Challenges (and successes) associated with applying mechanical damage analysis models on operator's pipelines

Tom Bubenik

DNV GL, USA

Background

- DNV GL assesses over a thousand mechanical damage anomalies each year for North American pipeline operators
  - Most analyses are based on in-line inspection caliper data
    - MFL or UTWM provide information on possible stress risers
  - We seek conservative solutions that provide a reasonable factor of safety against failure due to excess strain and/or fatigue
    - Safety factors on lives for dents with defects range from 2 to 5 (reflecting expected confidence in the calculated remaining life)
    - Safety factors on the life of dents without stress concentrators typically range from 10 to 100 (reflecting decreased confidence in remaining lives for plain dents)

Background

- DNV GL most frequently conducts strain analyses (e.g., ASME B31.8 Appendix R) and API 579 Level 2 fatigue assessments
  - ASME B31.8 Appendix R requires some data smoothing to obtain accurate dent strain estimates
    - Pipeline companies are using in-line inspection service providers to provide these strain estimates
    - We use cubic splines to fit the measured profiles in the axial and circumferential directions
  - API 579 Level 2 fatigue lives are based on S/N curves and elastic stress concentration factors (SCFs)
    - This type of assessment assumes no pre-existing flaw, such as a crack
  - Alternatively, we conduct Level 3 fatigue analyses using finite element analyses (FEA), Paris Law, assuming stress concentrators are crack-like

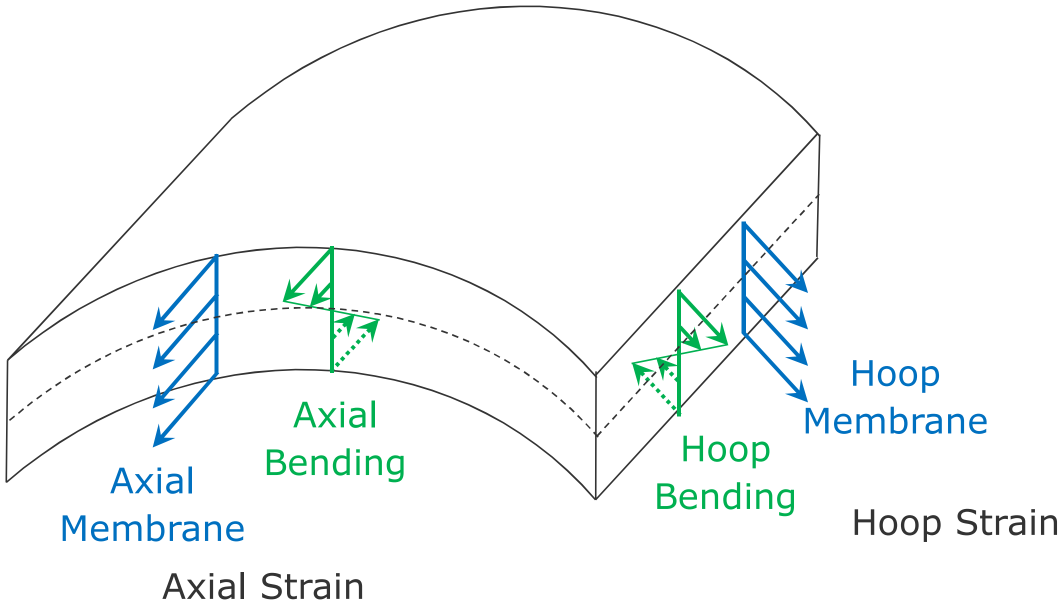
Background

- About 10% of the time, we perform API 579 Level 3 assessments with finite element analyses
  - Nonlinear material properties, large displacements

- We analyze some dents with removed metal as if cracks were present, calculating a fatigue life using Paris Law, SCFs for the dent, and SCFs for the removed metal

- We are considering the use of the PRCI/BMT Fleet analysis models
  - Complete formulations have not yet been published
  - Full publication is expected when the current stage of the PRCI/BMT project is complete

ASME B31.8 Appendix R - Strain Based Dent Acceptance



Circumferential membrane strain is assumed to be insignificant due to the flexibility of the pipe in the circumferential plane.

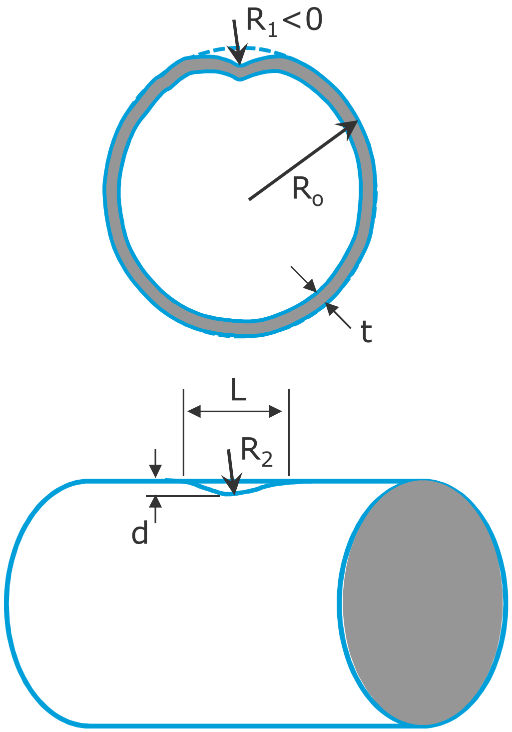
ASME B31.8 Appendix R - Dent Strains

- Hoop Bending Strain = $\varepsilon_1 = \frac{t}{2}\left[\left(\frac{1}{R_0}\right) - \left(\frac{1}{R_1}\right)\right]$

- Axial Bending Strain = $\varepsilon_2 = \frac{t}{2}\left(\frac{1}{R_2}\right)$

- Axial Membrane Strain = $\varepsilon_3 = \frac{2d^2}{L^2}$

- Axial and circumferential "dffective" strain



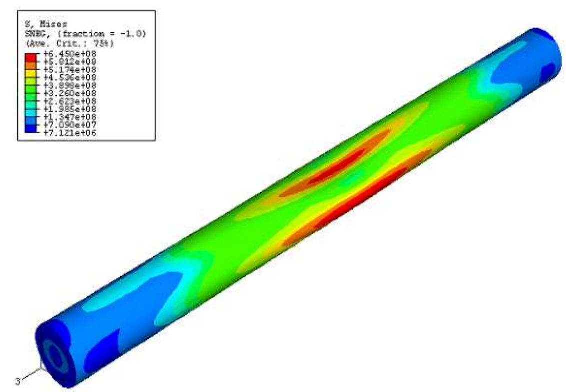
Not valid if the radius of curvature in any direction is less than 5 times the wall thickness!

ASME B31.8 Appendix R – "Combining" Strains

$$\text{Strain on inside of pipe} = [\varepsilon_1^2 - \varepsilon_1(\varepsilon_2 + \varepsilon_3) + (\varepsilon_2 + \varepsilon_3)^2]^{0.5}$$

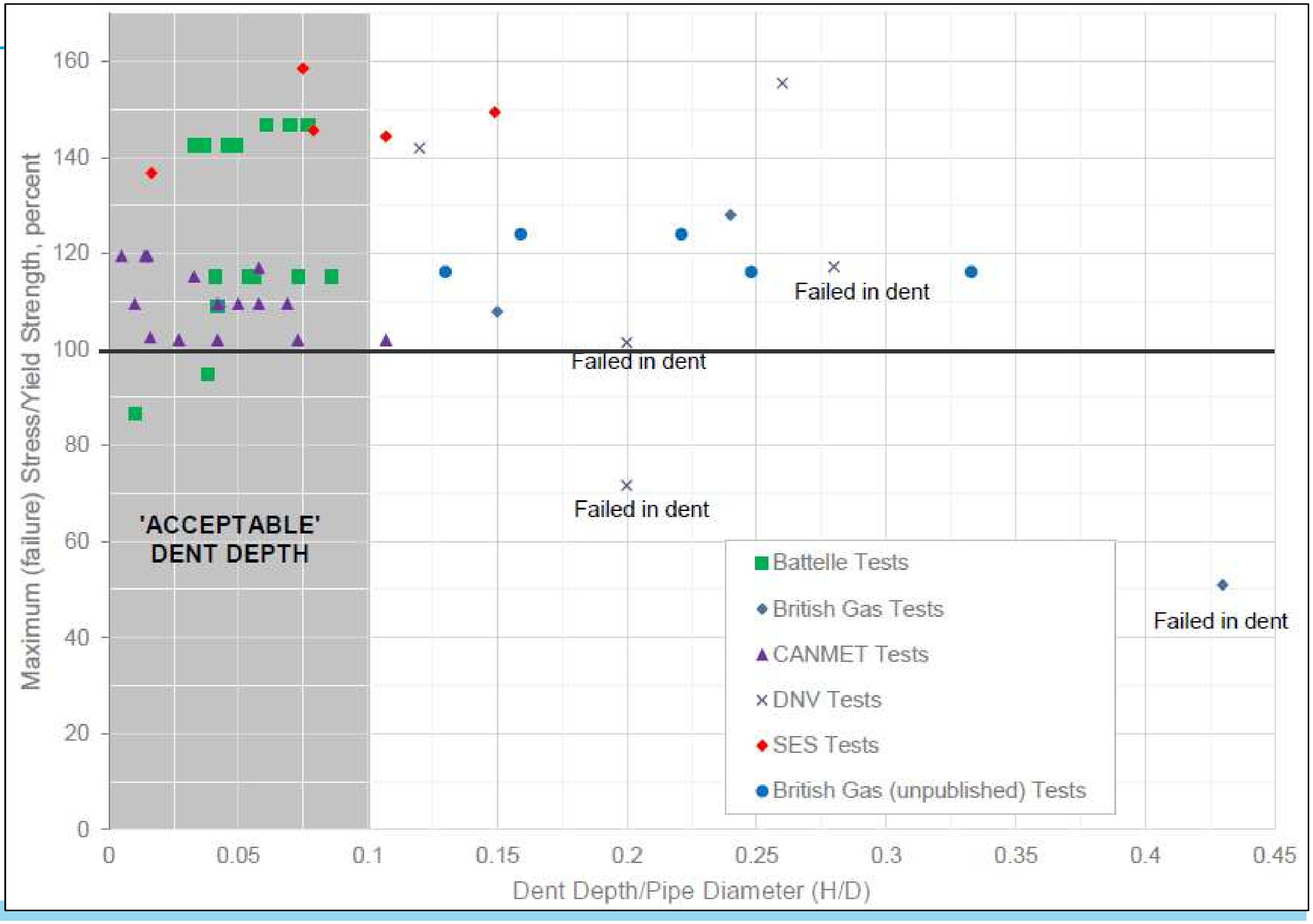
$$\text{Strain on outside of pipe} = [\varepsilon_1^2 + \varepsilon_1(-\varepsilon_2 + \varepsilon_3) + (-\varepsilon_2 + \varepsilon_3)^2]^{0.5}$$

- Note that these combined strain equations anticipate each of the three components of strain will be maximums at the same location
- This is likely the case for a dome-shaped dent, but it may not be the case for a dent with a complex shape
- The assessor should be aware of this possibility when seeking the maximum strain



API 579 Burst Pressure

- Repeated test programs demonstrate plain dents have little or no impact on burst pressures



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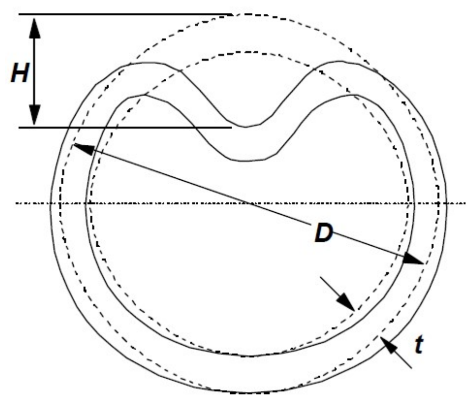
API 579 Dent Fatigue

- ASME 579, Part 12, Level 2 analysis for dents



$$N_c = 562.2\left[\frac{\sigma_{uts}}{2\sigma_A K_d K_g}\right]^{5.26}$$

$$\sigma_A = \sigma_a\left[1-\left(\frac{\sigma^C_{m,max}-\sigma_a}{\sigma_{uts}}\right)^2\right]^{-1}$$

$$\sigma_a = \frac{\sigma^C_{m,max}-\sigma^C_{m,min}}{2}$$

$$K_d = 1 + C_s\sqrt{\frac{t_c}{D_o}\left(d_{d0}\cdot C_{ul}\right)^{1.5}}$$

$$C_s = 2.0 \qquad \left(\textit{for smooth dents}, r_d \geq 5t_c\right)$$

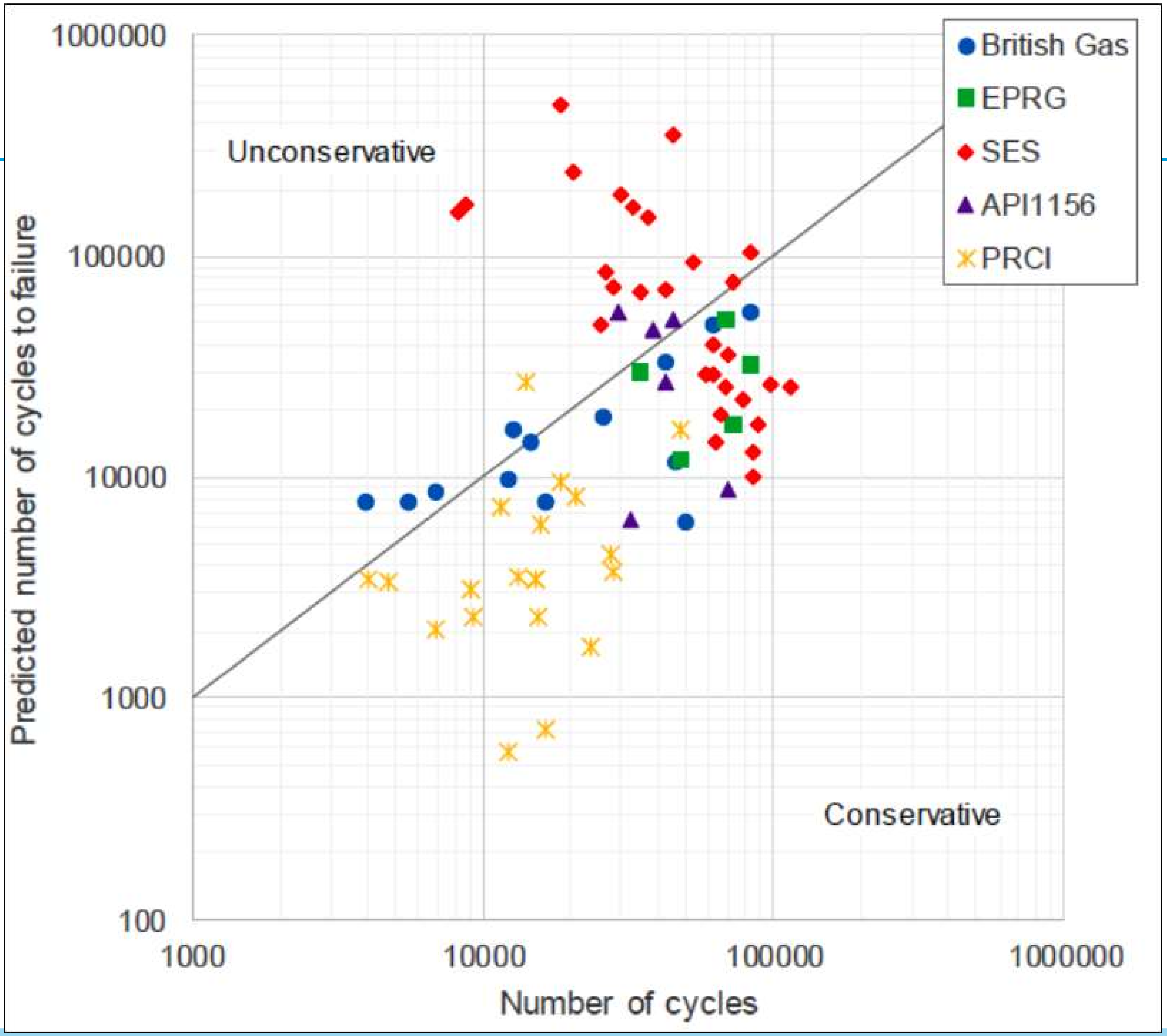
$$C_s = 1.0 \qquad \left(\textit{for sharp dents}, r_d < 5t_c\right)$$

$$K_g = 1 + 9\left(\frac{d_g}{t_c}\right)$$

API 579 Level 2 Analyses

- Key assumptions
  - Internal pressure loading only
  - Isolated dents and dent-gouge combinations
  - …
  - High cycle fatigue
  - For gouges, material has sufficient toughness ("the component is operating at or above the temperature that corresponds to 40 Joules (30 ft-lbs)…")

Dent Fatigue Accuracy



Dent and Gouge Assessments

- API 579 Level 2 allows a remaining strength factor to be determined for dent gouge combinations

$$RSF = \frac{2}{\pi}\arccos\left[\exp\left[\frac{-C_1 \cdot C_3}{C_2^2}\right]\right] \cdot \left(1 - \frac{d_g}{t_c}\right)$$

$$C_1 = \frac{1.5\pi E_y U_1}{\bar{\sigma}^2 \cdot A_{CVN,2/3} \cdot d_g}$$

$$C_2 = Y_1\left(1 - \frac{1.8 d_{d0}}{D_o}\right) + Y_2\left(\frac{10.2 d_{d0}}{2t_c}\right)$$

$$C_3 = \exp\left[\frac{\ln(U_2 \cdot CVN_{2/3}) - 1.9}{0.57}\right]$$

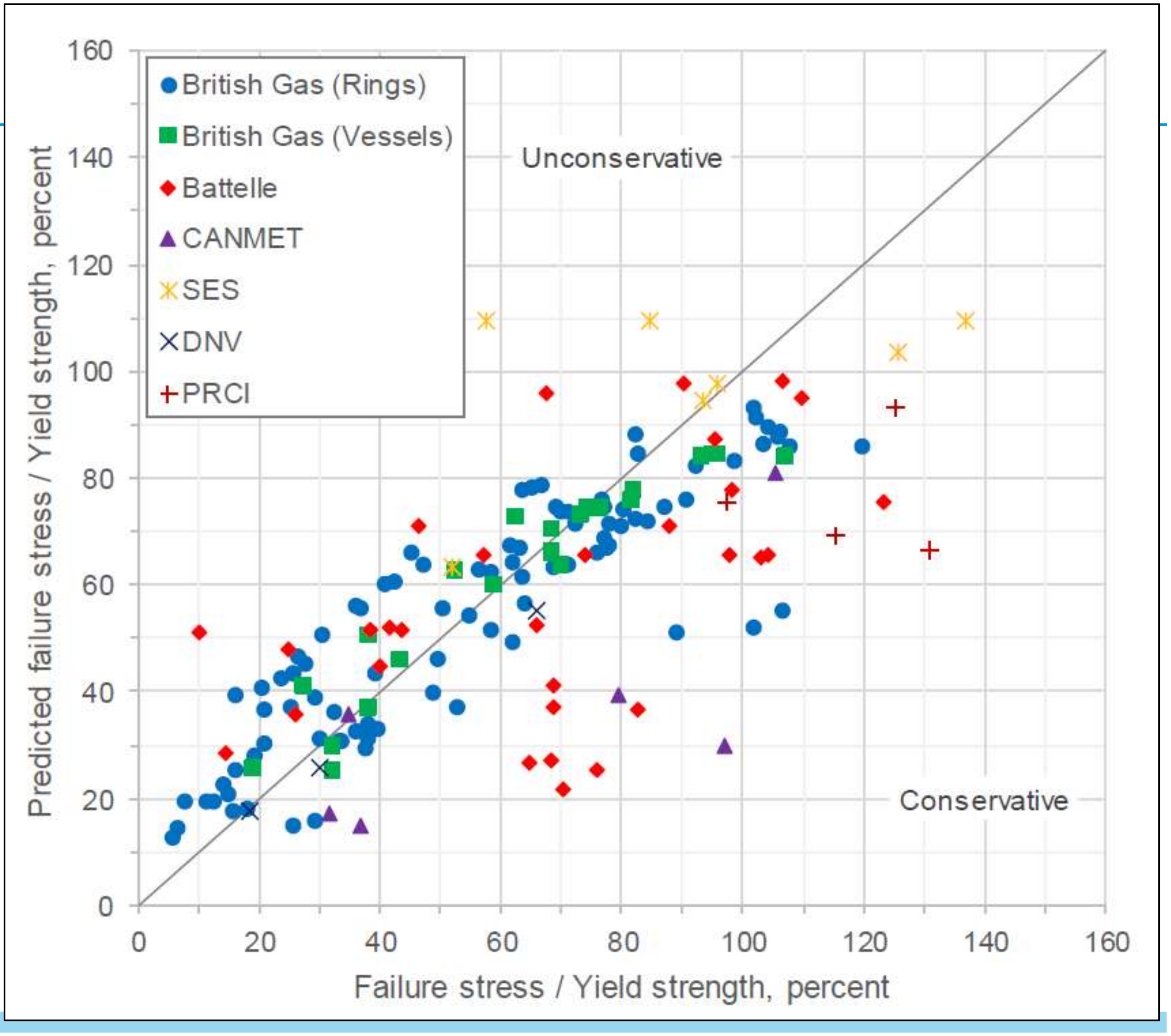
$$\bar{\sigma} = 1.15 \cdot \sigma_{ys}\left(1 - \frac{d_g}{t_c}\right)$$

$$Y_1 = 1.12 - 0.23\left(\frac{d_g}{t_c}\right) + 10.6\left(\frac{d_g}{t_c}\right)^2 - 21.7\left(\frac{d_g}{t_c}\right)^3 + 30.4\left(\frac{d_g}{t_c}\right)^4$$

$$Y_2 = 1.12 - 1.39\left(\frac{d_g}{t_c}\right) + 7.32\left(\frac{d_g}{t_c}\right)^2 - 13.1\left(\frac{d_g}{t_c}\right)^3 + 14.0\left(\frac{d_g}{t_c}\right)^4$$

Smooth Dent Gouge Accuracy

- Burst pressure accuracies can be off by 20 to 40 percent



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Uncertainties

- There is significant uncertainty in the input parameters for an assessment. We typically don’t have highly accurate information on
  - Dent geometry and symmetry
  - Actual material properties, especially around gouged material
  - Stresses: Cyclic, typically due to pressure, Axial, Residual stresses and strains
  - Stress concentrators and their geometries and characteristics (e.g., metal loss geometry)
  - When and at which pressure the dent was formed
  - Analysis model inaccuracies and biases

Uncertain Input Parameters – Dent Geometry

- Caliper or geometry in-line inspection tool accuracy depends on the type of sensor system used to make the measurements
  - Mechanical feelers (fingers/rollers)
  - Eddy current proximity sensors
  - Ultrasonic compression wave transducers
- It's difficult to verify the accuracy of caliper or geometry in-line inspection tools in the field
  - How much accuracy is needed?
- What about stress risers, their geometry, impact on material properties, residual stress?

Photo courtesy of Rosen Group

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Uncertain Input Parameters – Material Properties

- We often know the grade of pipe steel, but actual yield and tensile strengths are unknown
  - E.g., it's not unusual for actual yield strengths to exceed nominal values by 10% or more
- The denting process cold works the material, changing its mechanical properties
- Gouging, in particular, creates very localized damage with significant losses of ductility and toughness
- Many analyses are on vintage pipe materials, some of which have poor mechanical (toughness) properties

Uncertain Input Parameters – Stresses and Strains

- For liquid lines in particular, the pressure loading history is complex, creating the need for simplifying assumptions, such as rainflow cycle counting (RCC)
  - RCC ideally works in an elastic high-cycle environment, i.e., where damage related to plastic deformations do not accumulate

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Conclusion #1:
Highly Accurate Burst Pressure and Fatigue Life Estimates For Mechanical Damage Are A Pipe(liner's) Dream!

If We Cannot Accurately Estimate Burst Pressures and Fatigue Lives, What Can We Do?

- **Recognize our limitations:**

  It may not be practical to accurately analyze complex dents with gouges and cracks…

  But we can use existing and newly developed analysis models to prioritize mechanical damage for remediation

Using Existing Models to Prioritize Mechanical Damage – Step 1

- Systematically study input parameters to learn how they affect the calculated burst pressure or remaining lives – Knowing where changes in input parameters significantly affect calculated fatigue lives and burst pressures will guide us to where we need better input data:
  - Dent shape and geometry – Caliper tool improvements
  - Actual material properties – Better understanding of how post yield behavior influences failure
  - Stresses – Better understanding of residual and active stress fields
  - Stress concentrations and their geometries and characteristics – Better SCFs, better ILI capabilities
  - Pressure at which dent was formed – Fundamental understandings of how rerounding affects damage severity
  - Analysis model inaccuracies and biases – Informed safety factors for analyses

Using Existing Models to Prioritize Mechanical Damage – Step 2

- Learn which uncertainties cannot be overcome
  - If uncertainties mean a given mechanical damage *could* be critical, it should be treated as a short-term threat to integrity
    - Is a dent/gouge combination with cracking <u>always</u> an integrity threat?
  - Identify classes of damage that have such high uncertainty that they should be treated as a short- or mid-term threat
- Use existing models to guide the prioritization and urgency associated with remaining defects
  - How important is it to remediate immediately versus sometime in the future?

Using Existing Models to Prioritize Mechanical Damage – Step 3

- Identify classes of mechanical damage that are not serious threats to integrity
  - Does a 6% dent with 20% corrosion significantly threaten pipeline integrity?
    - Limited test data suggest the impact is small

- Simplify, simplify, simplify
  - If analysis procedures can't be easily implemented, they won't be used

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Using Existing Models to Prioritize Mechanical Damage – Step 4

- Identify the highest priority defects, then embark on a continuous improvement campaign
  - Use in-line inspection and/or release history to guide the number of defects to address each reassessment interval

Summary

- Existing analysis tools cover most of the mechanical damage and recent models improve our understandings, but most models don't provide guidance on how sensitive the results are to input parameters
  - Use the existing tools to quantify the impacts of input parameters, thereby identifying which parameters are most important
  - Use uncertainty analyses to account for other variabilities
- Learn which classes of damage cannot be accurately assessed due to input uncertainties, and treat these as possible near-term threats
- Learn which classes of damage are benign – identify when and where damage can be accepted using simplified analyses
- Build integrity management programs around continuous improvement, identifying the highest priority defects for remediation

Thank you for listening!

thomas.Bubenik@dnvgl.com
614-761-6922 (office); 614-296-4992 (cell)

www.dnvgl.com

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