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PROPOSED RECOMMENDED PRACTICE FOR ECA OF TRIPLE-POINT FLAWS IN MECHANICALLY LINED PIPES
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ABSTRACT

Mechanically lined pipes (MLP) are being increasingly used for the subsea transport of highly corrosive well fluids. To address a gap related to the lack of an industry recognised engineering critical assessment (ECA) approach for MLP with cracks that may initiate and grow at a triple-point between the liner, weld overlay and carbon steel pipe, EPRG is sponsoring a project to develop a dedicated ECA methodology.

The proposed methodology involves four assessment levels, each increasing in complexity. The ECA Level 0 provides workmanship criteria for pipelines subjected to low installation strains, which allow defining the required triple-point detectability limit solely based on the maximum strains and fatigue loads during installation and operation. For pipelines subjected to more onerous loading during installation or service, higher assessment levels are available. The ECA Level 1 allows fast screening assessment without mechanical testing or finite-element analysis (FEA). A crack tip opening displacement (CTOD) estimation scheme is developed for two representative MLP material combinations and a lower-bound fracture toughness curve is proposed based on the results of segment testing for several MLP material and geometry combinations. Those are used in the tangency method to estimate ductile tearing. A geometry-specific stress intensity factor (SIF) is proposed for accurate estimation of the fatigue crack growth as per the Paris law in any of the three higher assessment levels. The conservatism associated with ductile tearing estimation in the ECA Level 1 can be avoided by progressing to the ECA Level 2 where the CTOD is obtained from FEA using the project-specific material tensile properties. The knowledge of representative fracture toughness, either based on historical segment testing results or obtained from non-standard testing methods is the pre-requisite for applying the ECA Level 2. If fracture toughness is unknown, then segment testing is undertaken as per the ECA Level 3 to determine ductile tearing associated with the considered fracture scenario.

1. INTRODUCTION

There is increasing demand for subsea transport of well-produced fluids requiring the use of corrosion resistant pipes such as solid stainless steel or bimetallic pipes. The latter, which often offer the best compromise between corrosion resistance, tensile strength, and cost, are made of an outer carbon steel pipe hosting a thin internal layer of corrosion resistant alloy (CRA) such as S31603 (316L), N08825 (825), N06625 (625) or N08904 (904L). The CRA internal layer may be adhered metallurgically or mechanically by means of an interference fit. Although less mature than both solid stainless-steel and hot roll bonded clad pipes with a metallurgical bond, MLP with a mechanical bond, shown in Figure 1, are readily available and more cost attractive.

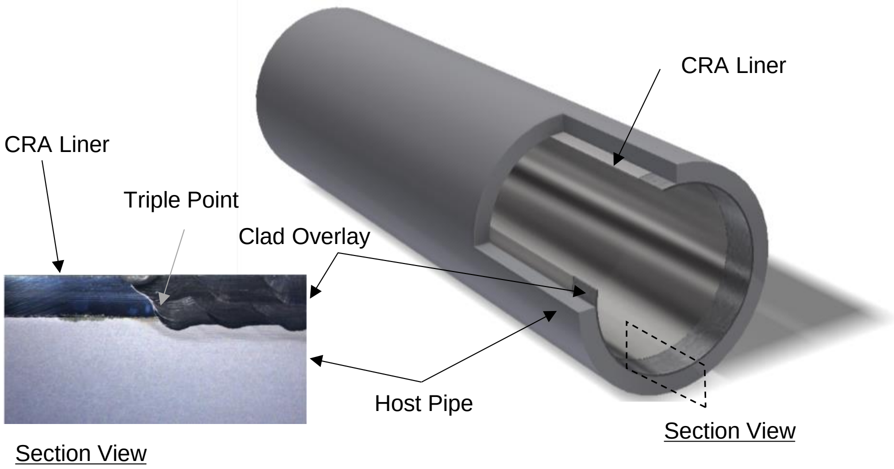


Figure 1: Mechanically Lined Pipe

To seal the annulus between carbon steel and CRA layers and allow automatic ultrasonic testing (AUT) of girth welds between MLP joints, the CRA liner is metallurgically bonded to the carbon steel outer pipe at the joint ends by overlay welding, typically deposited using alloy 625 consumable. At the triple-point between the liner, weld overlay and carbon steel pipe, cracks may initiate from fabrication flaws and grow during installation or operation, see Figure 2. Therefore, an ECA is required to evaluate the integrity of the CRA layer during the pipeline's life. The EPRG has acknowledged that no industry recognised ECA approach existed, and thus is sponsoring a project to develop a dedicated ECA methodology.

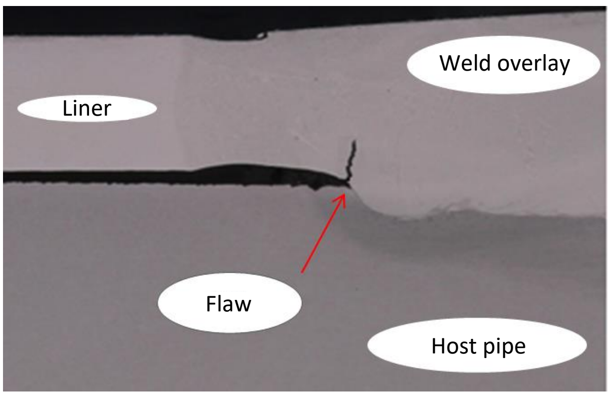


Figure 2: Crack at Triple-Point

2. ECA OF MLP WITH TRIPLE-POINT FLAWS

The proposed ECA approach comprises four levels. The workmanship criteria or, ECA Level 0, provides the relationship between the minimum detectable flaw height and fatigue allowance. The minimum detectable flaw height is defined as the 90% probability of detection at the 95% confidence interval (PoD 90%|95%) or the 85% probability of rejection at the 95% confidence interval (PoR 85%|95%). The fatigue allowance, which also depends on the installation and operation strains, is expressed as a percentage of the DNV F1 design S-N curve [1]. The ECA Level 0 is intended for assessment of pipelines installed by methods inducing low monotonic strains (e.g., S-lay, J-lay).

When higher (>0.4%), or cyclic strains are applied during installation (during reel-lay, for instance), then the ECA Level 1, 2 or 3 is required. To facilitate rapid integrity assessment, the CTOD estimation scheme and lower-bound fracture toughness resistance curve (CTOD-R) for the triple-point are proposed in the ECA Level 1. In addition, an MLP-specific SIF solution is defined.

In line with Level 1, fatigue crack growth (FCG) in the ECA Level 2 is estimated as per the Paris law [2], using the proposed geometry-specific SIF solution while ductile tearing is determined by the tangency method [3]. However, the ECA Level 2 employs FEA to derive the CTOD at the assessment strain for a range of flaw sizes, and a CTOD-R curve superior to the proposed lower-bound CTOD-R curve can be used, if justified.

Finally, the ECA Level 3 follows the same calculation approach as the ECA Level 2 but adds fracture segment testing to quantify ductile tearing and verify the crack ligament stability under installation and service fracture loads. It specifies specimen geometry, and procedures and equipment for pre-cracking segment specimens at the triple-point and conducting fracture testing and fractography.

3. WORKMANSHIP CRITERIA: ECA LEVEL 0

The workmanship criteria, in terms of the fatigue allowance for a range of minimum detectable flaw heights, are developed using the ECA Level 1 for MLP with predefined tensile and toughness properties, and fully circumferential triple-point flaws. The criteria are presented in the format shown in Figure 3.

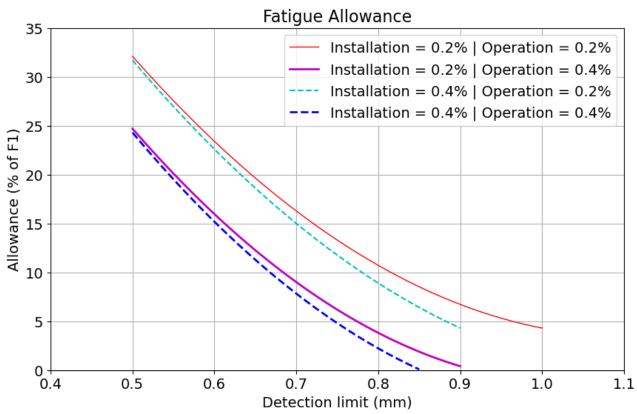


Figure 3: Graphical Illustration of Workmanship Criteria

Knowing the installation and operation fatigue loads, a combined fatigue histogram inclusive of appropriate design fatigue factors (DFF) as per [1], is defined. For the example combined histogram in Figure 4, the fatigue damage, $D_{fat} = 7.8\%$, is obtained from,

$$D_{fat} = \sum_{i}^{m} \frac{n_i}{N_i} \qquad \text{Equation 1}$$

where m is the number of bins in the combined histogram, and n_i and N_i are respectively the number of cycles in the i-th bin and corresponding number of cycles to failure for the DNV F1 design S-N curve. Assuming further that the pipeline is subjected to a maximum strain of 0.4% and 0.2% (excl. residual strain) during installation and operation respectively, a minimum detectable flaw (PoD 90%|95% or PoR 85%|95%) of 0.82 mm in height needs to be qualified. Alternatively, installation or operation fracture or fatigue loads should be optimised, or a higher assessment level undertaken to reduce conservatism.

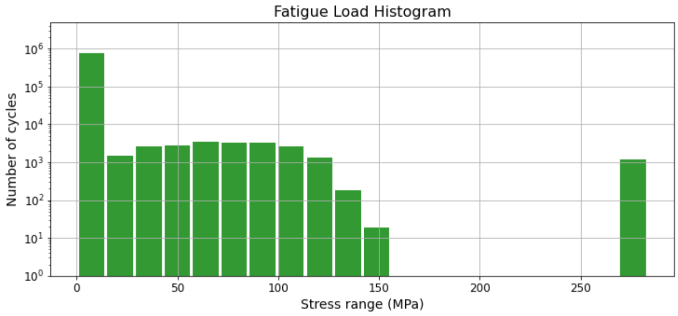


Figure 4: Example of Combined Installation and Operation Histogram

4. HIGHER ASSESSMENT LEVELS: ECA LEVELS 1 TO 3

4.1. General

The ECA Level 1 can be applied to scenarios where the maximum strains during installation and operation do not exceed 2% and 0.65% respectively (including residual strain). In contrast, there is no limitation on the maximum strain or number of installation or operation strain events in the ECA Level 2 or 3. For all three ECA levels, assessment starts with defining a minimum detectable flaw size at the triple-point (PoD 90%|95% or PoR 85%|95%); either partially or fully circumferential flaws can be assessed. The flaw growth is then estimated for a series of consecutive loads, including installation fracture, installation fatigue, operation fatigue and finally end-of-life (EoL) fracture.

The fatigue assessment approach, which is common for the three ECA levels, is explained first. This is followed by discussion on the fracture assessment which involves calculations as per the tangency approach and, for the ECA Level 3, fracture segment testing.

4.2. Fatigue Assessment

Fatigue crack growth during installation and service is determined as per the Paris law [2], using a geometry-specific SIF developed for MLP under tension,

$$K = Y\sigma\sqrt{\pi a} \qquad \text{Equation 2}$$

where σ and a are the remote stress and crack height, respectively. A dimensionless shape function, Y, is proposed to be a second order polynomial function of the normalised crack height, $\frac{a}{t}$, crack aspect ratio, $\frac{a}{c}$, and liner diameter to thickness ratio, $\frac{d_l}{t}$,

$$Y = f\left(\frac{a}{t}, \frac{a}{c}, \frac{d_l}{t}\right) \qquad \text{Equation 3}$$

Using this SIF solution instead of solutions available for flaws in flat plates (Raju and Newman, BS 7910 [4]), or pipes (e.g., Marie et al. [5]), increases accuracy of the FCG estimation and avoids excessive conservatism. Figure 5 illustrates the benefits of the proposed SIF solution (indicated with the solid lines) by comparing it to the Marie et al. solution (indicated with the dashed lines) for the three crack aspect ratios, $\frac{a}{c}$ = 0.025, 0.05 and 0.1.

Triple-point flaws grow in the weld overlay, which is often deposited using an alloy 625 consumable. It is shown in [6], that the FCG rate in alloy 625 is lower than that in carbon steel. Thus, if a FCG curve for the weld overlay material at the representative conditions (temperature and stress ratio, R) is not available, it is acceptable to apply the BS 7910 FCG curve for Steel in Air (Mean + 2SD, R ≥ 0.5) [4]. Before undertaking a FCG calculation, the installation and operational fatigue histograms are adjusted by appropriate DFF. Finally, the stress-intensity magnification factor and stress concentration factor are both taken to be 1 as the weld overlay is normally flush with the liner, see Figure 1.

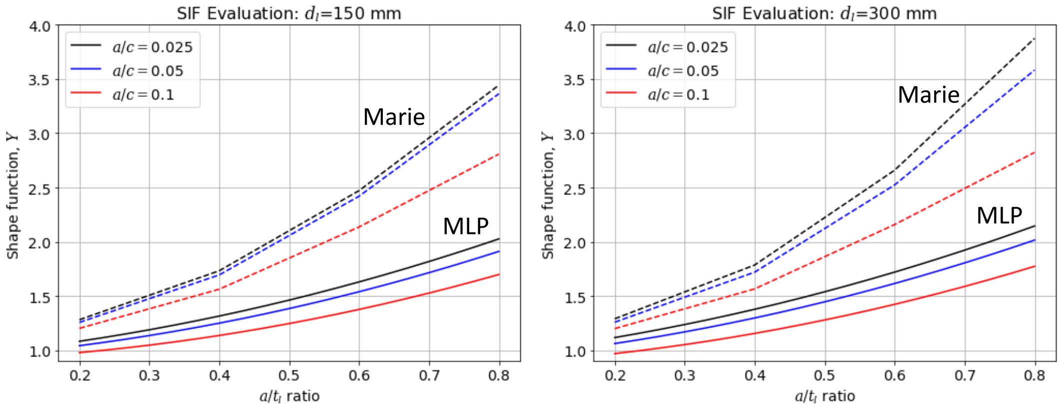


Figure 5: Comparison of SIF Solutions for MLP and Pipe

4.3. Fracture Assessment

4.3.1. General

Crack advance by ductile tearing is estimated by either the tangency method (ECA Levels 1 and 2) or segment testing (ECA Level 3). The tangency method requires inputs in terms of the CTOD, defined as crack opening at a 0.36 mm offset from the original crack tip [7] for a range of crack heights at the assessment strain, and fracture resistance curve (CTOD-R curve). The CTOD is obtained from a CTOD estimation scheme developed in this program (ECA Level 1) or FEA (ECA Levels 2 and 3). A typical FEA model is shown in Figure 6. A lower-bound CTOD-R curve is proposed for use with ECA Level 1; an R-curve superior to the lower-bound toughness can be used with higher ECA levels, if justified, see the Fracture Toughness section.

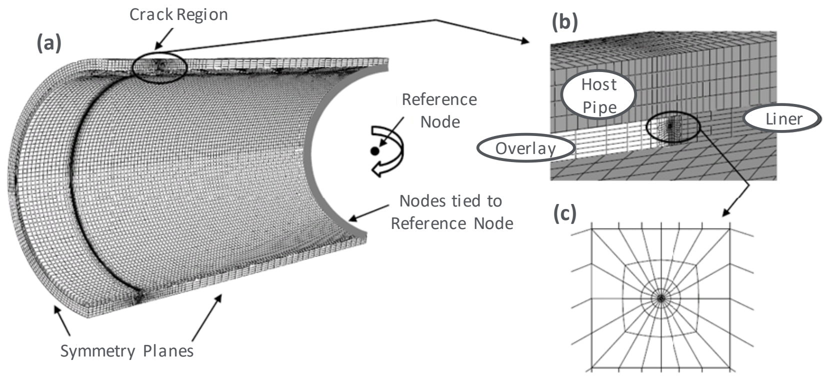


Figure 6: FEA Model of MLP: a) Overview, b) Triple Point, c) CRA Crack Tip Mesh

4.3.2. Crack Driving Force

A CTOD estimation scheme was proposed as part of the ECA Level 1 to allow rapid fracture assessment. The CTOD, δ, is defined as a function of a remote strain, ε, by

$$\delta = \begin{cases} \dfrac{\delta_A}{1.6 \times 10^{-5}} \varepsilon^2 & \text{for } \varepsilon \le 0.4\% \\ \delta_A + \dfrac{(\varepsilon - 0.004)(\delta_B - \delta_A)}{0.016} & \text{for } 0.4\% < \varepsilon \le 2\% \end{cases} \qquad \text{Equation 4}$$

where δ_A and δ_B are the CTOD values at 0.4% and 2% strain respectively, which depend on the normalised crack height, $\frac{a}{t}$, and length, $\frac{c}{t}$, crack aspect ratio, $\frac{a}{c}$, and liner thickness, t,

$$\delta_A, \delta_B = f\left(\frac{a}{t}, \frac{c}{t}, \frac{a}{c}, t\right) \qquad \text{Equation 5}$$

The CTOD vs. strain plots for the three crack aspect ratios, $\frac{a}{c} = 0.025$, 0.05 and 0.1, obtained from Equation 4 and Equation 5, are illustrated in Figure 7 for typical MLP with an alloy 316L liner and weld overlay undermatching the host pipe, and MLP with an alloy 625 liner and weld overlay overmatching the host pipe. The CTOD is higher for scenarios where weld overlay overmatches the host pipe in terms of a stress-strain curve.

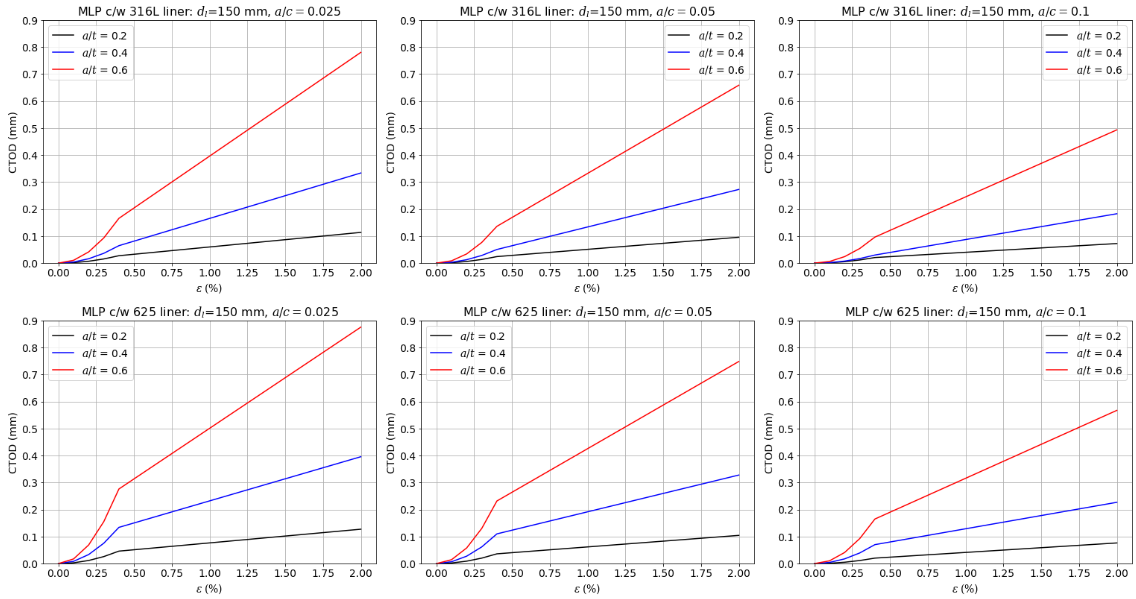


Figure 7: Illustration of CTOD Estimation Scheme:
(top) Weld Overlay undermatching Host Pipe, (bot) Weld Overlay overmatching Host Pipe

In ECA Levels 2 and 3, the CTOD is estimated with FEA undertaken using the project-specific tensile properties and fracture loads. For scenarios involving multiple tensile strain events (e.g., reel-lay installation), FEA is run separately for each crack opening event and material condition (e.g., as-received (AR), strained (S) and strained and aged (S&A)) to determine the corresponding CTOD as a function of the crack height and assessment strain. The characteristic lower and upper bound tensile properties are defined as per DNVGL-RP-F108 [3].

4.3.3. Fracture Toughness

To ensure conservatism of the ECA Level 1, it is proposed to consider a lower-bound CTOD-R curve illustrated in Figure 8. It is based on the results of segment testing for several MLP material and geometry combinations. An R-curve in the Level 2 ECA, superior to that in Figure 8, can either be estimated from historical segment testing for the same MLP supplier, grade, and weld overlay procedure, or determined by a non-standard fracture testing method, e.g., micro-specimen testing. The latter approach is outside the scope of this program. The level 3 ECA does not require an R-curve as ductile tearing is determined directly from segment testing. However, the CTOD applied in segment testing needs to account for any crack extension associated with the tested strain event. The tangency method is used therefore to estimate ductile tearing during the tested strain event and correct the target CTOD in segment testing. In this case, an R-curve in the tangency calculation can be selected based on previously completed segment testing for a representative liner and weld overlay thickness/grade, and weld overlay procedure. Alternatively, the lower-bound R-curve in Figure 8 can be applied.

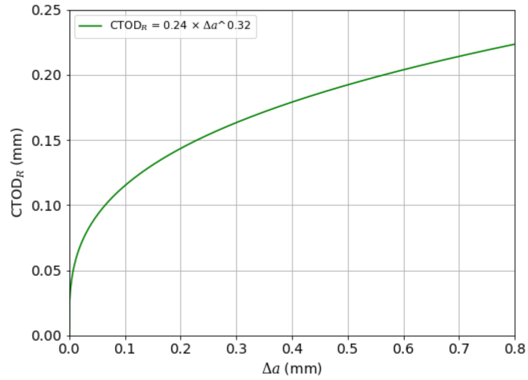


Figure 8: Lower-Bound Fracture Toughness Resistance Curve for Triple-Point

4.3.4. Tangency Method

To determine ductile tearing associated with a given strain event, the crack driving force (CDF) in terms of CTOD at the assessment strain is plotted for a range of flaw heights on a diagram such as shown in Figure 9. The fracture toughness resistance curve, CTOD-R, is plotted on the same diagram so that it originates on the abscissa at a point corresponding to the starter flaw height, a. The corresponding crack advance in the through-thickness direction, Δa, is a horizontal projection of the distance between the start of the CTOD-curve and cross-over between the CTOD-R and CDF curves, see the plot to the left in Figure 9. Once Δa is determined, the crack extension in the circumferential direction (for partially circumferential flaws only) is taken to be $2\Delta c = 2 \times \Delta a$. Crack growth is considered unstable when no cross-over between the CTOD-R and CDF curves exists, see the plot to the right in Figure 9 [3].

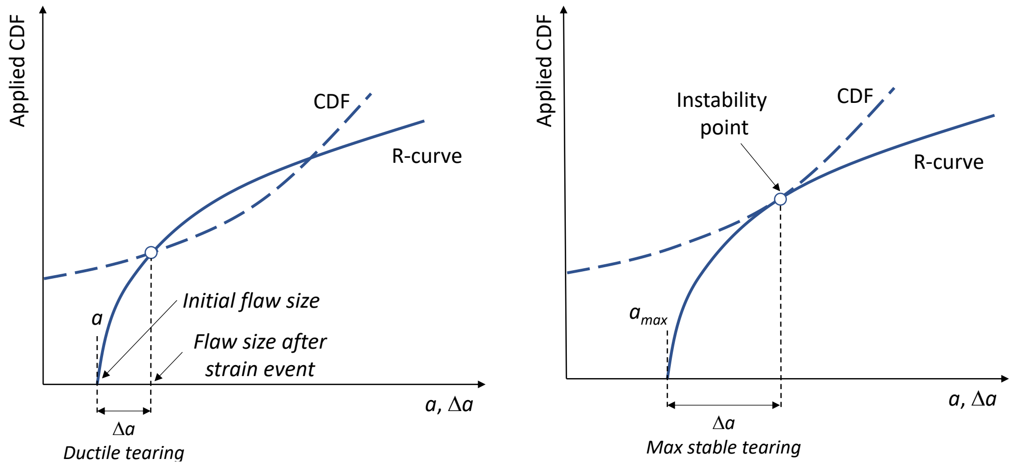


Figure 9: Tangency Diagram: Illustration of Tangency Method

4.3.5. Segment Testing

The load applied during testing is expressed in terms of CTOD determined from FEA of a given strain event. A stationary crack size in this FEA is representative of the crack at the end of a considered fracture event, i.e., after accounting for crack growth during that strain event. The crack extension is estimated using the tangency method assuming representative fracture toughness from historical testing or, if not available, the lower-bound toughness introduced in the Fracture Toughness section. This ensures conservatism of fracture testing. The actual ductile tearing Δa for the considered strain event is measured directly from the segment specimen fracture face during fractography.

Set-up and fracture testing

The segment testing is undertaken using a set-up illustrated in Figure 10. As a minimum 3-off segment specimens are tested for each fracture scenario under monotonic load conditions. For fracture scenarios involving cyclic straining (such as reel-lay installation), spooling-on, aligning and any subsequent retraction strain cycles are tested separately. Following mounting a pre-cracked segment specimen on the tensile test machine, a microscope is set up to monitor CTOD at whichever side of the specimen exhibits a larger crack. A digital camera on the opposite side verifies no unusual behaviour such as brittle fracture. If required, the specimen is heated or cooled to the required test temperature, which is maintained during the test. It is then loaded in tension while the CTOD is monitored with a microscope. The CTOD is measured at a 0.36 mm offset from the original crack tip [7], following a procedure detailed in Figure 11. The load is released, and the specimen removed from the test machine. Finally, fractography is performed to measure the initial crack height and determine the crack growth by ductile tearing.

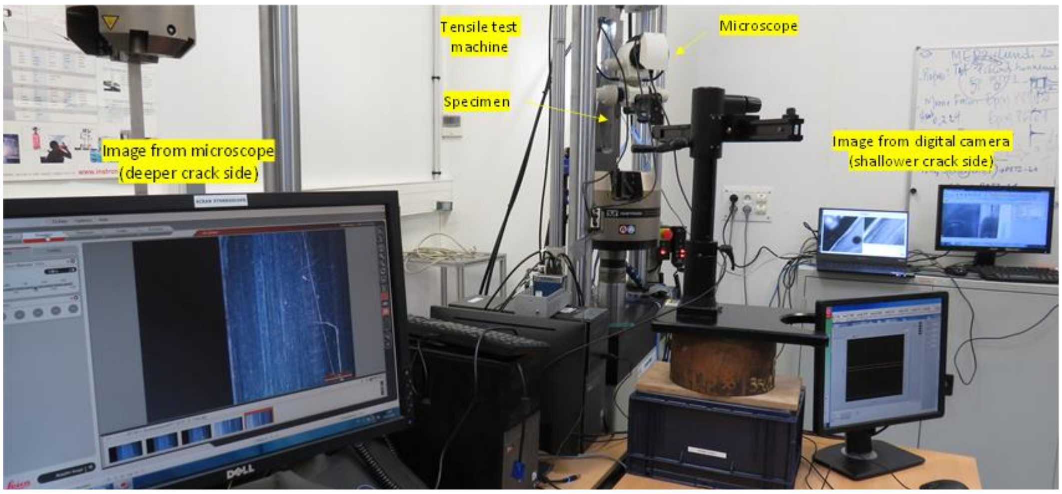
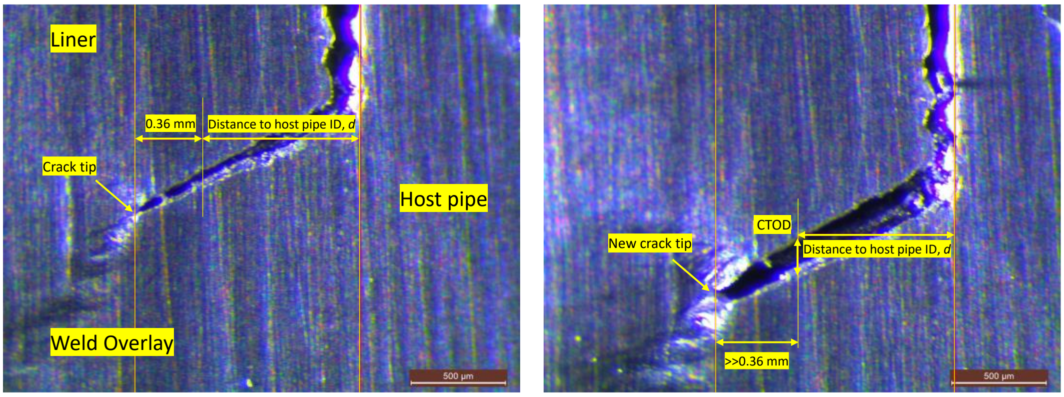


Figure 10*: Segment Testing Set-Up*



1. Slightly pre-load a segment specimen
2. Identify the original crack tip and 0.36 mm offset locations
3. Identify the distance from the 0.36 mm offset location to the host pipe ID, d

4. After applying tensile load, mark the distance d
5. Gradually increase tensile load until the target CTOD, measured at the distance d is reached

Figure 11*: CTOD Measurement during Segment Testing*

Fabrication of segment specimens

Strips are first extracted from a girth welded MLP pup piece and machined into dumbbell blanks. These are pre-conditioned, if required, as per the Pre-conditioning section, side-grooved at the triple-point location and pre-cracked as per the Pre-cracking section. Finally, segment specimens, shown in Figure 12, are machined from pre-cracked dumbbell blanks and subjected to fracture testing as discussed in a previous section. Segment specimens have a cross-section in the range between ½ $B \times B$ and $B \times B$, where B is lower than the minimum MLP thickness. Narrower ½ $B \times B$ specimens are recommended for low diameter pipes to avoid non-uniform crack growth (crack front bowing) during pre-cracking. To facilitate gripping, segment specimens are machined flat at the outer surface of the carbon steel host pipe while shims are used at the inner surface of the CRA layer. To justify the geometry of a segment specimen, shown in Figure 12, the constraint at the crack tip in a segment specimen has been shown to be a close match to that in MLP [8].

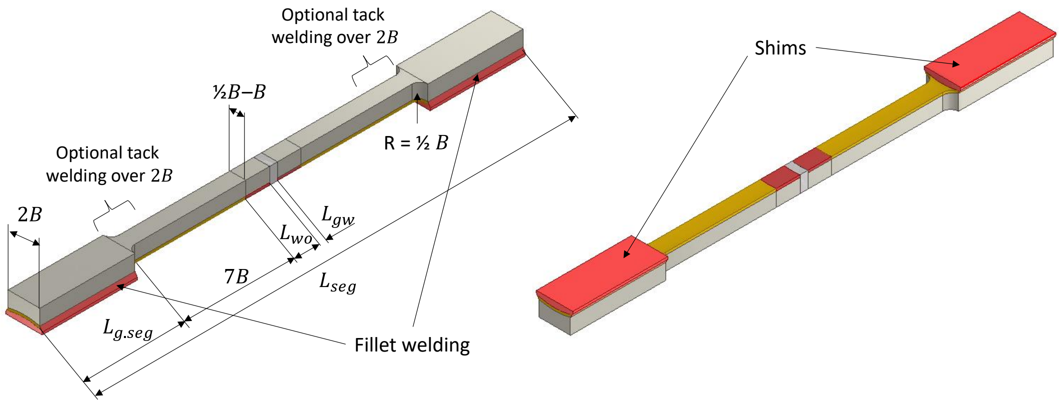


Figure 12*:* Segment Specimen Geometry

Pre-conditioning

Pre-conditioning of dumbbell blanks prior to pre-cracking and machining into segment specimens is required if a considered fracture scenario is preceded by plastic deformation and ageing (e.g., EoL following reeled installation). Dumbbell blanks are mounted on a tensile test machine, secured in grips, and subjected to monotonic or cyclic straining to reproduce the plastic deformation experienced during installation, subsea operation, or both. The final strain event ends in tension for the case of strain-based assessment, or compression for a stress-based ECA [3]. To facilitate gripping and prevent liner buckling, shims with a curved top face and flat bottom face, like those in Figure 12, are fillet welded to the CRA and carbon steel layers along the gripped ends. Anti-buckling clamps and shims with fillet welds ensure that strain is uniformly distributed during both compression and tension. Load applied during straining is monitored with two strain gauges attached to a carbon steel layer at the triple-point and connected to a data logger. On completion of straining, dumbbell specimens are removed from the tensile test machine and subjected to ageing for 1 hour at 250°C in a furnace [1].

Pre-cracking

Pre-cracking of dumbbell blanks is performed using a tool, shown in Figure 13. It applies cyclic lateral deflection to the liner end sticking beyond the carbon steel layer so that the liner remains elastic, see Figure 14. To facilitate pre-cracking and allow non-destructive monitoring of fatigue crack growth, a consistency trial involving pre-cracking and fractography is first completed, where the relationships are defined between: (i) the liner lateral stiffness (under the load illustrated in Figure 14) and average crack height observed at both sides of the specimen, and (ii) the average crack height at the specimen's sides and weighted average crack height determined during fractography.

Pre-cracking of dumbbell blanks, used subsequently to fabricate segment specimens, starts with applying cyclic liner deflection while periodically monitoring the liner lateral stiffness. Fatigue pre-cracking progresses until the stiffness corresponding to the target crack height is reached. The blank width is then locally reduced at the triple-point location, see Figure 15. Crack height is measured at both blank sides with a microscope and average crack height calculated. Pre-cracking continues until the average crack height at the blank sides corresponds to the target weighted crack height. Figure 16 shows an example of a fatigue crack. The weighted average crack height is confirmed during fractography after segment testing is finished. Upon completion of pre-cracking, dumbbell blanks are machined into segment specimens, ready for testing.

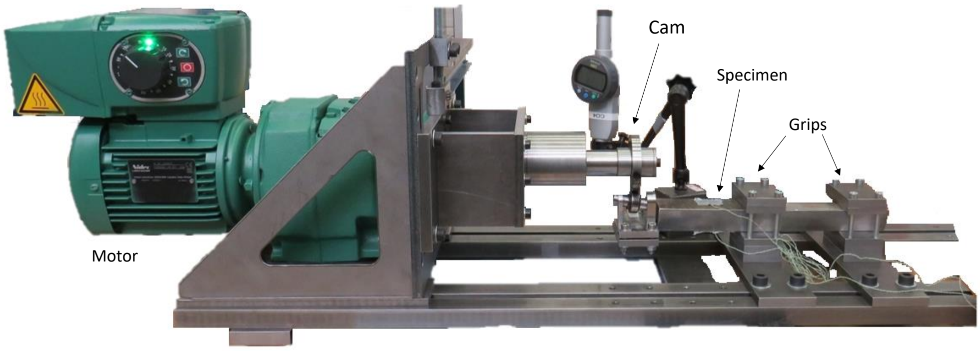
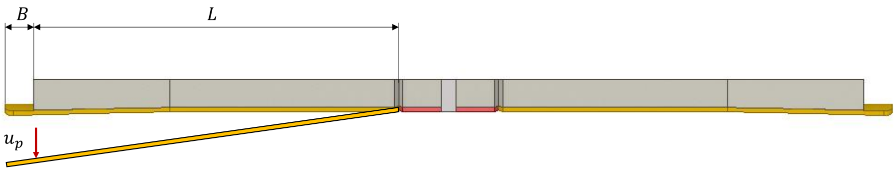


Figure 13*:* Pre-Cracking Tool



(Liner deformation not to scale)
Figure 14*:* Illustration of Liner Deflection during Pre-Cracking

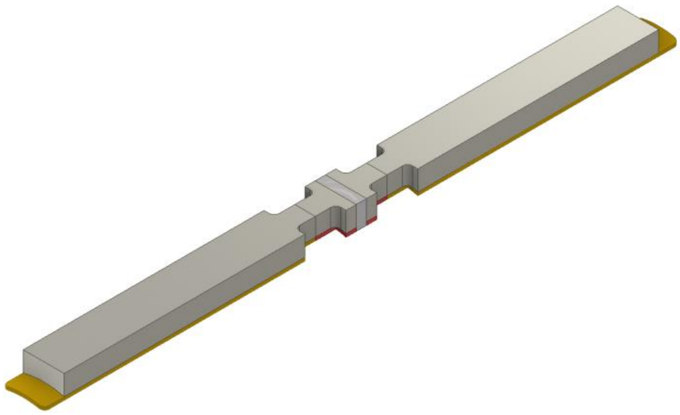


Figure 15*:* Locally Reduced Width of Blank at Crack Location

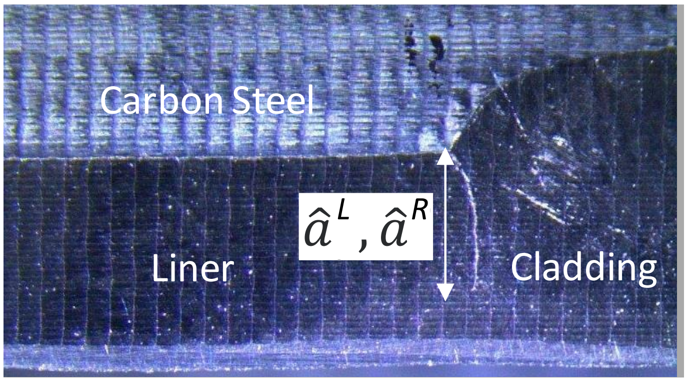


Figure 16*:* Example of Fatigue Pre-Crack

Fractography

Fractography is undertaken to verify the pre-cracking validity (uniformity of the crack front) and measure the initial crack height and crack advance by ductile tearing. Specimens are first heated in a furnace to 700°C for 4 hours to tint a fracture face, chilled in liquid nitrogen and finally broken open. The target crack height and crack advance by ductile tearing are measured at 9-off locations along the crack front as shown in Figure 17. The weighted average crack height and crack growth are obtained following the procedure in [9].

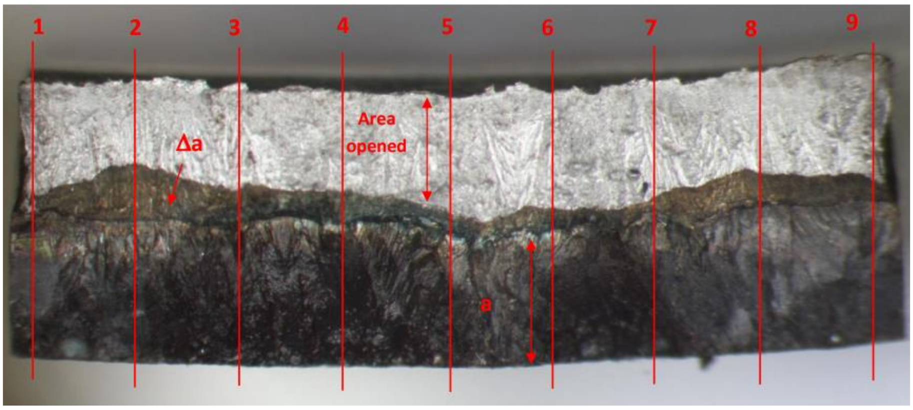


Figure 17*:* Example of Fracture Face

5. DISCUSSIONS AND CONCLUSIONS

The demand for subsea transport of well-produced fluids requiring the use of corrosion resistant pipes is increasing. Mechanically lined pipes often offer best compromise between corrosion protection, lead time and cost. However, the lack of an industry recognised ECA approach for MLP with triple-point flaws slowed down widespread use of MLP for subsea applications. The authors have, therefore, proposed an ECA methodology for confirming the MLP integrity at the triple-point location. The new procedure is currently being reviewed by the EPRG technical committee. Approval of this procedure by EPRG will confirm its soundness and provide the oil and gas industry with means of demonstrating the MLP integrity, promoting a wider acceptance of MLP for demanding subsea developments.

6. ACKNOWLEDGMENTS

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