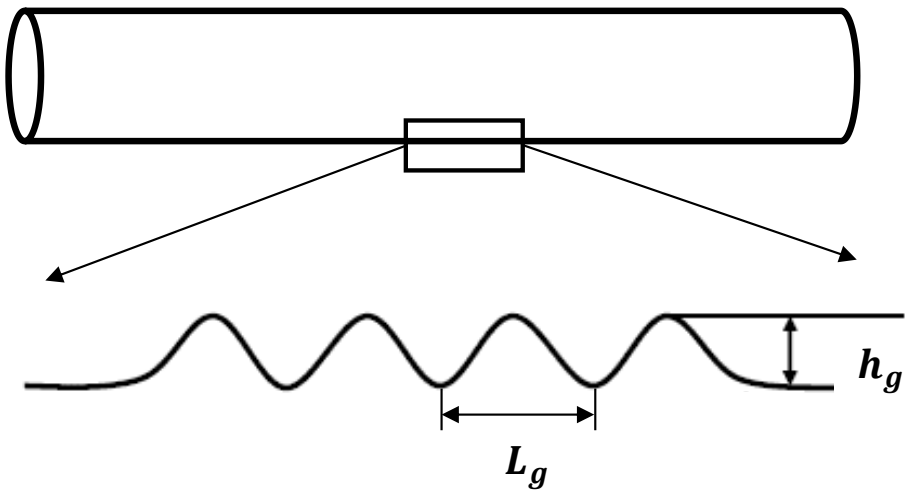
Variables	Unit	Description
$\varepsilon_c^{crit,2D}$	%	2D CSC
ε_u	%	Pipe uniform strain
ε_e	%	Strain where the Lüders extension ends
ε_r	%	Reference strain
f_p		Pressure factor
h_g	mm	Height of geometry imperfection
f_n		Net-section stress factor
D	mm	Pipe OD
t	mm	Pipe wall thickness
R_{YT}		Pipe Y/T ratio

Input Parameters	Applicable Range
D/t	(20, 104)
f_p	(0.0, 0.8)
R_{YT}	(0.70, 0.96)
h_g/t	(0.01, 0.30)
ε_e (%)	(0, 2.0)
f_n	(0, 0.40)

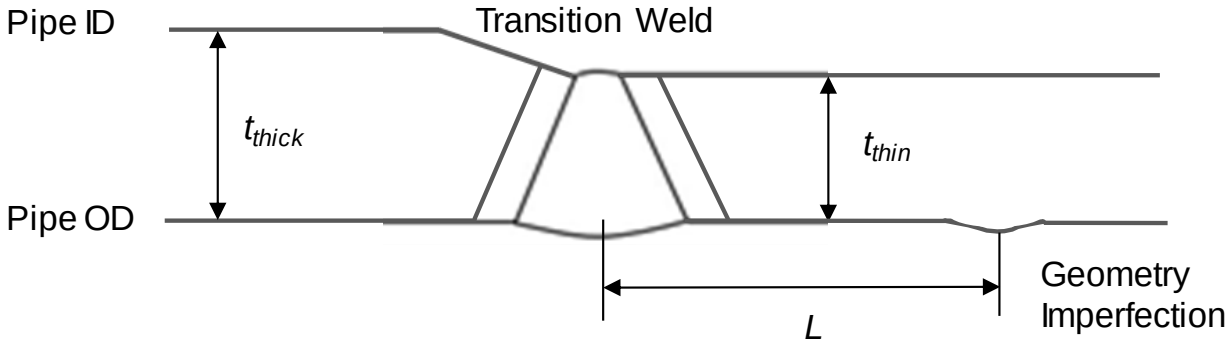
CSC Assessment – Geometry Imperfections

- Geometry imperfections
  - Generated during pipe manufacturing especially for those with expansion procedures, e.g., UOE
  - In the form of non-uniform OD along the length of the pipe
- Effects on CSC
  - If the geometry imperfection height h_g↑, the CSC ↓
  - Interaction between girth weld and geometry imperfection may further reduce CSC
- Treatment of girth weld effect
  - Treated as an equivalent geometry imperfection

Surface undulations generated in UOE pipe



Interaction between transition weld and geometry imperfection



Assessment of CSC for Girth Welds

- CSC equations for plain pipes
  - Recommended geometry imperfections
    - ►h_g = 0.08t for pipes manufactured with expansion procedures (e.g., UOE)
    - ►h_g = 0.04t for pipes manufactured without expansion procedures
- CSC equations for regular girth welds
  - Replace h_g/t with h_g^e/t from the following equation:

    h_g^e/t = max (h_g/t, 0.04) if $h/t < 0.5$

    where h/t is the ratio of girth weld high-low misalignment over pipe WT, the h_g^e/t , h_g/t, and h/t are in the unit of mm/mm (in/in)
  - Applicable range of input parameters is the same as that of CSC equations for plain pipes
- CSC equations for transition girth welds
  - Replace h_g/t with h_g^e/t_{thin} from the following equation:

    h_g^e/t_{thin} = 1.70 $*$ $\left(h_g/t_{thin}\right)$ + 0.13

    where the h_g^e/t_{thin} and h_g/t_{thin} are in the unit of mm/mm (in/in)
  - Applicable range of input parameters

Input Parameters	Applicable Range
D/t_{thin}	(51, 72)
f_p	(0.0, 0.72)
R_{YT}	(0.77, 0.88)
h_g/t	(0.01, 0.30)
ε_e (%)	(0, 2.0)
f_n	(0, 0.40)
h/t	(0, 0.5)

Recommended safety factor ≤ 0.80

Determine the Required Parameters

- Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T
  - The upper-bound Y/T ratio in the longitudinal direction of the actual pipe joint
  - For transition welds, the R_{YT} of the thin-wall pipe should be used.
- Determine the pipe yield strength
  - The upper-bound pipe yield strength in the longitudinal and circumferential directions
  - For transition welds, use the yield strength of the thin-wall pipe
- Determine the normalized geometry parameters
  - For transition welds, the geometry parameters (i.e., geometry imperfection and weld high-low misalignment) should be normalized by the thin-wall pipe thickness

Guidelines for Strain Based Assessment of Dents

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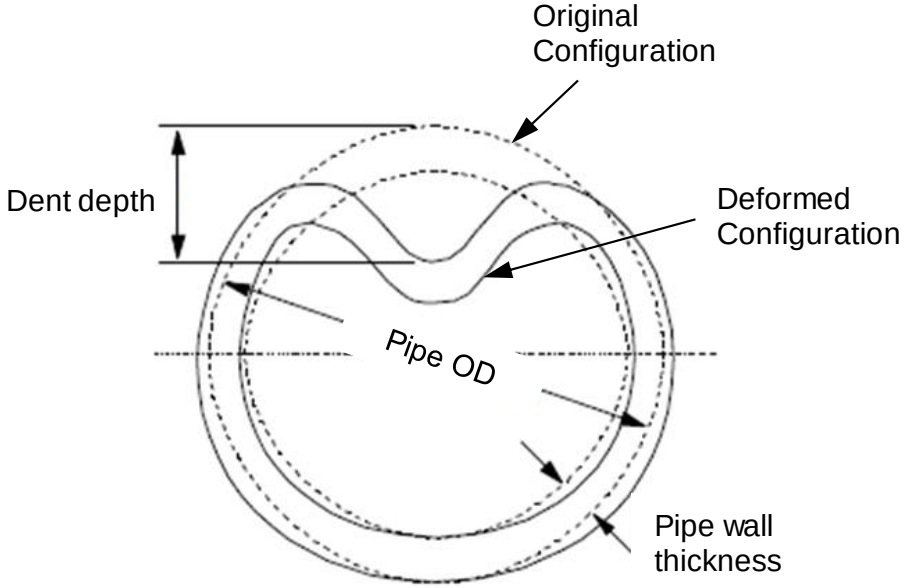
Introduction of Dents and Dent Size

- Dents in a pipe are
  - Permanent plastic deformation, which produces a gross disturbance of the pipe circular cross section
- Dent type
  - Plain dents
- Dent size
  - Dent depth



Acceptable Applications

- Acceptable Applications
  - Plain dents of smooth profiles with no other injurious defects such as gouges or corrosion;
  - Plain dents which occur on the outside surface of the pipe and are inward deviation of the pipe cross section; and
  - Plain dents which are restrained or unrestrained and formed during construction or in-service.
  - Pipe segments subjected to displacement-controlled longitudinal loading, e.g., stable slope movement.
- Exclusions
  - Dents interacting with girth welds, seam welds, and major structural discontinuities such as stiffening rings and piping tees;
  - Pipe materials showing creep behaviors under operating conditions; and
  - Pipe segments subjected to load-controlled longitudinal loading, e.g., free span.
- Failure modes
  - Compressive buckling

Dent Restraint and Forming Conditions

- Dent Restraint and Forming Conditions
  - The compressive strain capacity determined following this guideline is targeted for the unrestrained dents formed during construction.
  - For restrained dents or dents formed in-service, the compressive strain capacity determined following this guideline tends to underestimate the actual compressive strain capacity (i.e., conservative).

Dent Types		Related Field Conditions	
Formed in Construction	**Unrestrained**	• The dent was formed during construction (without internal pressure); • The dented pipe experienced hydrostatic testing; • The dented pipe experienced operating pressure fluctuations; and • The dented pipe experienced large longitudinal compressive strain due to ground movement.	The object caused the dent was removed after the indentation.
	Restrained		The object caused the dent stayed in place after the indentation.
Formed in Operation	**Unrestrained**	• The dent was formed in operation (with internal pressure); • The dented pipe experienced operating pressure fluctuations; and • The dented pipe experienced large longitudinal compressive strain due to ground movement.	The object caused the dent was removed after the indentation.
	Restrained		The object caused the dent stayed in place after the indentation.

CSC Assessment – Equations for Dented Pipes

- CSC Equations for Dented Pipes
  - Use the CSC equations for plain pipes, and
  - Replace h_g/t with h_g^e/t from the following equation:

$$h_g^e/t = 0.01 * [0.019 * (D/t) + 1.4]\left(100 * d_{dp}/D\right)^{[-0.023*(D/t)+1.9]}$$

where d_{dp} is the dent depth of pressurized pipe, and

the d_{dp}/D, D/t, and h_g^e/t are in the unit of mm/mm (in/in)

  - Recommended safety factor ≤ 0.80
  - Applicable range of input parameters

Input Parameters	Applicable Range
D/t	(51, 72)
f_p	(0.72, 0.80)
R_{YT}	(0.77, 0.88)
d_{dp}/D	(0, 0.08)
ε_e (%)	(0, 2.0)
f_n	(0, 0.40)

Determine the Required Parameters

- Determine the pipe yield-to-tensile strength ratio (R_{YT}), i.e., Y/T
  - The upper-bound Y/T ratio in the longitudinal direction of the actual pipe joint
- Determine the pipe yield strength
  - The upper-bound pipe yield strength in the longitudinal and circumferential directions
- Determine the dent depth
  - The maximum dent depth at the internal pressure equal or lower than the lower-bound pressure during normal operation should be used.
  - If the dent depth is measured at the internal pressure which is higher than the lower-bound pressure in normal operation, the measured depth should be corrected (usually increased) for the pressure effect.

Summary of the Presentation

- Overview of strain-based design and assessment (SBDA)
- Guidelines for material specifications
- Level 1 guidelines
  - Strain-based assessment of corrosion anomalies
  - SBDA of girth welds
  - Strain-based assessment of dents

Thank You for Your Attention!