EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland • 6–10 June 2022

Line Pipe Capability Assessment for the Safe Transportation of Hydrogen

06 June 2022

PRCI MAT-9-2 Project – Introduction

- Background: Develop testing recommendations, supported by materials tested to-date, for future line pipe testing for hydrogen-blend or hydrogen pipelines
- Research Objectives/Project Deliverables:
  - Literature review to summarize factors that infer line pipe (API 5L & CSA Z245.1) susceptibility to hydrogen cracking
  - Literature review will include testing completed by the US Government (e.g., NIST) and public test data
  - Impact of loading and defects on hydrogen crack initiation/propagation will be considered
  - Report will provide recommendations for future testing programs, including identification of key variables, to support understanding of hydrogen's effects on a variety of line pipe

Hydrogen – Global & Local Investment

- It is estimated that $500B is being invested globally into hydrogen through 2030, with ~$150B in 'mature' projects (already in planning/development phases)
- Most reports provide high-level commentary on how to actually safely implement a hydrogen-fueled future, often stating a varying level of allowable hydrogen blend concentrations (e.g., 2-10%)
- What is the basis for these blends and are they applicable to transmission lines?

Work Performed

- Identification of Key Variables
  - Key variables that affect hydrogen embrittlement across various line pipe attributes, such as microstructure, discontinuities, YS/UTS, etc.
  - Key variables that should enable pipeline operators to utilize test data to assess the eligibility of their pipeline network for hydrogen/hydrogen-blends, and select material for new infrastructure
- Base metal, long seam, and girth welds are considered
- Over 200 literature sources have been collected, including NIST, national labs, USA, France, Norway, Germany, PRCI, and other industry researchers

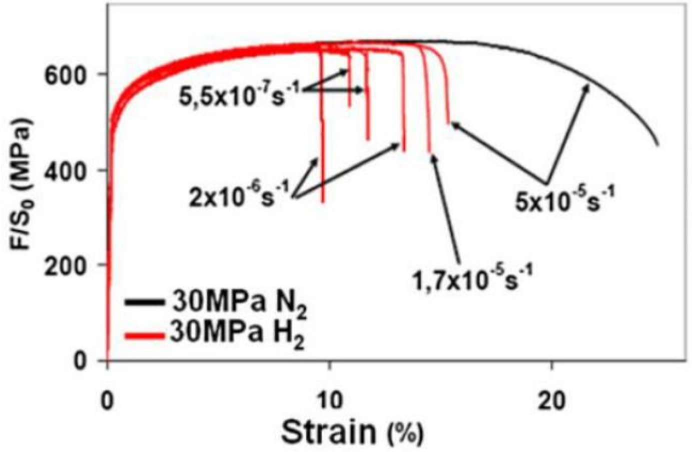
Included & Excluded Works

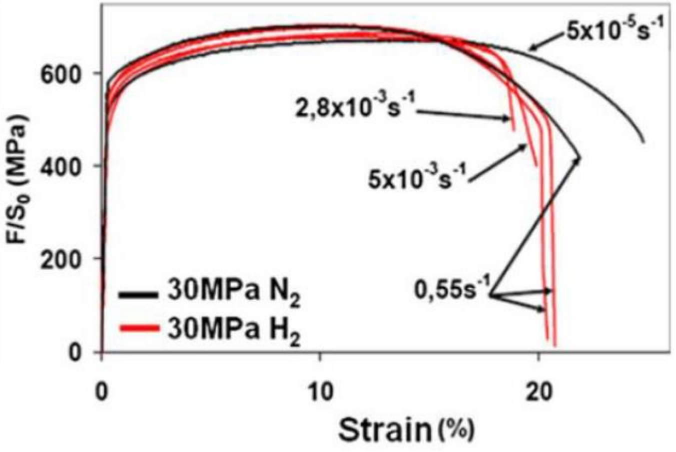
- Excluded from MAT-9-2 report
  - Method of hydrogen uptake and embrittlement (e.g., hydrogen enhanced decohesion (HEDE), hydrogen enhanced localized plasticity (HELP), adsorption induced dislocation emission (AIDE), etc.) was not studied
  - These mechanisms are studied in detail in other publications and regardless of the exact mechanism, hydrogen will actively compromise a steel line pipe's mechanical properties

- Included in MAT-9-2 report
  - Identification of critical variables or parameters that lead to greater embrittlement
  - Comparison of tested materials to existing transmission pipeline attributes to assess viability of blending into existing networks

Impact on Steel Line Pipe - Static Loading

- Hydrogen has a negligible impact on YS and UTS under constant applied loading
- Reduction in elongation (ductility) is observed
- Higher strain rates results in greater reduction in ductility
  - Will affect how we manage pipelines operating through plastic strain/external load events (e.g., geohazards)





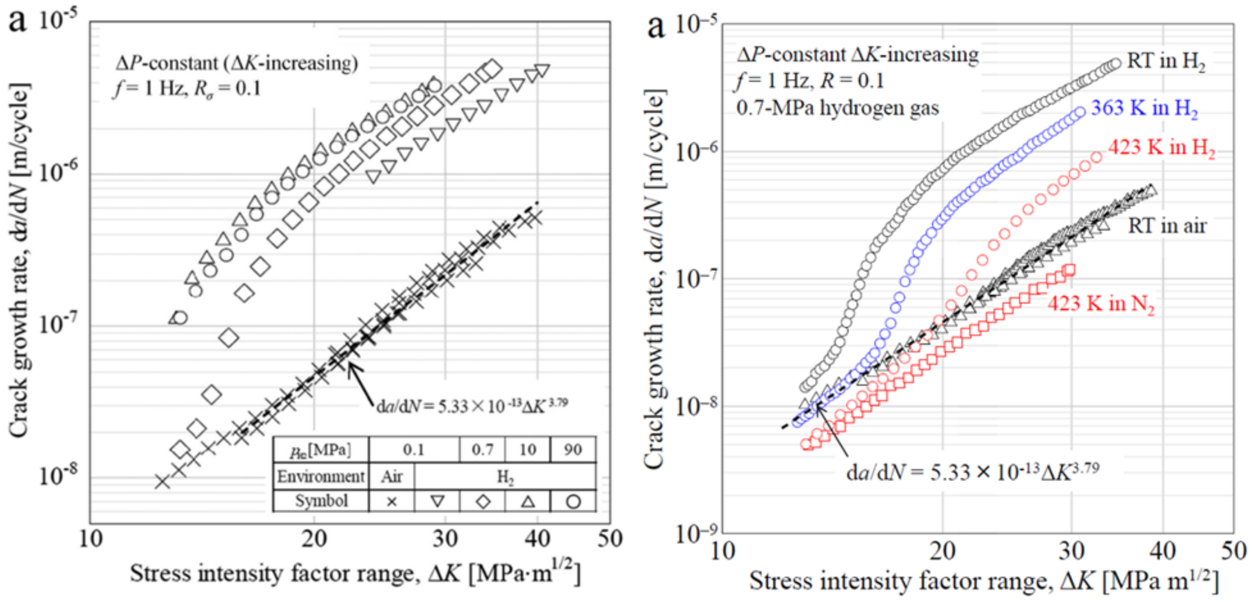
X80 material (Briottet, 2012)

Impact on Steel Line Pipe - Pressure & Temperature

- In fatigue loading (testing & operational), pressure and temperature can significantly vary & their effect must be understood

- Pressure
  - Small amounts of hydrogen produce measurable reductions in fatigue & toughness performance

- Temperature
  - Greatest reduction in fatigue performance occurs near room temperature



C-Mn steel (Yamabe, 2016)

Impact on Steel Line Pipe - Effect of Microstructures

- Microstructures appear to play a secondary role
- Across multiple studies, contradictory findings were often observed between the role of various phases
- Two consistent factors were observed:
  - Polygonal ferrite consistently exhibited poorer fatigue performance
  - Banded ferrite-pearlite structures & cracking perpendicular to bands exhibit better fatigue performance (L-R direction)

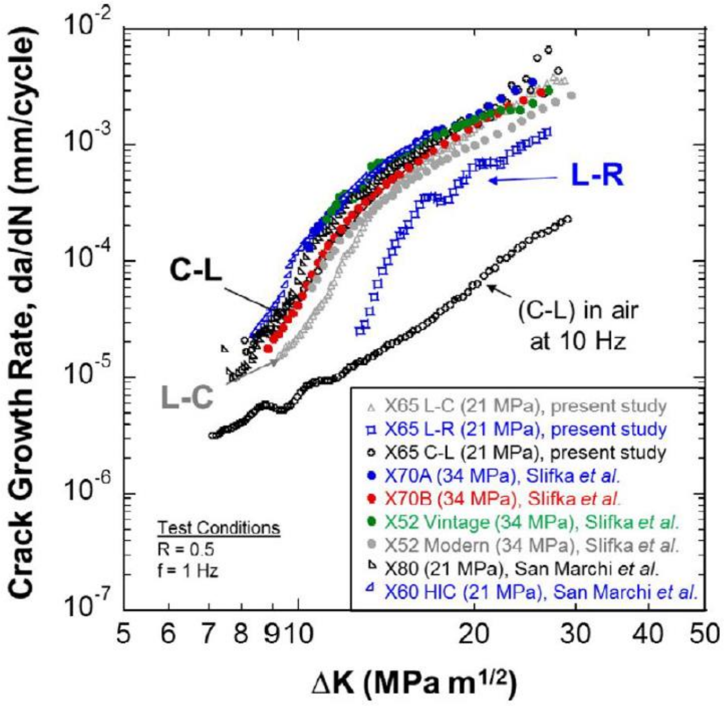


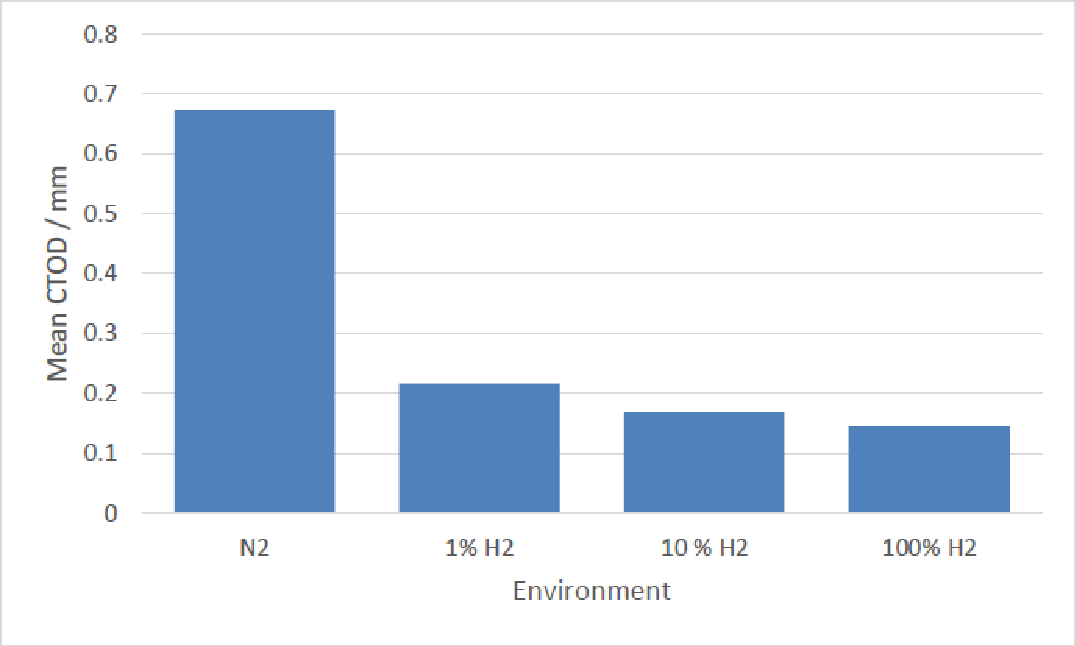
Figure 5 – Compilation of FCGR Across Multiple Steels. Banded microstructures: X52 vintage (70% PF, 30% P), X65 (90% PF, 10% F). Uniform microstructures: X70A (90% PF, 10% AF), X70B (90% PF, 10% B), X52 modern (90% PF, 10% AF), X80 (90% PF, 10% coarse AF), X60 HIC (100% PF) [61].

Ronevich, 2016

Impact on Steel Line Pipe - Toughness

- CTOD
  - CTOD specimens consistently observed a 30-70% reduction in toughness in hydrogen

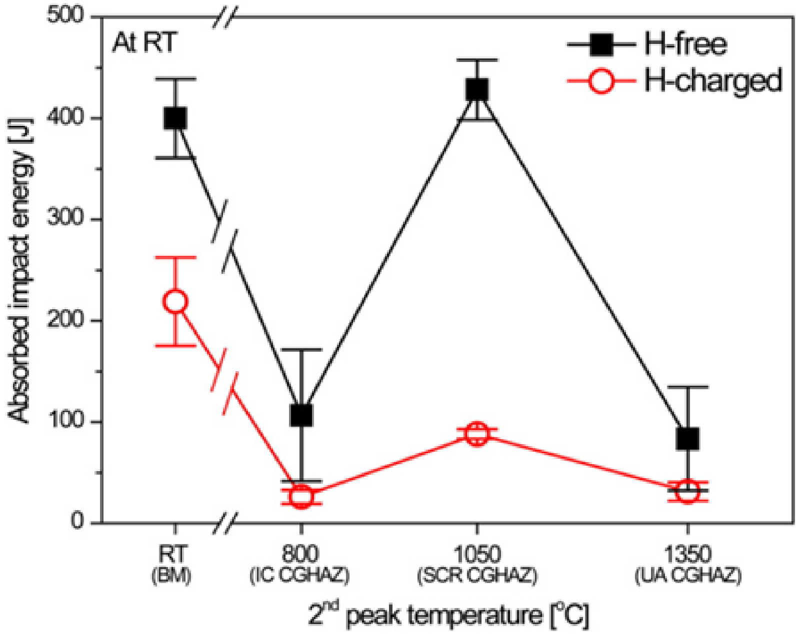
X70 Pipe Body



Gallon, 2020

- Charpy V-Notch
  - Inconsistent results were observed, some with reductions in CVN toughness and others without after hydrogen charging

X70 Simulated HAZ



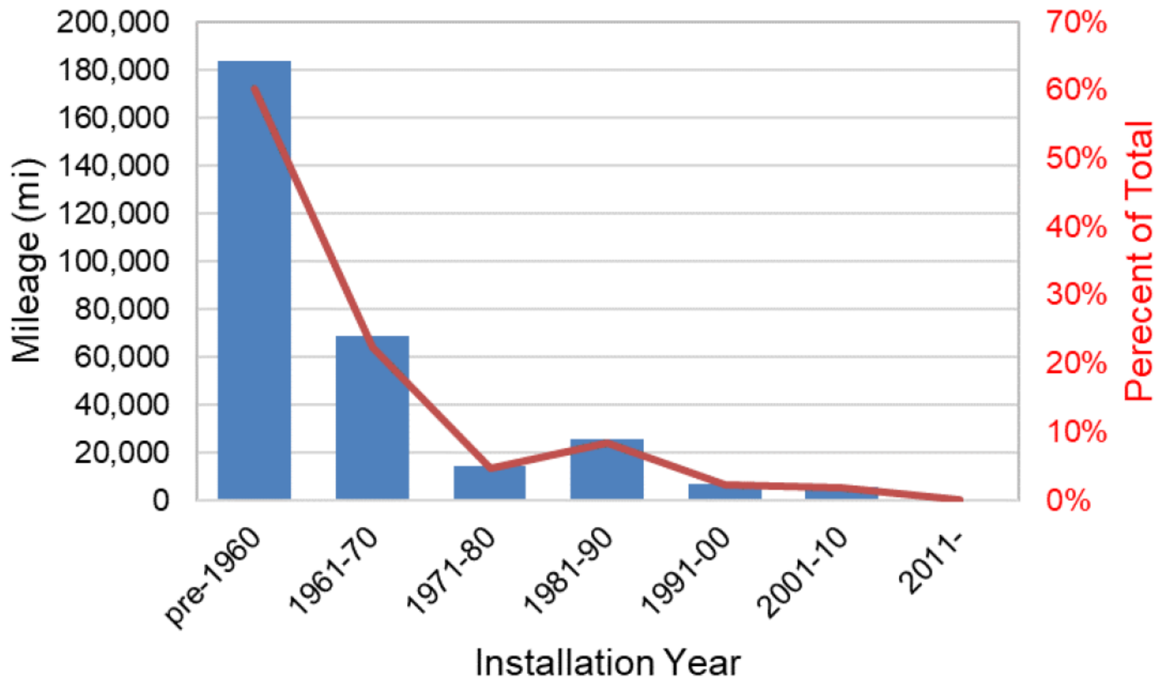
Lee, 2013

Impact on Steel Line Pipe - Long Seam & Girth Welds

- There are far fewer fatigue studies for long seam & girth welds compared to pipe body/base metal
- Weld metal has equivalent or lower FCGR than the line pipe base metal
- HAZ has equivalent or greater FCGR than the base metal/weld metal
  - HAZ testing presents testing challenges due to weld geometry
  - Weld metal testing presents challenges due to residual stress variations & imperfections

NA Installed Transmission Infrastructure - Mileage

- The vast majority of installed transmission pipelines, which are likely to experience higher hydrogen damage from higher pressures, are:
  - Pre-1970s
  - Comprised of grades no greater than X52



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Installed Pipe Attributes vs Test Data

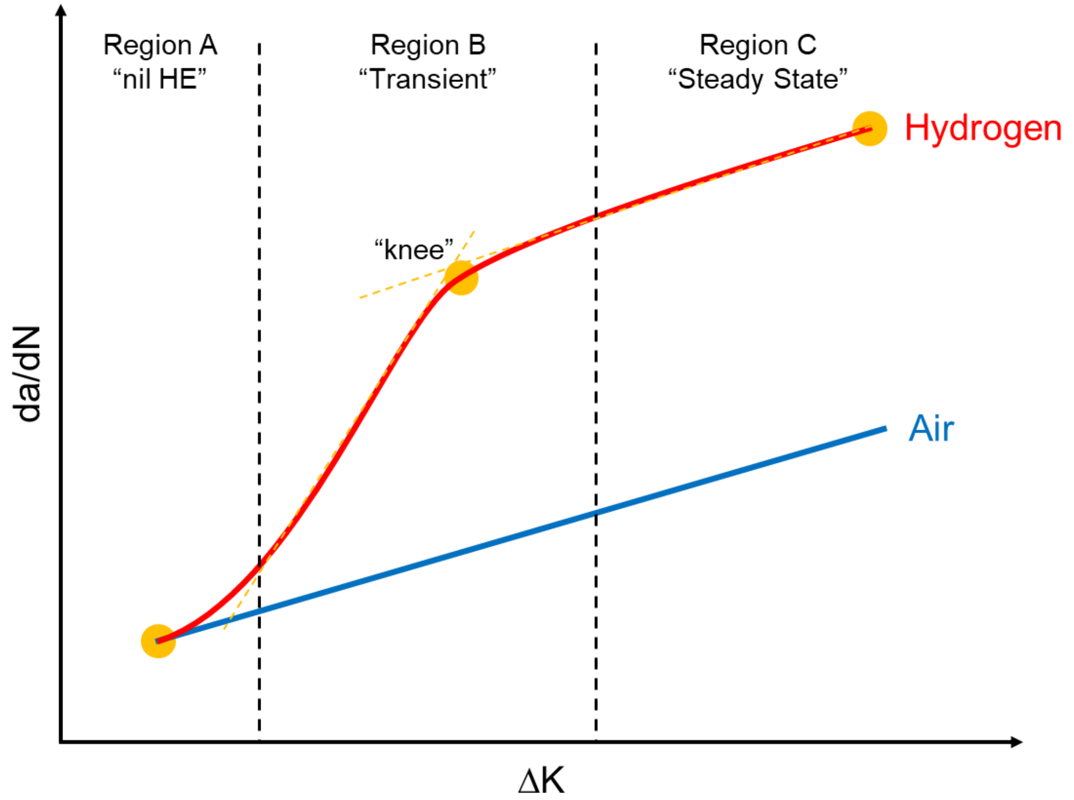
- Critical comparison of all unique materials which were fatigue tested across all collected literature yielded:
  - 22 unique materials, many of which contained unspecified manufacturing years
  - 2 unique long seams (1 ERW, 1 SAW)
  - 7 unique girth welds (2 SMAW, 5 GMAW)
- Majority of FCGR data is post-1990, implying that most tested materials are likely “modern” materials if not stated
- Existing transmission network: insufficient pre-1970s X52 data points
- Future network: insufficient modern X60-X70 datapoints

Grade	No. of Unique Materials	Manufacturing Years
Gr. B	1	N/A
X42	2	N/A
X46	0	N/A
X52	4	1964, 1990s, 2000s, 2011
X60	3	1972, 1980, N/A
X65	1	N/A
X70	3	2005, N/A
X80	3	N/A
X100	2	1990s, N/A
Other	3	N/A

Fatigue Testing Summary - FCGR Extraction

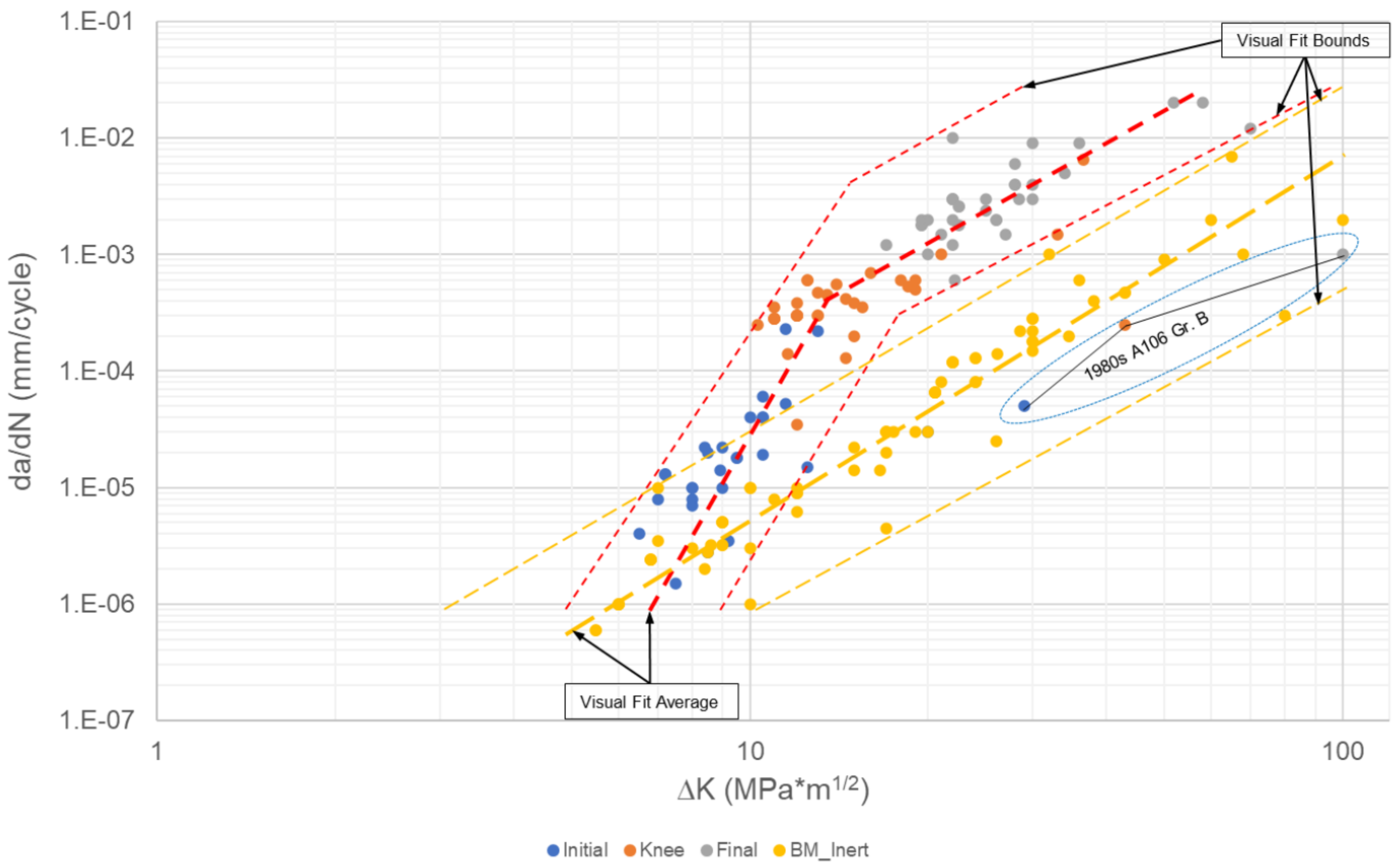
- Extract initial, transition, and end datapoints for replicate bi-linear FCGR curves

- Region A
  - At low ΔK, most line pipe steels do not experience embrittlement
- Region B or "knee"
  - Transition region where rapid increase in FCGR is observed before a transition to lower FCGR
- Region C
  - Higher FCGR and similar slope



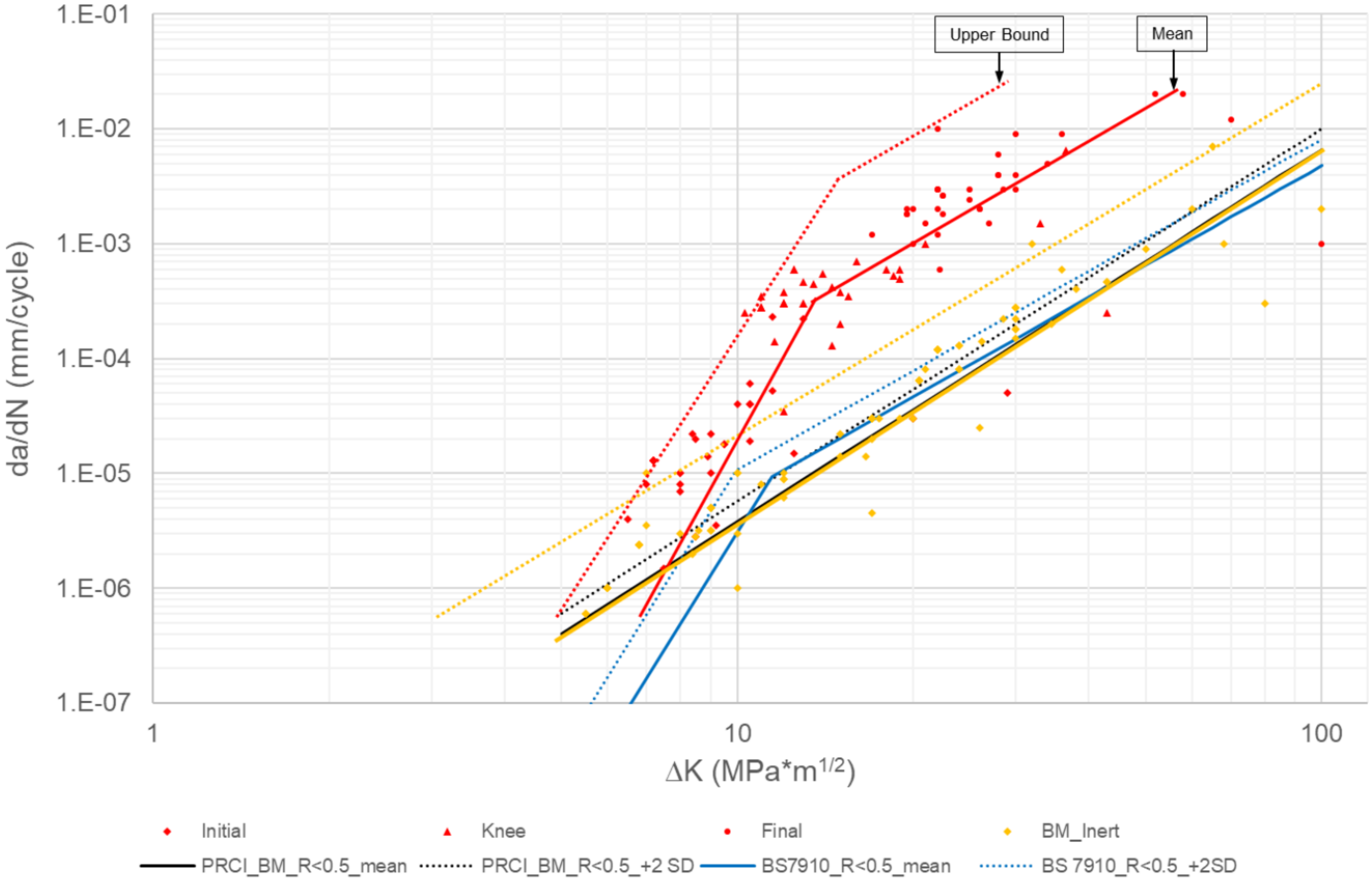
Fatigue Testing Summary - Pipe Body FCGR in Hydrogen

- Compilation of all years & grades
- 1-2 orders of magnitude increase in FCGR



Fatigue Testing Summary - Pipe Body FCGR - Comparisons

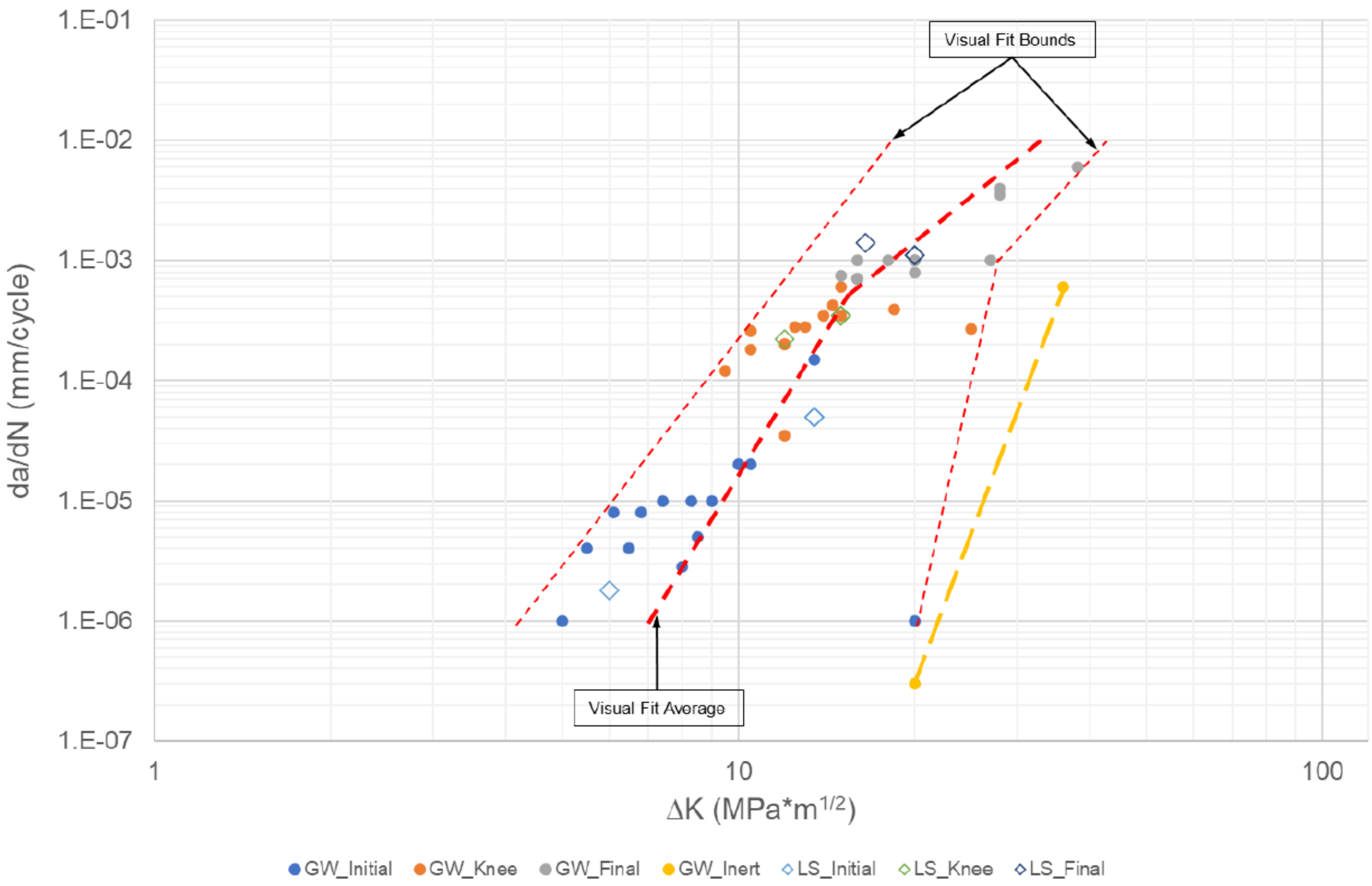
- Collected H_2 literature compared to published inert pipe body test data from PRCI and BS7910 (mean, 2 SD)
  - Significantly more variability in H_2 test data
- Significantly more variability in air test data observed than literature
  - Variability has been reported as ±13-50% for inert testing[1,2]



[1] Slifka, 2018
[2] Drexler, 2016

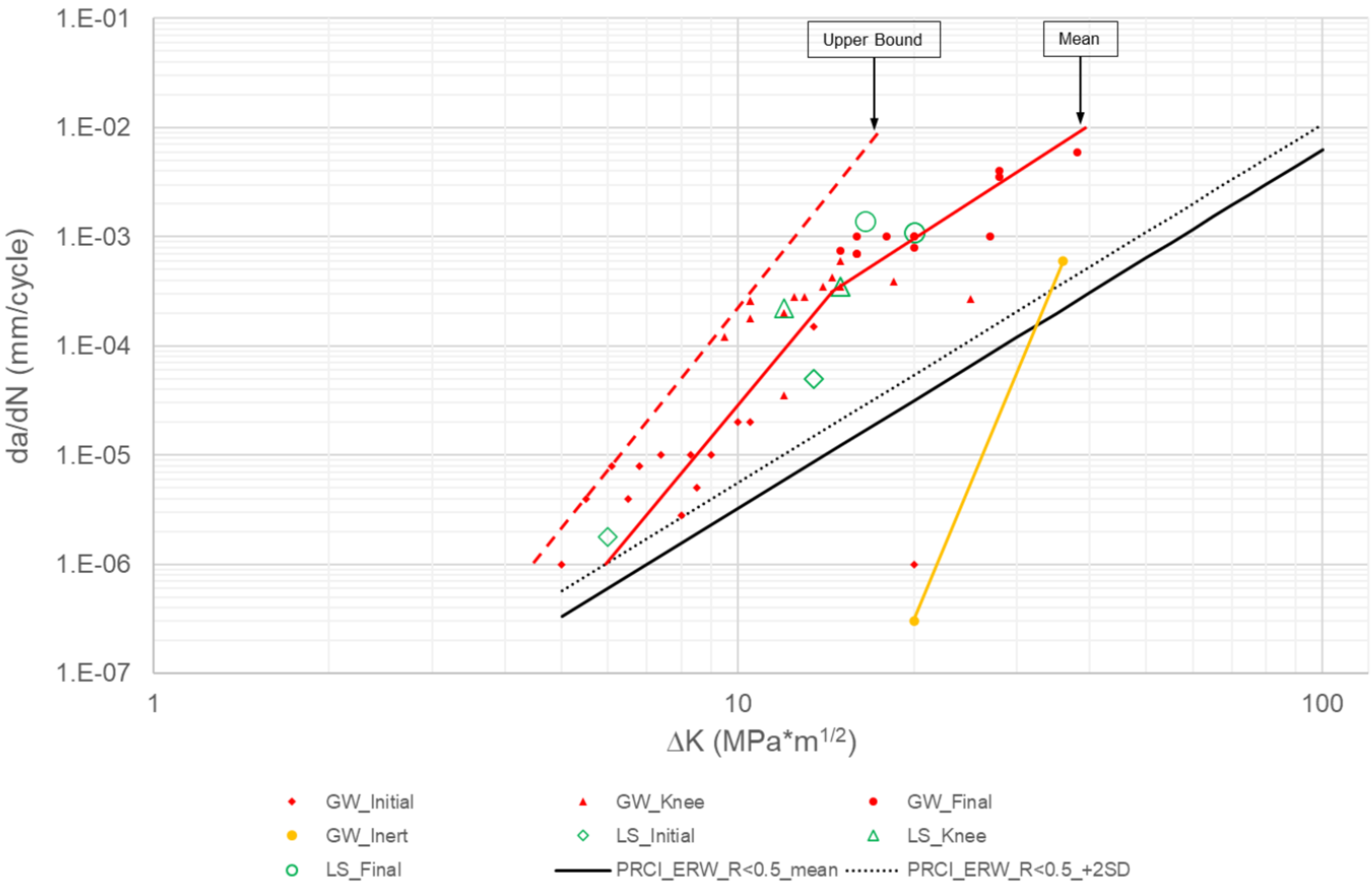
Fatigue Testing Summary - Long Seam & Girth Weld

- Plot shows both long seam and GW results, and worst performance of HAZ or WM (if both were tested)
- Very wide range of fatigue performance observed for all welds



Fatigue Testing Summary - Long Seam & GW Comparisons

- Collected H_2 literature compared to published inert ERW test data from PRCI
- Significantly different trend in weld data is observed
  - Test data: GW
  - Literature: ERW



Project Summary - Gaps & Path Forward

- Expansion in number of unique materials & welds
  - Pre-1970s line pipe as this comprises most of the current gas transmission network
  - Expansion of HAZ testing for both seam weld and girth weld
  - Expansion of modern X70 line pipe data points

- Microstructural & Testing Gaps
  - Limited datapoints suggest that normalized heat treatments produce poorer fatigue performance → may be an issue for modern ERW pipes
  - Banded ferrite-pearlite structures with a perpendicular crack offer improved fatigue performance, however more data points are required to confirm this trend
  - Further work is required to validate or invalidate CVN testing as a safe toughness measurement for hydrogen pipelines

Thank you for your attention.