SAND2023-05020C

Comparison of linear-elastic fracture and elastic-plastic fracture of ferritic steels in gaseous hydrogen

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15th International Conference on Fracture (ICF15)
11-16 June 2023
Atlanta GA

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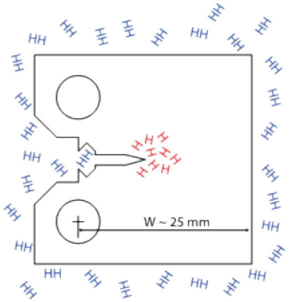
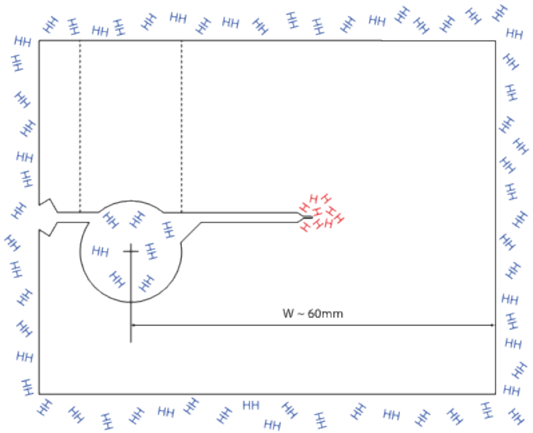
How is fracture measured in gaseous hydrogen?

- **Hydrogen pressure vessels**
  - **ASME BPVC VIII.3 KD-10**
    - ***Fatigue*: ASTM E647**
      - **Linear-elastic fracture mechanics method**
      - **Compact Tension specimen (CT)**
    - ***Fracture*: ASTM E1681**
      - **Linear-elastic fracture mechanics method**
      - **Modified Bolt-Load Compact specimen**
      - **Compact specimen (similar to CT specimen)**
- **Hydrogen pipelines**
  - **ASME B31.12 - refers to BPVC VIII.3 KD-10**

Compact Tension

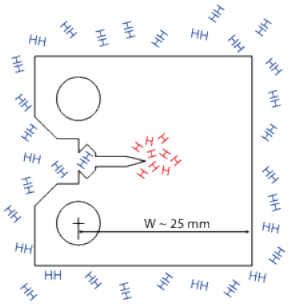




Modified Bolt-Load Compact

How large are typical linear-elastic specimens?

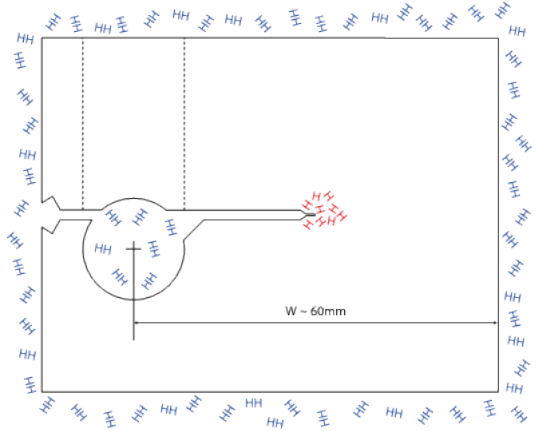
Compact



ASTM E399 specimen
(small)
W = 25 mm
B = 12 mm

E647 specimen
W = 45 mm
B = 6 mm

Modified Bolt-Load Compact



E1681 specimen
W = 60 mm
B = 30 mm

915 mm OD x 10 mm WT
W = 26.4 mm
B = 9.5 mm

406 mm OD x 6.4 mm WT
W = 26.4 mm
B = 5.1 mm

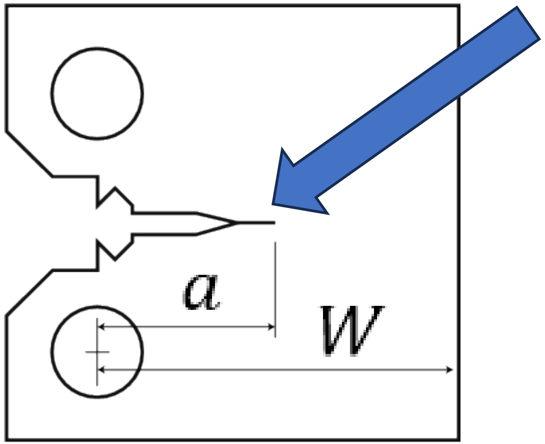
Example CT specimen extraction from line pipe (CL orientation)

Validity requirements for linear-elastic fracture

- **Compact**
- **Compact Tension**
- **Modified Bold-Load Compact**

$$(W - a) \geq 2.5\left(\frac{K_{IEAC}}{S_y}\right)^2$$

a = crack length
W = specimen width
K_{QH} = stress intensity factor
S_y = yield strength



This LEFM requirement is common to ASTM E647, E1681, and E399 for plane-strain, linear-elastic fracture resistance

Secondary validity requirement in ASTM E1681

Thickness *independent* requirement for K_{IEAC}:

$$(W - a) \geq 2.5\left(\frac{K_{IEAC}}{S_y}\right)^2$$

Qualification of thickness *dependent* stress intensity factor threshold (K_{EAC}) for environmental-assisted cracking:

$$(W - a) \geq \frac{4}{\pi}\left(\frac{K_{EAC}}{S_y}\right)^2$$

Assume a / W = 0.5, then:

$$W \geq \frac{8}{\pi}\left(\frac{K_{EAC}}{S_y}\right)^2$$

For example:

- K_{EAC} = 100 MPa $m^{1/2}$
- S_y = 700 MPa

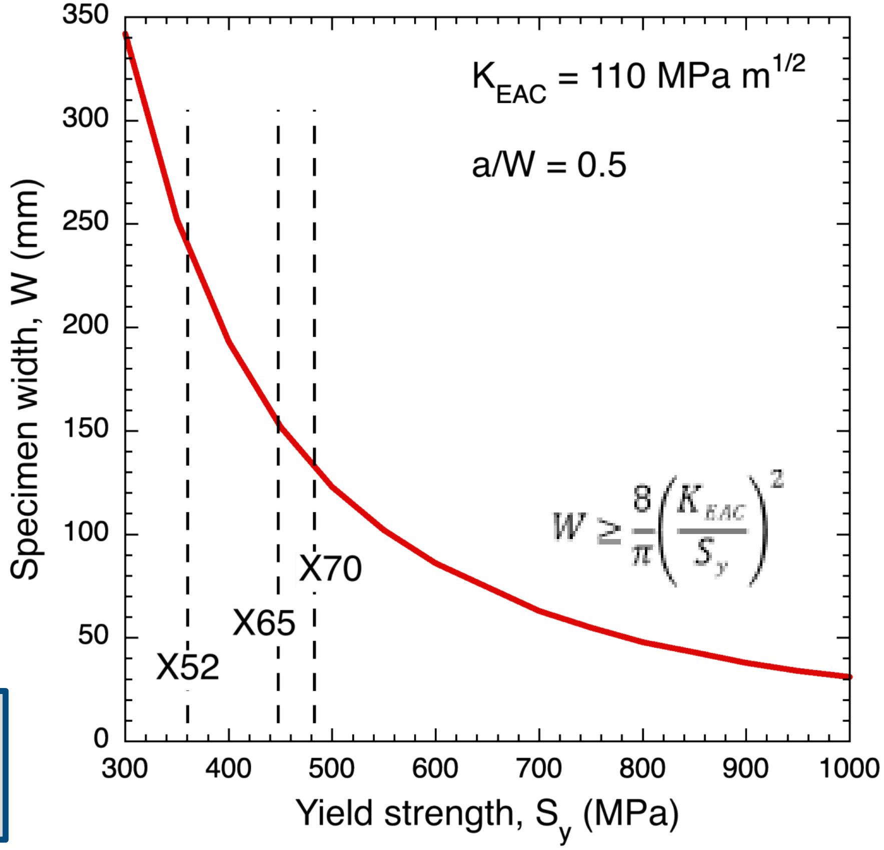
→ $W \geq 52$ mm

What is the minimum specimen size?

Consider the case of low-strength, ductile metals, such as line pipe steel

- **ASME B31.12**
  - Minimum K_{IH} = 55 MPa $m^{1/2}$
- **ASME test method: BPVC VIII.3 KD-10**
  - K_{IH} = ½ K_{EAC} (if no crack propagation)
- **Therefore, in practice, specimens are typically 'over loaded':**
  - $K_{EAC} \geq$ 110 MPa $m^{1/2}$

Specimen size requirements for line pipe steels cannot be satisfied



Elastic-plastic fracture is necessary for ductile metals

ASTM E1820 provides methods for evaluation of elastic-plastic fracture of ductile metals, characterized by J_{IC}

Specimen size requirement from ASTM E1820:

$$(W-a) > 10\frac{J_{IC}}{\sigma_Y}$$

Conversion between linear-elastic and elastic plastic fracture:

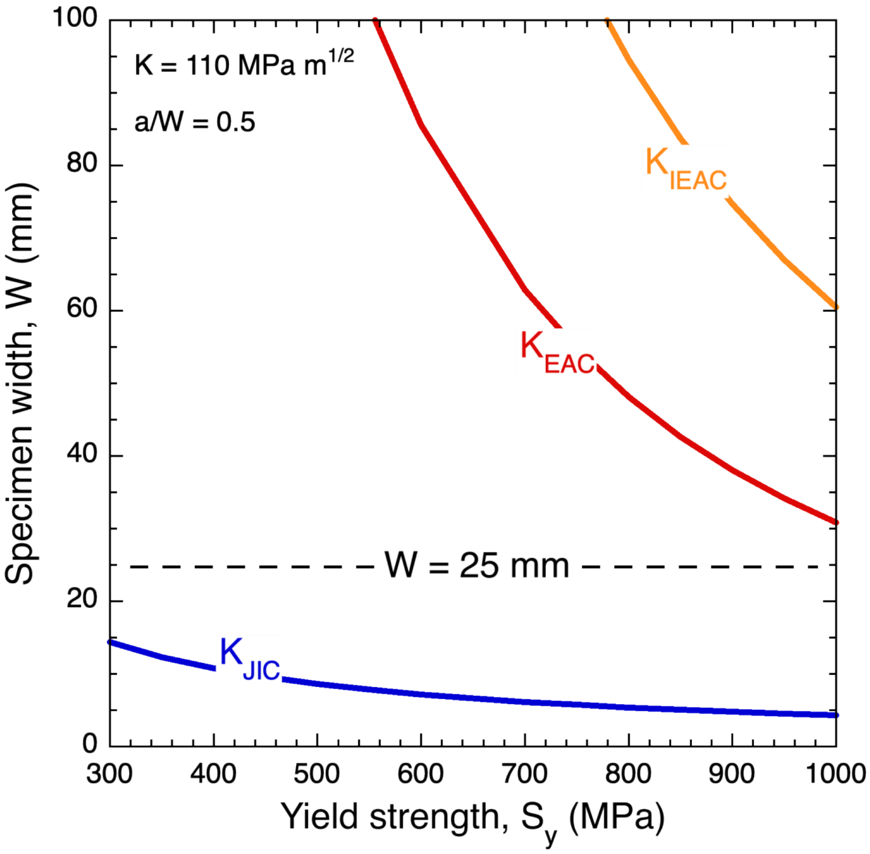
$$K_{JIC} = \sqrt{E'J_{IC}}$$

$$(W-a) > 10\frac{\sigma_Y}{E'}\left(\frac{K_{JIC}}{\sigma_Y}\right)^2$$

J_{IC} = elastic-plastic fracture toughness
σ_Y = effective yield strength
K_{JIC} = linear-elastic fracture toughness
E' = plane-strain elastic modulus

$$10\frac{\sigma_Y}{E'} \sim 0.015 \text{ to } 0.03$$

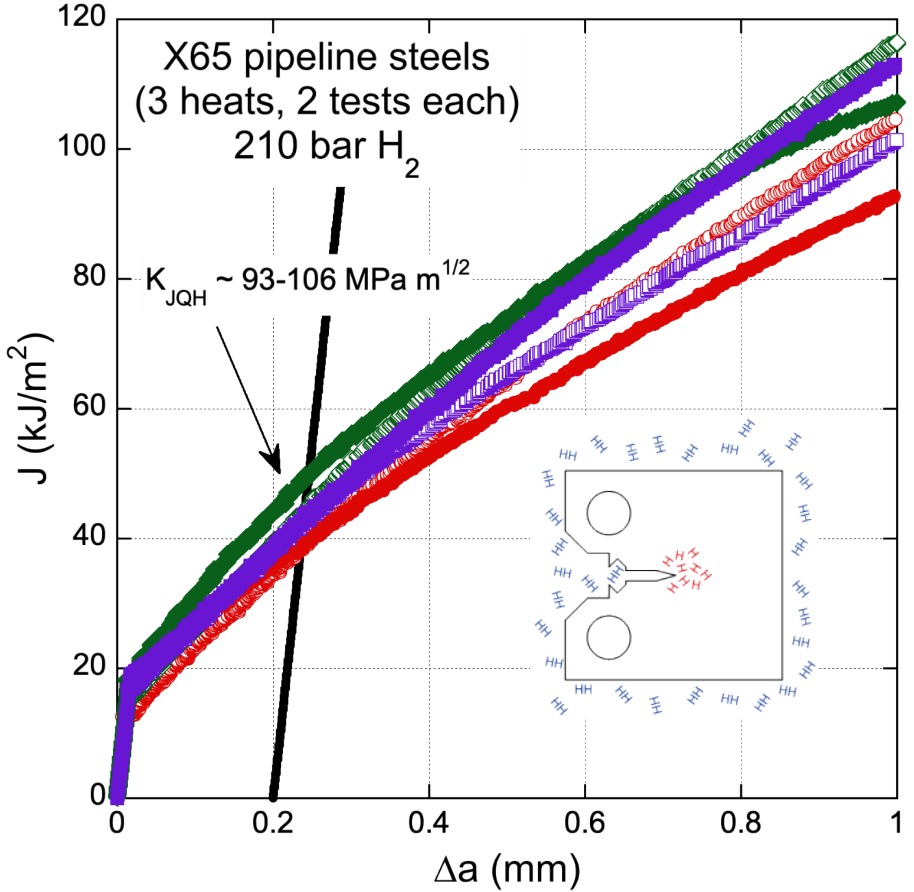
Comparison of specimen sizes



- **ASTM E1681 requires exceptionally large specimens for determining fracture thresholds of low-strength, high ductility steels**
- **ASTM E1820 elastic-plastic fracture can be measured using specimens that are ~100x smaller than ASTM E1681 specimens**
  - **Compact tension specimens with *W* > 25mm are generally adequate to satisfy requirements of E1820**

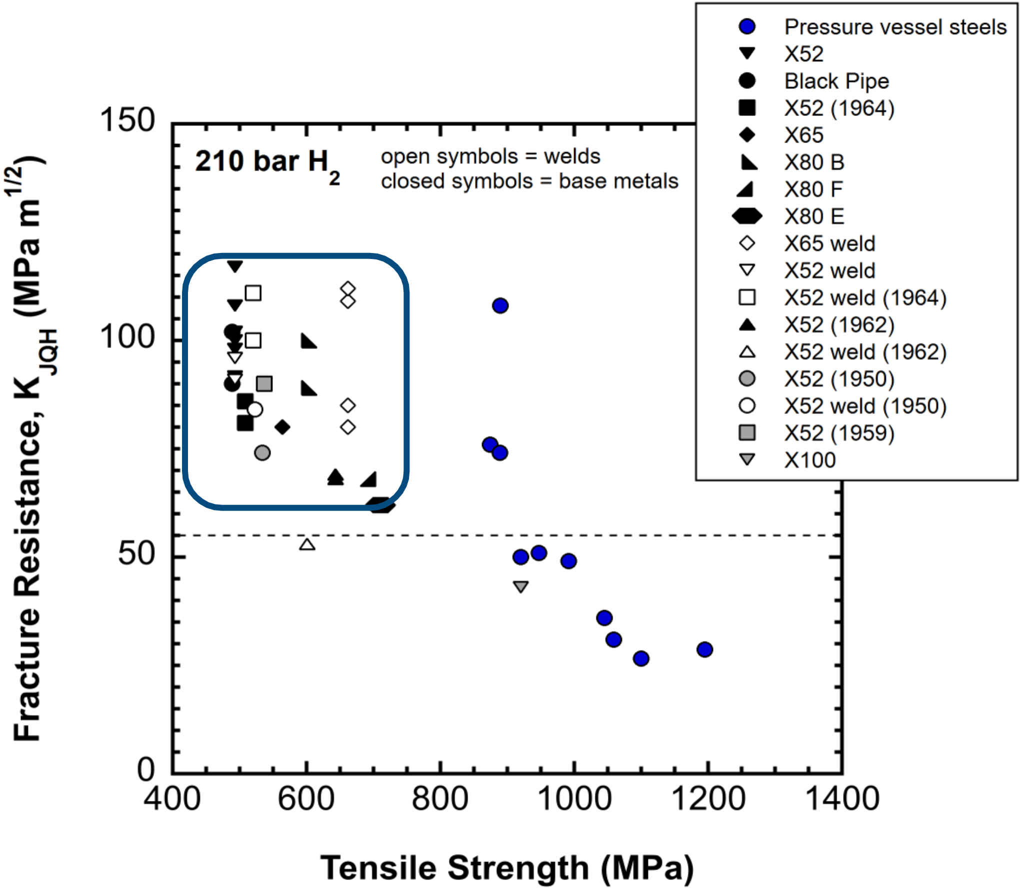
Application of fracture testing to GH2 environments

- **Elastic-plastic fracture test method (ASTM E1820) is used to evaluate J_{IC} (JR curve & 0.2mm offset)**
  - **For tests in gaseous hydrogen (GH2), fracture is designated: J_{QH} and K_{JQH}**
  - **These measurements satisfy the requirements of specimen size**
  - **Thin specimens do not always satisfy requirements of crack front straightness**

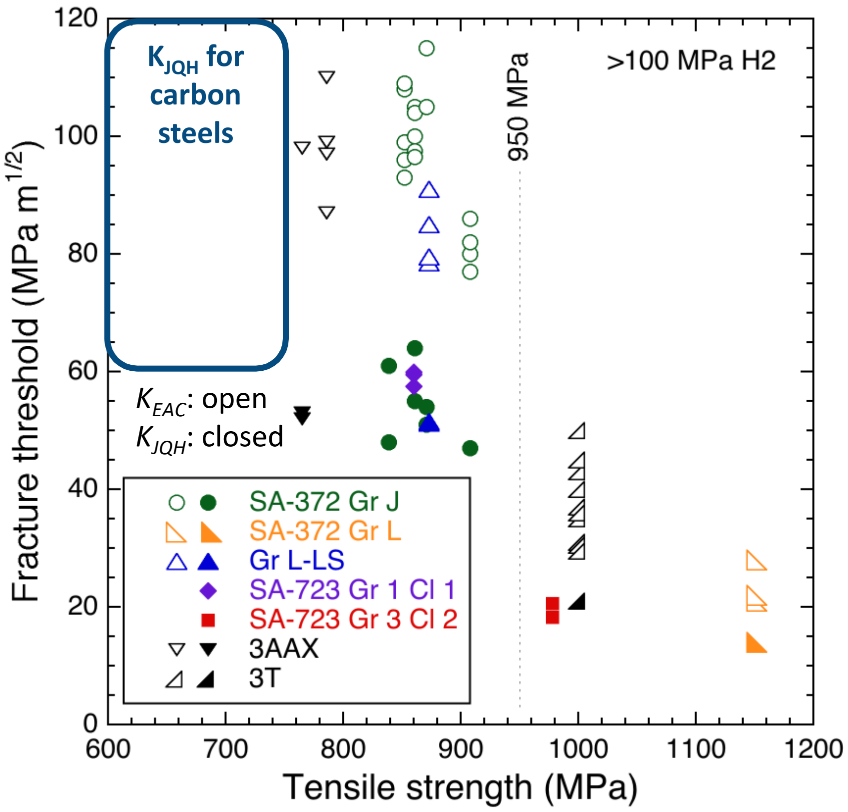


GH2-assisted fracture is characterized by plasticity

- **Low-carbon steels display K_{JQH} ~ 60 to 120 MPa $m^{1/2}$ depending on the strength**
- **High-strength steels (tensile strength >950 MPa) display K_{JQH} < 50 MPa $m^{1/2}$**
- **Impractically large specimens would be needed to satisfy linear-elastic methods**
  - **both for fracture threshold (E1681) and fracture toughness testing (E399)**



Comparison of LEFM and EPFM in GH2



- **LEFM measurements (ASTM E1681)**
  - **ASME KD-10 designates threshold for fracture in GH2 as K_{IH} = ½ K_{EAC} for no crack propagation (NCP)**
  - **Otherwise, measured values depend on loading condition and violate specimen size requirements**
- **EPFM measurements (ASTM E1820)**
  - **Method not included in ASME codes**
  - **Measured values are significantly lower than threshold values: $K_{EAC} >> K_{JQH}$**

Additional considerations

- **Threshold measurements (ASTM E1681)**
  - The crack tip strain evolves differently in threshold measurements
  - Strain is normally applied in an inert environment (i.e., bolt loading), thus plasticity-mediated fracture in hydrogen is circumvented – in other words, strain must accumulate in the presence of hydrogen to manifest hydrogen-assisted fracture
  - Compatible with stress-based fracture; not strain-based fracture (see Nibur *et al*, Met Trans 44A (2013) 248-269)
- **Initiation measurements (ASTM E1820)**
  - Strain accumulates in the presence of GH2 in a rising load fracture test, thus plasticity-mediated fracture processes are captured
  - Compatible with both stress-based and strain-based fracture

Concluding remarks

- **Threshold and LEFM test methods (ASTM E1681 and E399) are not adequate to evaluate GH2-assisted fracture of pipeline and pressure vessel steels**
  - **Specimen size requirements essentially manage plasticity**
  - **ASTM E1681 over-predicts fracture resistance of these steels in GH2 due to plasticity**
  - **ASME KD-10 attempts to manage this by definition for case of NCP: $K_{IH} = ½ K_{EAC}$**
    - **Result: LEFM bounds resistance to GH2-assisted fracture inconsistently**
- **EPFM test methods (ASTM E1820) capture strain-based fracture processes that characterize hydrogen-assisted fracture of pipeline and pressure vessel steels**

Elastic-plastic fracture test methods are recommended for the qualification of engineering alloys for GH2 service

Thank You!

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Special thanks to Sandia's Hydrogen Effects on Materials Laboratory (HEML) team:

Joe Ronevich

James McNair
Brendan Davis
Keri McArthur

Rob Wheeler
Fernando Leon-Cazares
Milan Agnani