Paper 3: Fatigue Crack Growth Modelling for Safe and Efficient Hydrogen Pipeline Design

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Overview

- Fatigue analysis in pipeline design
- Effect of Hydrogen on fatigue life of pipelines
- Parametric fatigue study of pipelines designed to ASME B31.12
- Results and discussion
- Conclusions
Fatigue life assessment in natural Gas pipeline:
- S-N Curve (BS 7910, DIN 2413 etc.) -> Total Life
  - Simple (requires peak stress only)
  - Except DIN 2413-1993, no Linepipe specific curve
- IGE/TD/1 and AS 2885.1, not a real S-N curve (Fracture Mechanics based of Hydrotest survive cracks)
Fracture Mechanics based -> Crack Growth Life
- Complex calculations, step-by-step crack growth
- Requires Stress Intensity Factor and FCGR equation

Types of Fracture Mechanics based analysis
- Identified/detected crack
  - Crack dimensions and geometry features are measured
  - Crack dimensions are assumed features are assumed
- Workmanship based cracks
  - Crack dimensions and geometry features can have a range
  - Assumption of having simultaneous geometry feature can lead to stresses above Yield Strength.
  - Best approach is probabilistic analysis, not suitable for present study (billions of cases)
- Hydrotest survived cracks
  - Can be very conservative specially for low design factor pipelines
Effect of Hydrogen on fatigue life of pipelines

- Fracture behavior
  - Formation, initiation, propagation
  - Reduction in effective toughness (Hydrogen Embrittlement)
  - Accelerated fatigue Crack Growth rate (FCGR)

- Fatigue:
  - Applies even at low pressures, though worse at increasing fugacity
  - Larger impact at high $\Delta K_{IC}$
  - Larger impact at high $R$-ratios

\[
\frac{da}{dN} = \log(K) = \log(\text{air}) - \log(H_2)
\]
Parametric fatigue study of Hydrogen pipelines

- **Objective**
  - Develop simplified S-N curves for Hydrogen like existing curve in IGE/TD/1 and AAS 2885.1

- **Analysis parameters**
  - **Crack type**: Inside surface Semi-Elliptical crack
  - **Crack size**: Depth=Thickness/4, Length=1.5xThickness (assumed crack dimensions)
  - **Diameter, D**: DN100 to DN1050 (4” to 42”)
  - **Pressure, P**: ASME B16.5 pressure ratings: 1.96, 5.11, 6.81, 10.21 and 15.32 MPa
  - **Thickness, t**: Calculated based Design Factors 0.3, 0.4, 0.5, 0.6, 0.67, and 0.72.
  - **Cycling pressure, ΔP**: 10 to 90% of the P with R-ratio of:
    
    \[
    R = \frac{P-\Delta P}{P}
    \]
  - **Material**: API 5L Grades B to X70 (70ksi).
  - **Flow stress**: \((\text{SMYS}+\text{SMTS})/2\)
Parametric fatigue study of Hydrogen pipelines

- **ASME B31.12 design options:**
  - Option B: Maximum Design Factor 0.72, Material Performance Factor =0.72, $K_{IH}=55$ MPa*$m^{0.5}$
  - Option A: Maximum Design Factor 0.5, Material Performance Factor to B31.12
    $K_{IH}$ Converted from CVN=10J, 27J and 57J using Rolfe-Novak equation divided by 2

- **Fatigue Crack Growth Rate (FCGR):**
  - ASME B31.12 (developed by NIST)
    \[
    \frac{da}{dN} = a_1 \Delta K^{b_1} + \left[(a_2 \Delta K^{b_2})^{-1} + (a_3 \Delta K^{b_3})^{-1}\right]^{-1}
    \]
  - ASME BPVC Code Case 2938 (developed by Sandia Lab)
    \[
    \frac{da}{dN} = C \left[\frac{1 + C_H R}{1 - R}\right] \Delta K^m
    \]
  - Original model developed by Sandia (Pressure modified version of CC 2938)
    \[
    \frac{da}{dN_{low}} = C \left[\frac{1 + C_H R}{1 - R}\right] \Delta K^m \left(\frac{f}{f_{ref}}\right)^{1/2}
    \]
Results and Discussion

ASME B31.12, Option B, $K_{IH}=55\ \text{MPa}\cdot\text{m}^{0.5}$
Results and Discussion

ASME B31.12, Option B, DN100-DN600

ASME B31.12, Option B, DN650-DN1050
Results and Discussion

ASME B31.12, Option B, DN100-DN1050, $K_{IH}=55$ MPa$^{0.5}$ and $K_{IH} \geq 70$ MPa$^{0.5}$
Results and Discussion

ASME B31.12, Option A, DN100-DN600

ASME B31.12, Option A, DN650-DN1050
Results and Discussion

ASME B31.12, S-N Curves
Conclusion

1. Analysis of more than 216,000 cases (base cases) with three different FCGR equations show that results are scattered, and a single lower bound S-N curve leads to a conservative equation with limited usefulness.

2. Individual results of three FCGR equations are different, but the overall and lower bound S-N is not influenced by the choice of FCGR equation.

3. A lower bound curve to cover all pipe diameters (DN100-DN1050) leads to a conservative S-N curve, but if the diameter range is split into two ranges i.e., DN100-DN600 and DN650-DN1050, unnecessary conservatism for the smaller diameter range can be avoided.

4. In the small diameter range (DN100-DN600), for pipe designed to ASME B31.12 Option A, the fatigue life is less sensitive to material toughness than the large diameter range (DN650-DN1050). Additionally, an API 5L PSL2 compliant pipe in small diameter range has a similar lower bound S-N curve than a pipe designed to ASME B31.12 option B with the same Design Factor.

5. For ASME B31.12 Option B designs in the small diameter range (DN100-DN600), the minimum specified $K_{IH} = 55$ MPa(m)$^{0.5}$ guarantees to meet a toughness-independent lower bound S-N curve.

6. In order to achieve toughness independence state for the large diameter range (DN650-DN1050), the material toughness in Hydrogen needs to be increased to $K_{IH}= 70$ MPa(m)$^{0.5}$. 
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Thank you