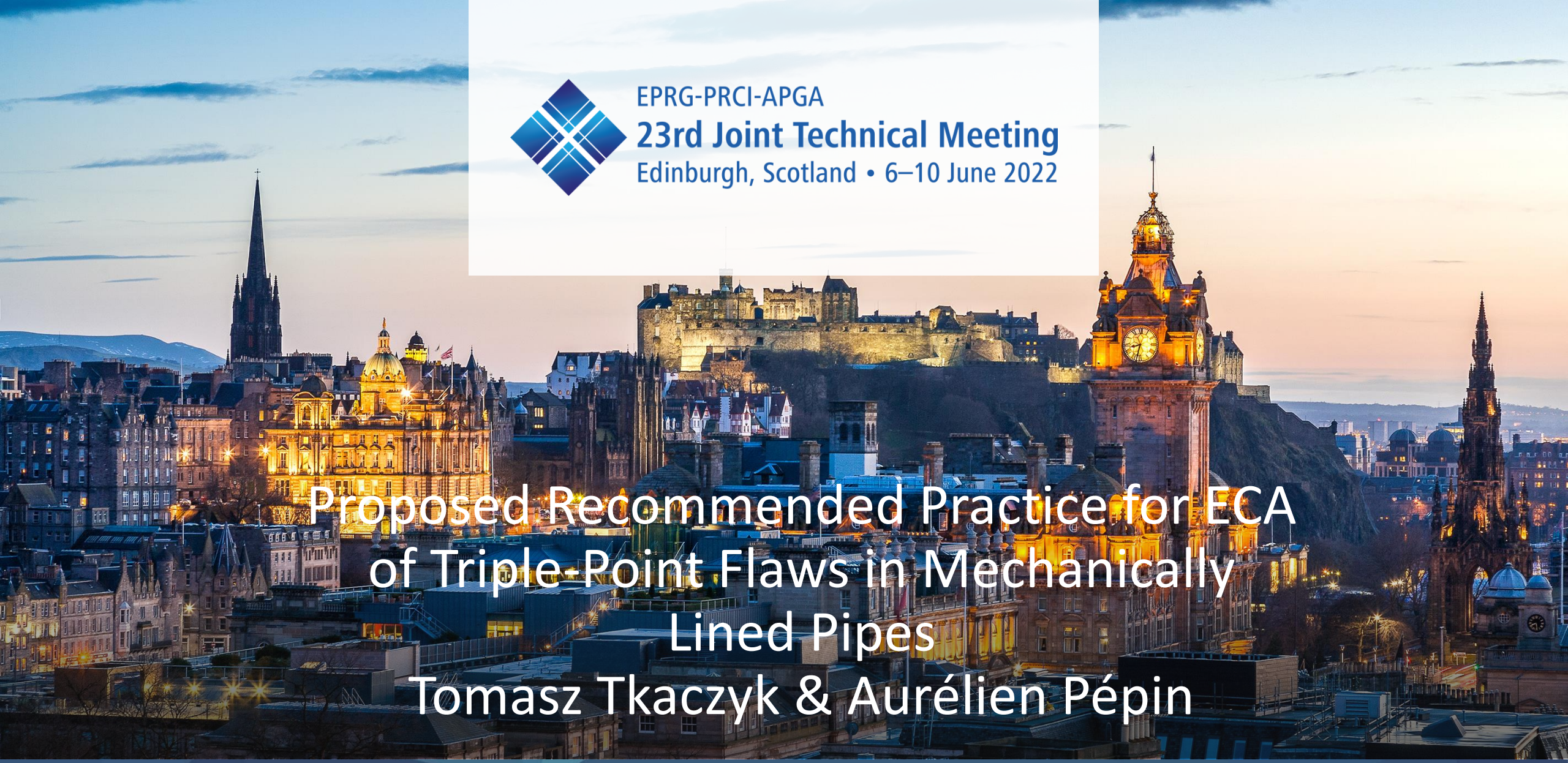

EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland • 6–10 June 2022

Proposed Recommended Practice for ECA of Triple-Point Flaws in Mechanically Lined Pipes

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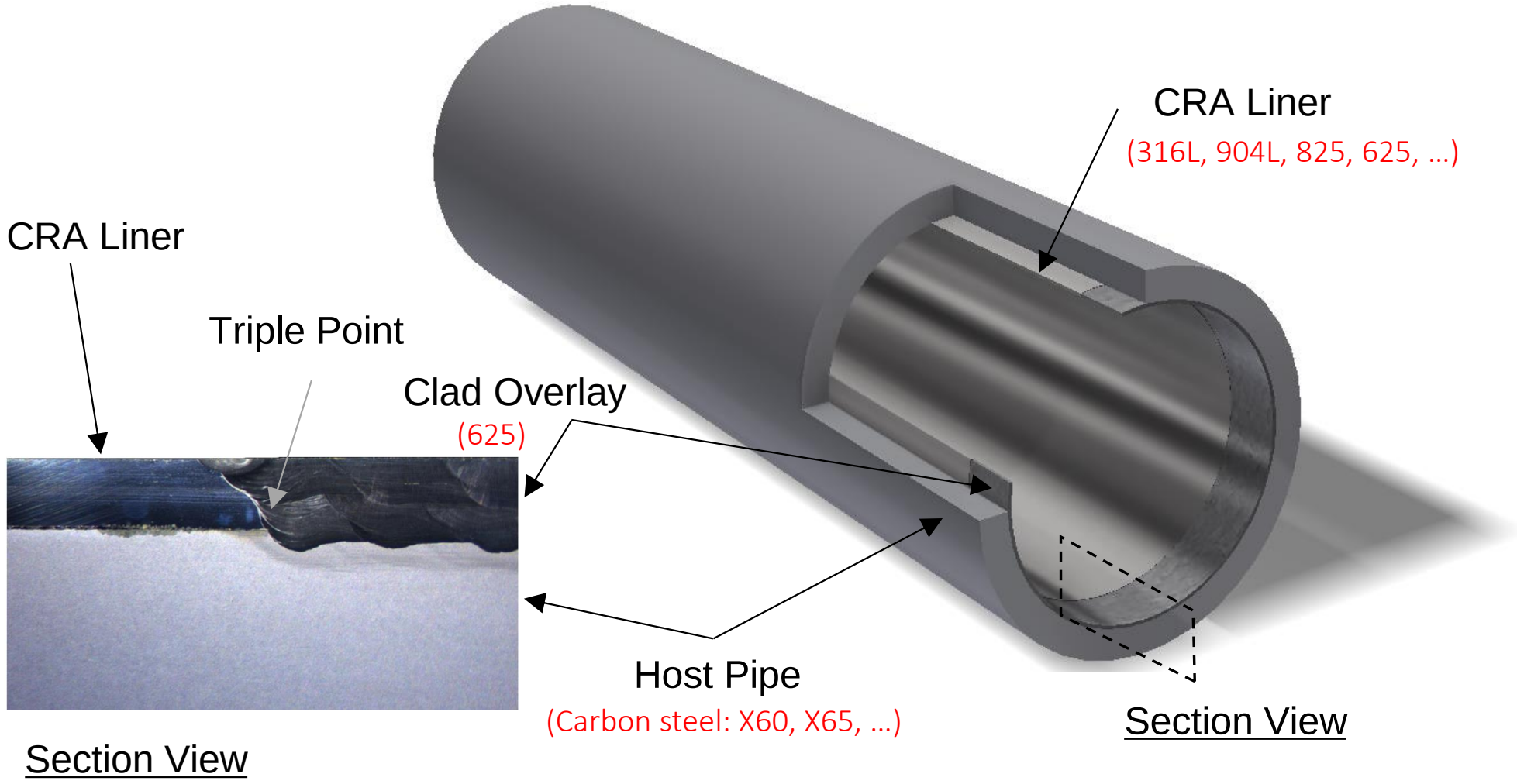
23 June 2022

Agenda

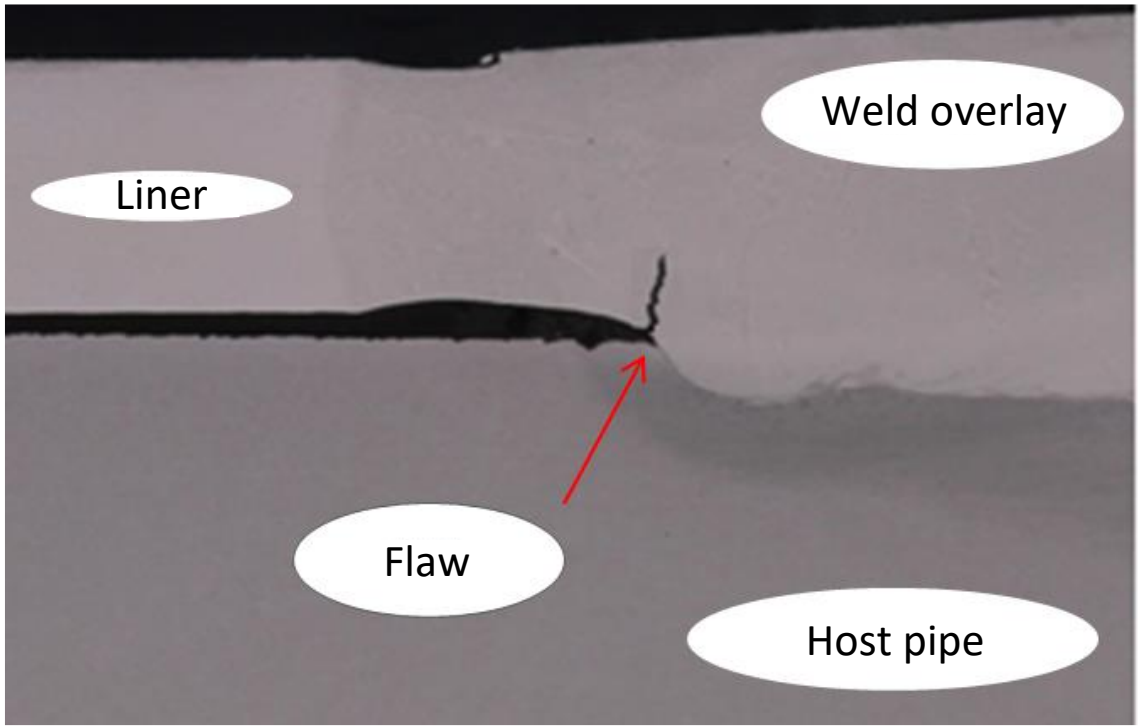
- Mechanically lined pipe (MLP)
- Problem statement
- Four-level engineering critical assessment (ECA)
  - Level 0: Workmanship criteria
  - Level 1: Screening ECA
  - Level 2: Simplified ECA
  - Level 3: Comprehensive ECA
- Fatigue and fracture assessments
  - MLP-specific stress intensity factor and crack driving factor solutions
  - Fracture segment testing
- Conclusions and recommendations for further work

Mechanically Lined Pipes



Problem Statement

- Cracks may initiate at the triple-point from fabrication flaws, and grow during installation and subsea operation
- CRA layer is relatively thin and NDE has a finite detectability limit
- ECA is required to evaluate the integrity of the CRA layer during the pipeline's life
- No crack driving force or stress intensity factor solutions available
- No fracture testing procedures exist
- No recognised ECA approach available
- MLP cannot be repaired at fabrication yard or installation vessel

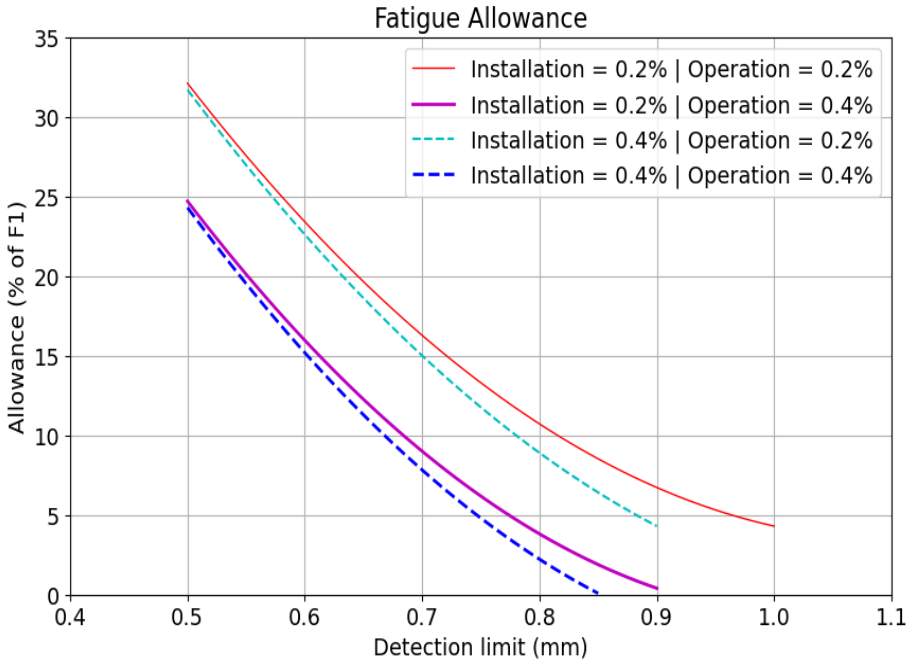


Four Level ECA Approach

- Level 0: Workmanship Criteria
  - Defines the min. detectable flaw height requirements for given fracture and fatigue loads
    - Fatigue load: **Fatigue damage** expressed as a percentage of the DNV F1 S-N design curve
    - Fracture load: Installation and operation **strains**
- Levels 1 to 3: Screening, Simplified and Comprehensive ECA
  - Verify the integrity of the MLP with a triple-point flaw
    - Starter flaw size = Detectability limit, **PoD 90%|95%** or **PoR 85%|95%**
  - Fatigue assessment
    - **Fatigue crack grow** calculation as per the **Paris law** with an **MLP-specific stress intensity factor** solution
    - Fatigue crack growth curve for Steel in Air, $R \geq 0.5$ can be used (crack grows in alloy 625 weld overlay)
  - Fracture assessment
    - **Ductile tearing** estimated with the **tangency method** (Level 1 & 2) or **segment testing** (Level 3)
    - **Crack driving force** obtained from an **MLP-specific CTOD** solution (Level 1) or **finite-element analysis** (Levels 2 & 3)
    - **Lower-bound fracture toughness** defined (Level 1)
    - **Higher fracture toughness** can be used (Level 2)

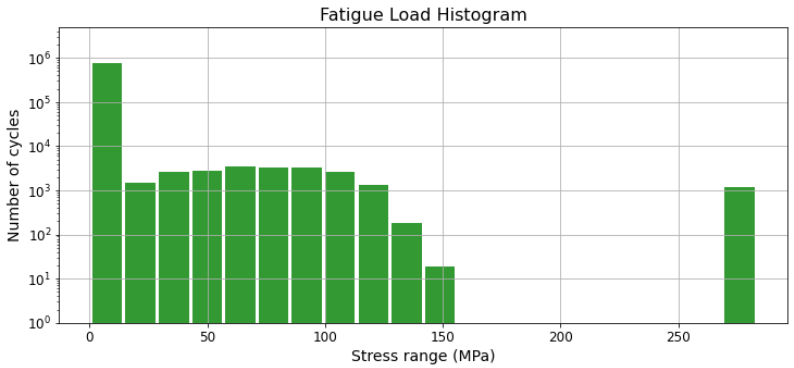
Level 0: Workmanship Criteria

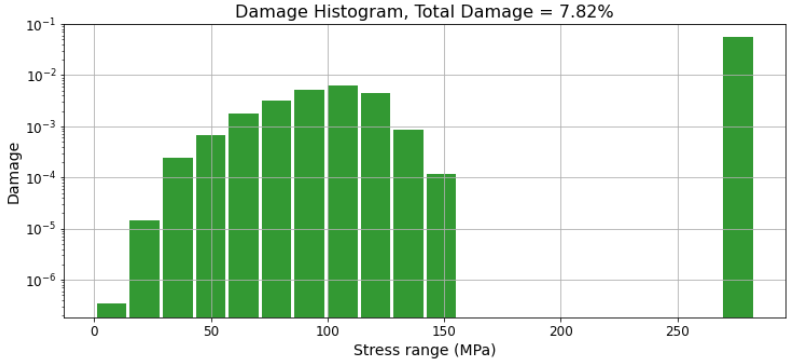
- Application
  - J & S-lay: Installation and operation strains ≤ 0.4%
- Conservative assumptions
  - Fully circumferential triple-point flaws
  - Pre-defined tensile properties
  - Pre-defined lower-bound fracture toughness: $\delta_R = 0.24\ \Delta a^{0.32}$
  - Fatigue load expressed as percentage of DNV F1 design S-N curve
- Usage
  - Knowing two of the following, determine the third parameter
    - Installation/operation strains
    - Fatigue damage (input) or allowance (output)
    - Min detectable flaw height (input) or max allowed flaw height (output)



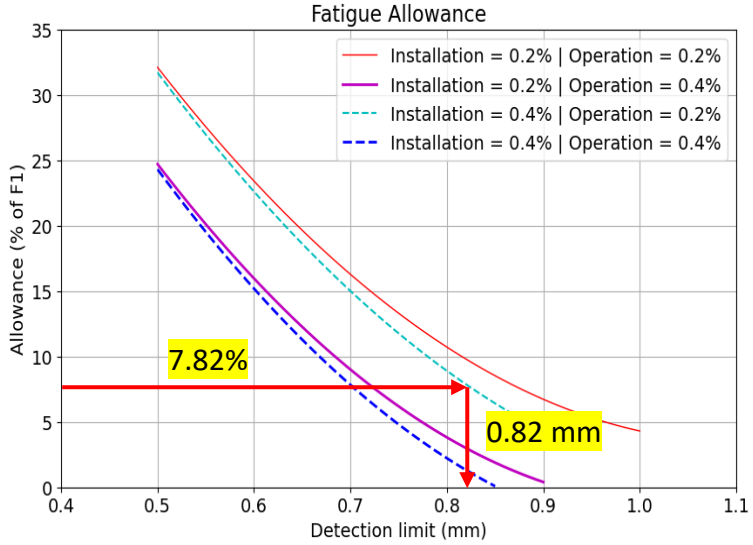
Level 0: Workmanship Criteria

- Example
  - Fracture loads
    - Installation strain: **0.4%**
    - Operation strain: **0.2%**





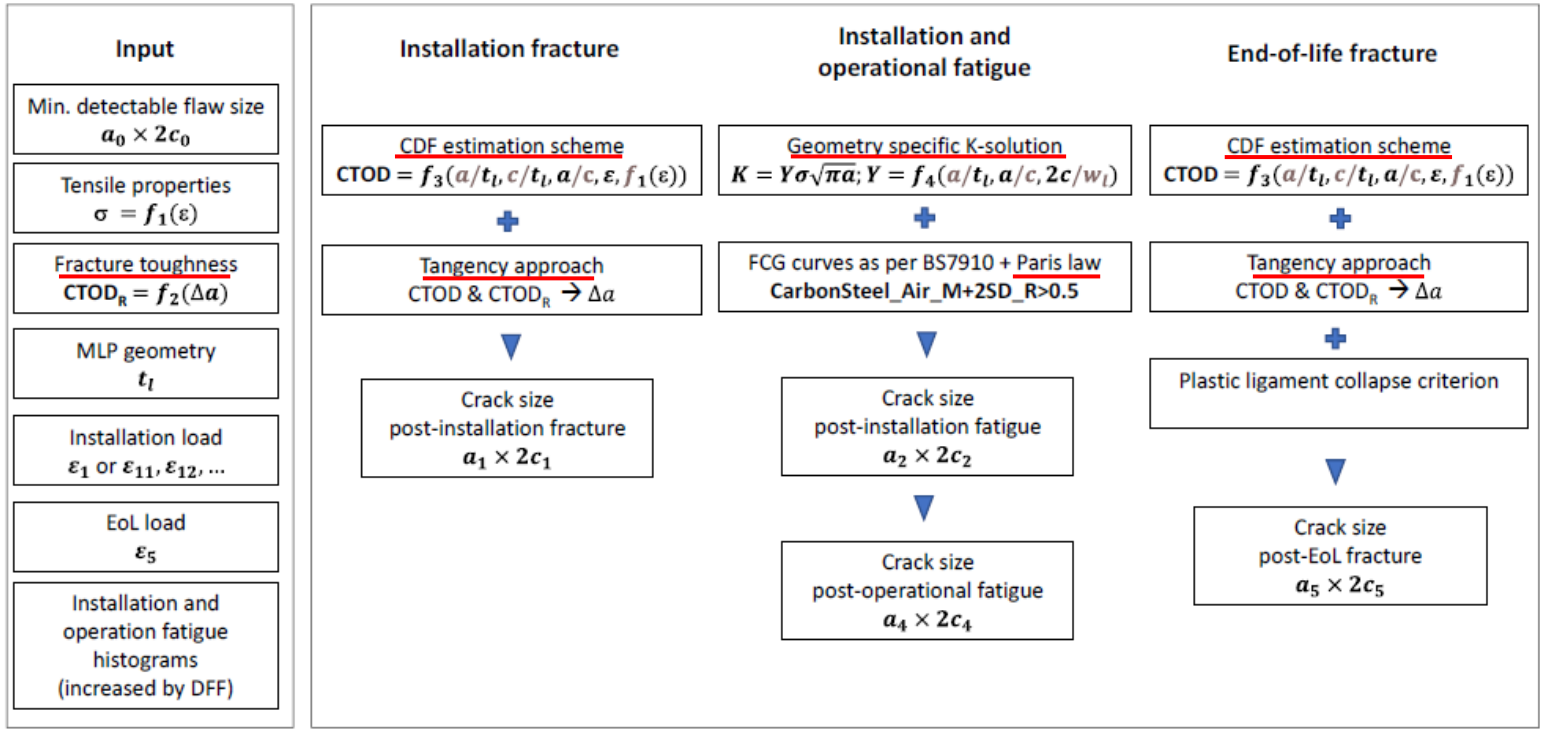
  - Fatigue loads
    - Apply relevant DFF (e.g., installation = 1; operation = 3) on given installation and operation histograms
    - Combine histograms
    - Determine the corresponding fatigue damage: **7.82%** of DNV F1 design S-N curve



  - Required min detectable flaw height
    - PoD 90%|95% = **0.82 mm**

Level 1: Screening ECA

- Application: R, J & S-lay
  - Installation strain ≤ 1.75%
  - Operation strain ≤ 0.4%
- Assumptions
  - MLP-specific K-solution
  - **MLP-specific CTOD-solution** (pre-defined tensile properties)
- **Lower-bound toughness** ($\delta_R = 0.24\ \Delta a^{0.32}$)



Level 2: Simplified ECA

- Application: R, J & S-lay
  - No limit on installation or operation strains
  - No limit on number of strain or facture events
- Assumptions
  - MLP-specific K-solution
  - **Applied CTOD from FEA**
  - **Requires fracture toughness** as input

Installation fracture • Reel-lay, S-lay or J-lay	FEA: Tangency calculation:	$(a_0, a_0+...; 2c_0)$ a_0, δ_0 or $(\delta_{01}, \delta_{02}, ...), \delta_R$	→ δ_0, or $(\delta_{01}, \delta_{02}, ...)$ → $a_1 = a_0 + \Delta a_1$ & $2c_1 = 2c_0 + 2\times\Delta a_1$
Installation fatigue • Fatigue in catenary	Fatigue calculation:	$(a_1, 2c_1)$	→ $a_2 = a_1 + \Delta a_2$ & $2c_2 = 2c_1 + 2\Delta c_2$
SoL fracture (optional) • Fracture at start-of-life	FEA: Tangency calculation:	$(a_2, a_2+...; 2c_2)$ a_2, δ_2, δ_R	→ δ_2 → $a_3 = a_2 + \Delta a_3$ & $2c_3 = 2c_2 + 2\times\Delta a_3$
Operational fatigue • Fatigue in service	Fatigue calculation:	$(a_3, 2c_3)$	→ $a_4 = a_3 + \Delta a_4$ & $2c_4 = 2c_3 + 2\Delta c_4$
EoL fracture • Fracture and stability check at end-of-life	FEA: Tangency calculation:	$(a_4, a_4+...; 2c_4)$ a_4, δ_4, δ_R	→ δ_4 → $a_5 = a_4 + \Delta a_5$ & $p_5 = t_l - a_5$

Level 3: Comprehensive ECA

- Application: R, J & S-lay
  - No limit on installation or operation strains
  - No limit on number of strain or facture events
- Assumptions
  - MLP-specific K solution
  - Applied CTOD from FEA
  - **Ductile tearing from segment testing**

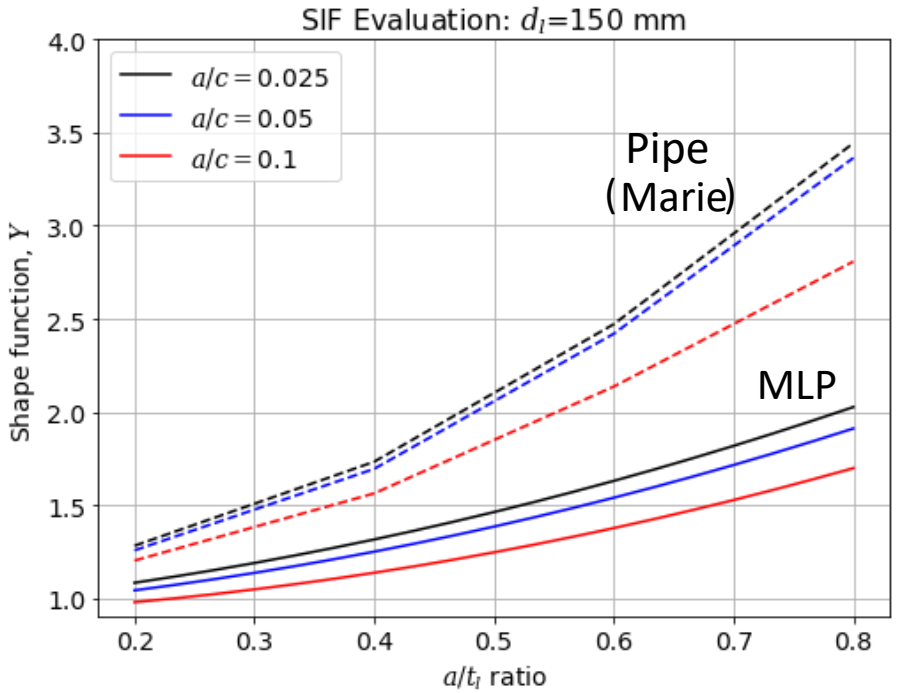
Installation fracture • Reel-lay, S-lay or J-lay	FEA: Segment testing:	$(a_1, 2c_1)$ a_0, δ_1 or $(\delta_{11}, \delta_{12}, \ldots)$	→ δ_1 or $(\delta_{11}, \delta_{12}, \ldots)$ → $a_1 = a_0 + \Delta a_1$ & $2c_1 = 2c_0 + 2\times\Delta a_1$
Installation fatigue • Fatigue in catenary	Fatigue calculation:	$(a_1, 2c_1)$	→ $a_2 = a_1 + \Delta a_2$ & $2c_2 = 2c_1 + 2\Delta c_2$
SoL fracture (optional) • Fracture at start-of-life	FEA: Segment testing:	$(a_3, 2c_3)$ a_2, δ_3	→ δ_3 → $a_3 = a_2 + \Delta a_3$ & $2c_3 = 2c_2 + 2\times\Delta a_3$
Operational fatigue • Fatigue in service	Fatigue calculation:	$(a_3, 2c_3)$	→ $a_4 = a_3 + \Delta a_4$ & $2c_4 = 2c_3 + 2\Delta c_4$
EoL fracture • Fracture and stability check at end-of-life	FEA: Segment testing:	$(a_5, 2c_5)$ a_4, δ_5	→ δ_5 → $a_5 = a_4 + \Delta a_5$ & $p_5 = t_l - a_5$

Fatigue Assessment

- MLP-specific stress intensity factor solution
  - Lower K than for an equivalent flaw in a plate or pipe

$$K = Y\sigma\sqrt{\pi a}$$

$$Y = f\left(\frac{a}{t}, \frac{a}{c}, \frac{d_l}{t}\right)$$

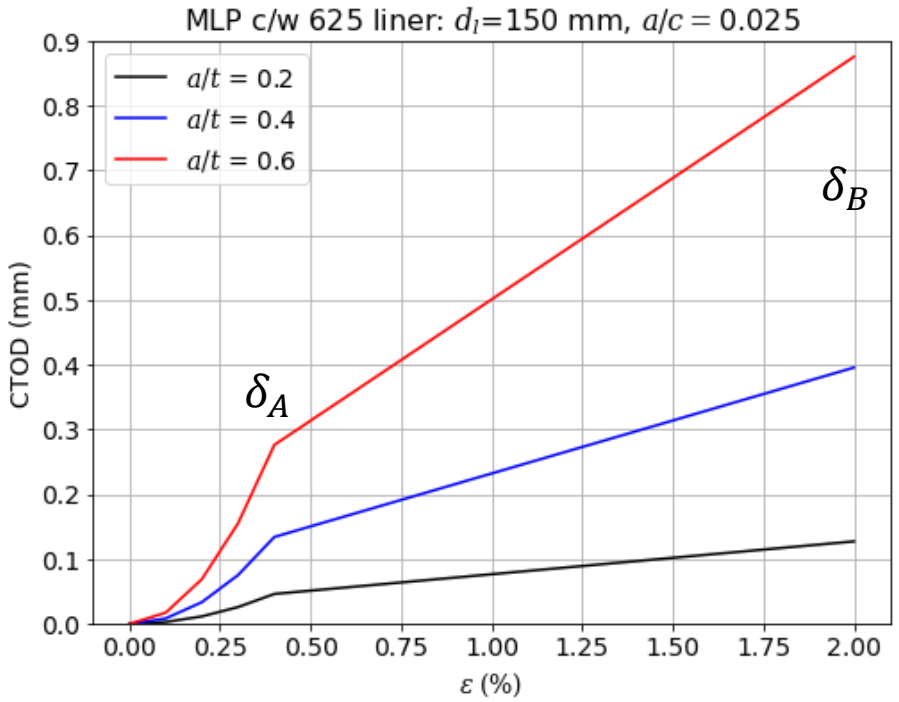


Fracture Assessment

- MLP-specific crack driving force solution (**Level 1**)

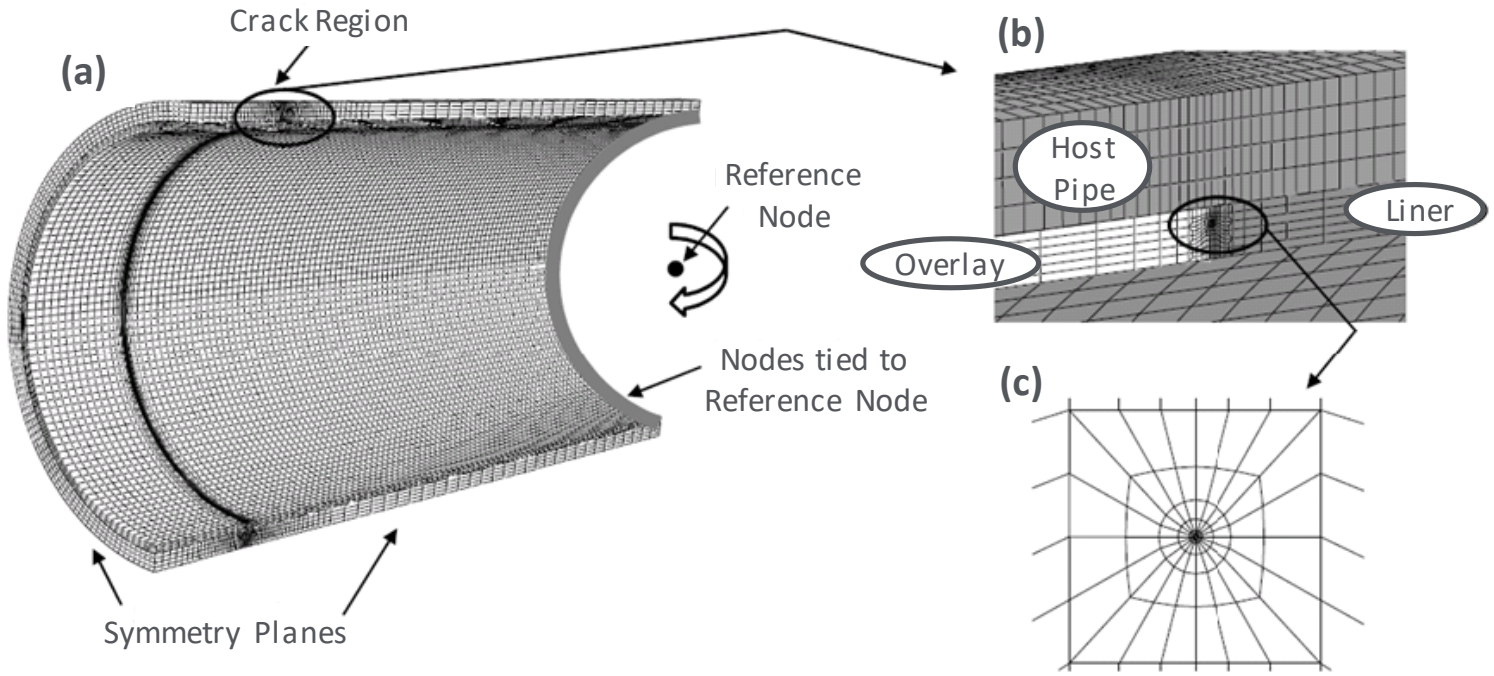
$$\delta = \begin{cases} \dfrac{\delta_A}{1.6 \times 10^{-5}} \varepsilon^2 & \text{for } \varepsilon \le 0.4\% \\ \delta_A + \dfrac{(\varepsilon - 0.004)(\delta_B - \delta_A)}{0.016} & \text{for } 0.4\% < \varepsilon \le 2\% \end{cases}$$

$$\delta_A, \delta_B = f\left(\frac{a}{t}, \frac{c}{t}, \frac{a}{c}, t\right)$$



Fracture Assessment

- Crack driving force (**Levels 2** & **3**)

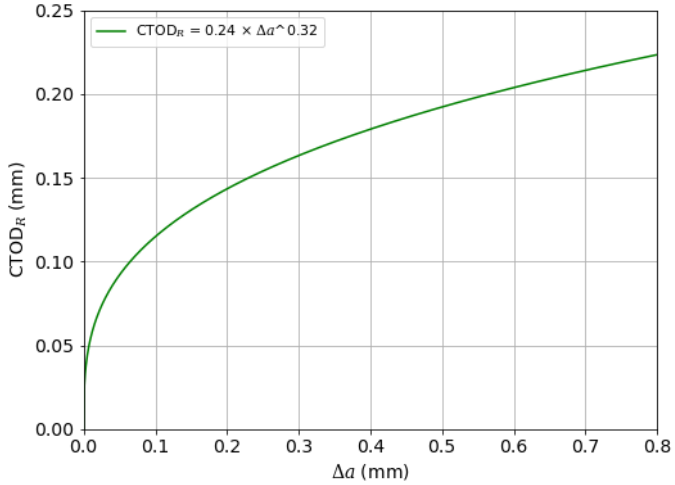


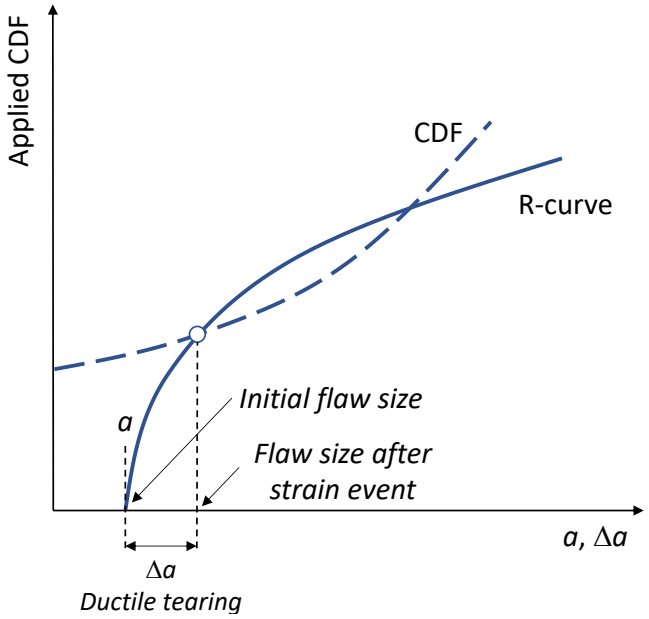
Fracture Assessment

- Lower-bound fracture toughness (**Level 1**)
  - Based on generic SEN(T) and segment testing
    - SEN(T) testing of alloy 625 weld overlay
    - Segment testing of triple-point region (MLP with alloy 625 and 904L liners)

- Higher fracture toughness (**Level 2**)
  - Based on historical segment testing for a specific vendor, material grades and weld overlay procedure, or
  - Obtained from non-standard fracture toughness testing

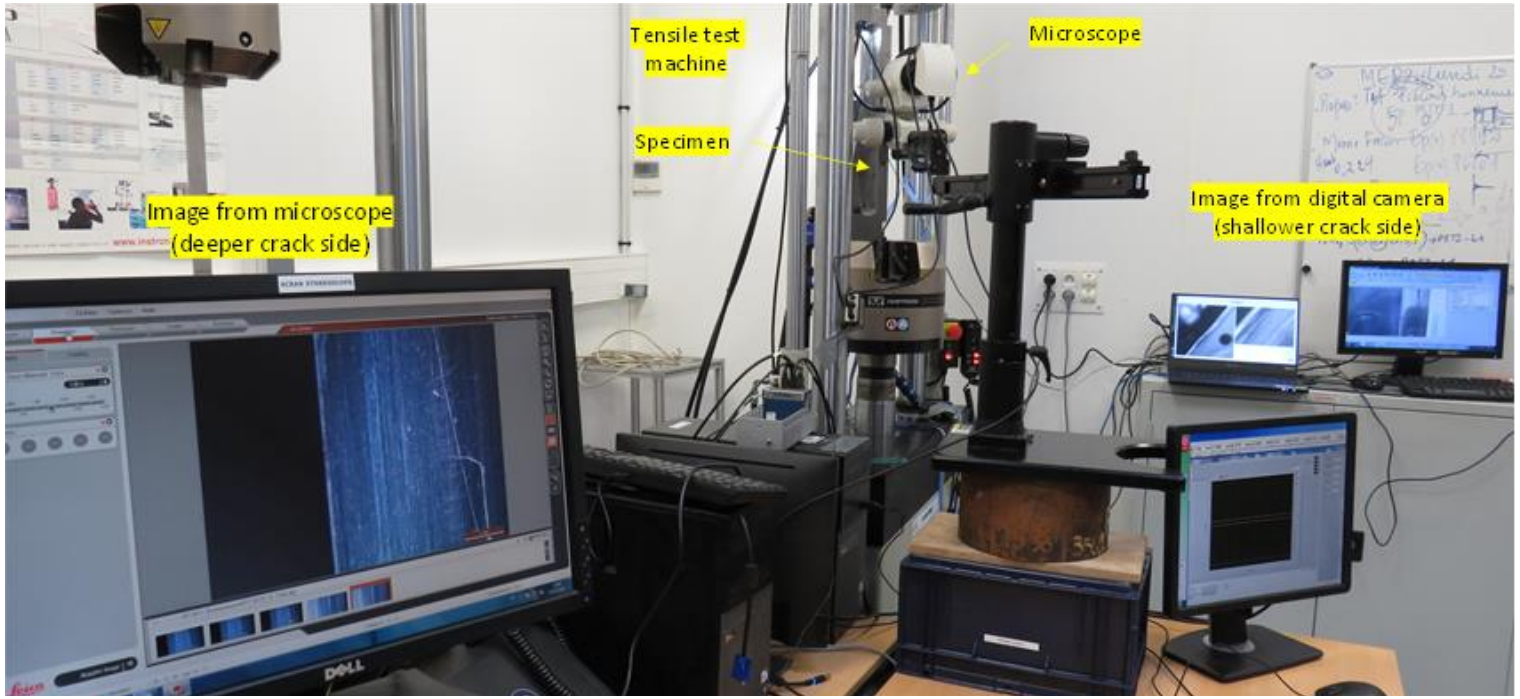
- Tangency method for ductile tearing estimation

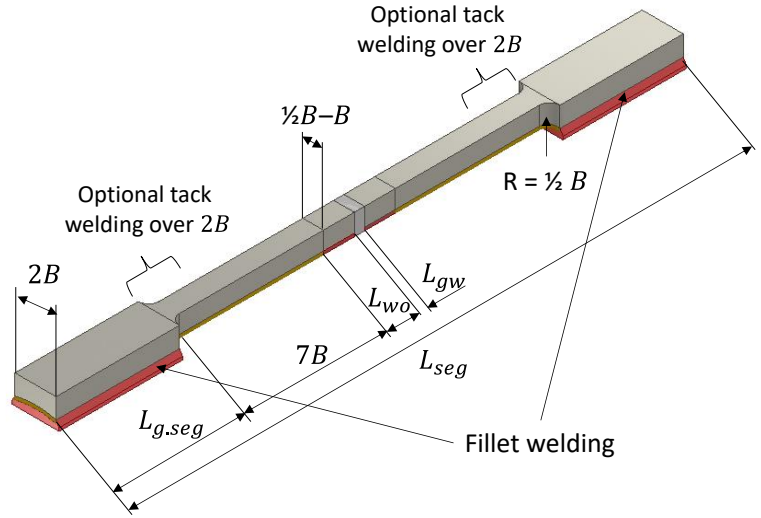


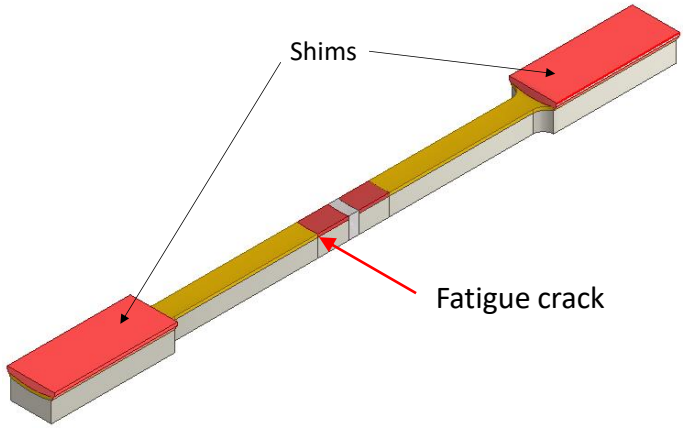


Segment Testing

- Set-up and segment specimen geometry

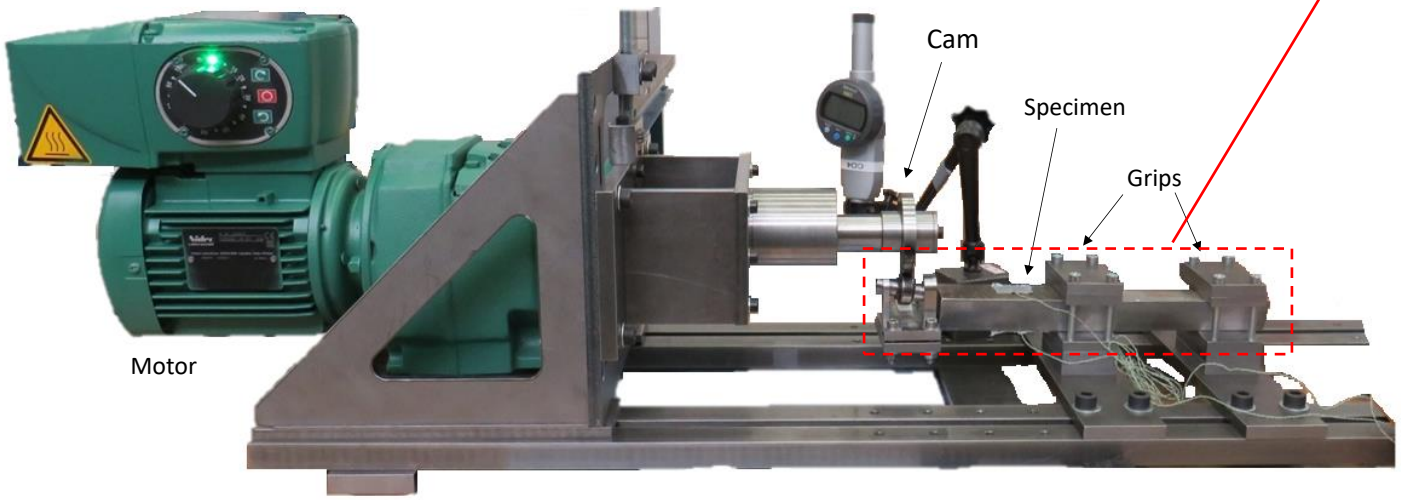


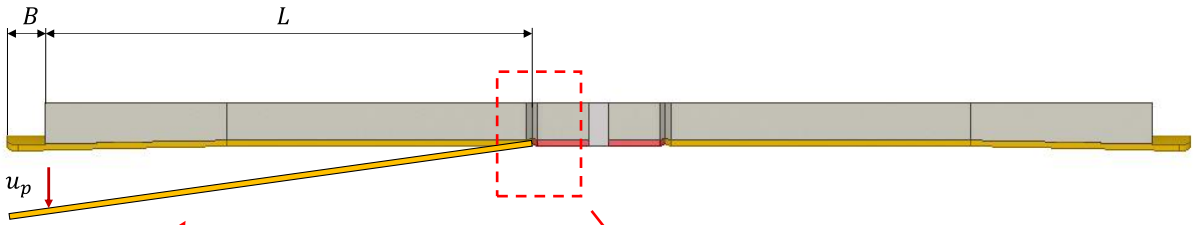


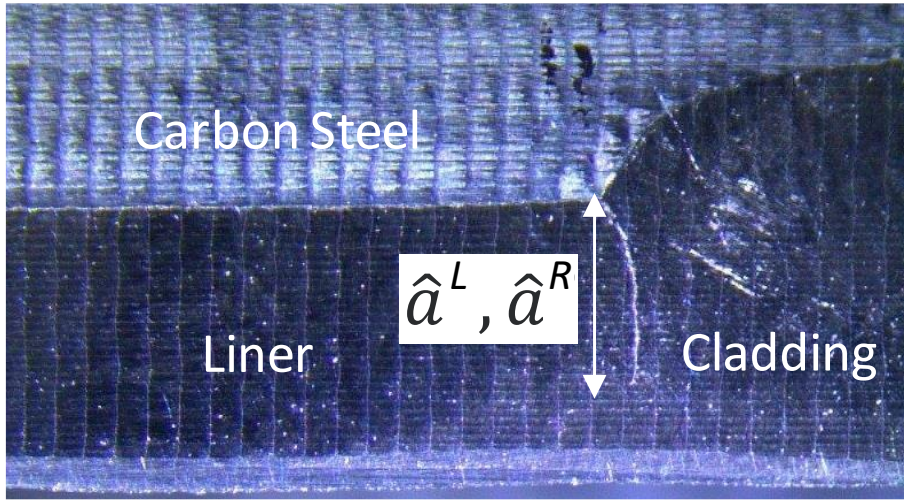


Segment Testing

- Fatigue pre-cracking

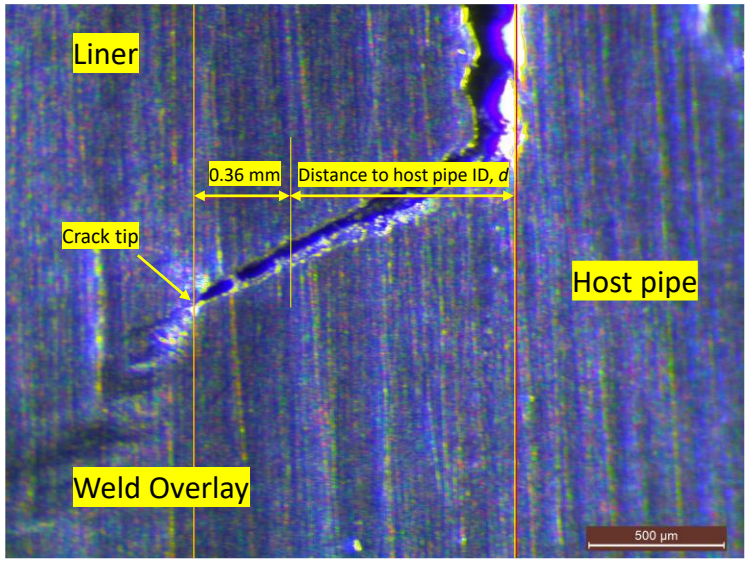


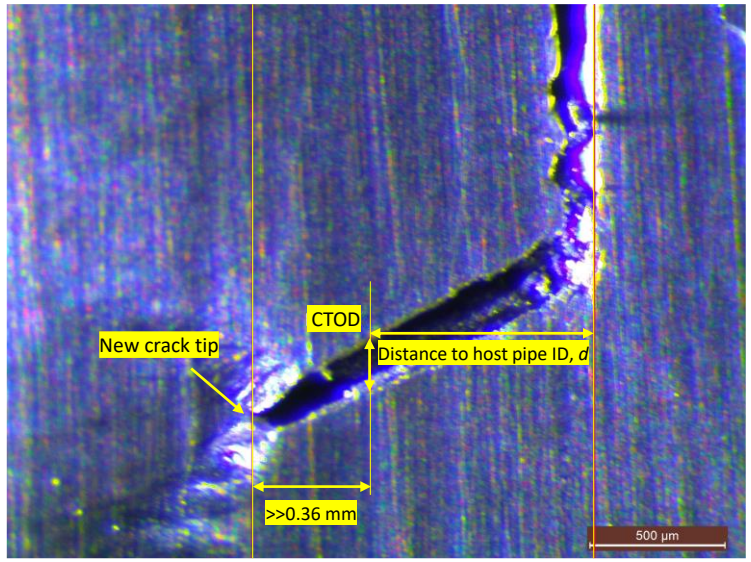


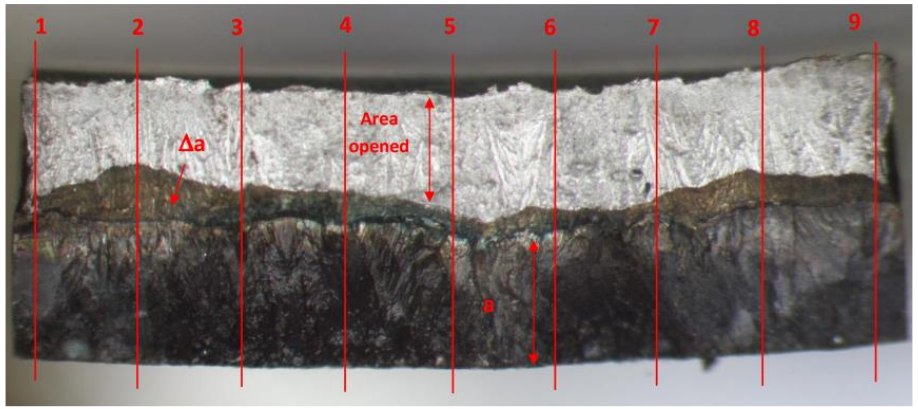


Segment Testing

- Fracture testing and fractography







Conclusions and Recommendations for Further Work

- Four-level ECA approach proposed
  - Level 0: Workmanship criteria defined
  - Levels 1 to 3: Combined fatigue and fracture assessment
- Fatigue assessment
  - Levels 1 to 3: MLP-specific stress intensity factor solution defined for use with the Paris law
- Fracture assessment
  - Crack driving force
    - Level 1: MLP-specific crack driving force solution defined
    - Levels 2 & 3: FEA used to determine the applied CTOD
  - Toughness
    - Level 1: Lower-bound CTOD-R defined
    - Level 2: Higher toughness based on historical segment or non-standard fracture testing can be used
  - Ductile tearing
    - Level 1 & 2: Tangency method applied to estimate ductile tearing
    - Level 3: Segment testing procedure developed and validated
- Recommendations for further work
  - Develop non-standard fracture testing method to be used within the Level 2 framework

Thank you for your attention