Review and evaluation of alternative characterization methods for the fracture resistance measurement of high toughness line pipe steels
Running ductile fracture

Dynamic failure mechanisms of pipe lines driven by the internal pressure and the fracture resistance of the material

[Shibanuma, 2018]

[Mannucci, 2002]
Context and Motivations

Running ductile fracture

In the classical methods (as the BTCM), the crack velocity could be estimated based on the CVN-Energy.

Loss of validity of the classical methods for high toughness steels (CVN > 200)

How to measure a relevant value of fracture resistance for high toughness steels?

In the classical methods (as the BTCM), the crack velocity could be estimated based on the CVN-Energy.
Context and Motivations

Two projects between EPRG and Fraunhofer EMI

Measuring the fracture resistance of high toughness steels

Project 216

Literature review to identify alternative methods for the measurement of the fracture resistance

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Project 216a

Quantitative evaluation of the pre-selected test methods
A criterion is required to compare quantitatively the loading conditions of full-scale and lab-scale tests.

Fig. 10. Shift in CVN dissipation for the initiation, plastic deformation, and propagation components as total energy increases: 1—Trend D; 2—Trend I; 3—Trend P; □—propagate; ○—deformation; △—initiation.

[Leis, 2015]

[Schindler, 2010]

[Leis, 2015]

[Schindler, 2010]
Fracture mechanics

Loading of the crack tip

For purely elastic materials

\[ T = \sigma_{xx} - \sigma_{yy} \mid r \to 0, \theta = 0 \]

For elastic-plastic materials

\[ T_{ef} = \sigma_{xx} - \sigma_{yy} \mid r = X_{ref}, \theta = 0 \]

\[ \sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos \left( \frac{\theta}{2} \right) \left[ 1 - \sin \left( \frac{\theta}{2} \right) \sin \left( \frac{3\theta}{2} \right) \right] + O \left( r^{\frac{1}{2}} \right) \]

\[ \sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos \left( \frac{\theta}{2} \right) \left[ 1 + \sin \left( \frac{\theta}{2} \right) \sin \left( \frac{3\theta}{2} \right) \right] + O \left( r^{\frac{1}{2}} \right) \]

\[ \sigma_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos \left( \frac{\theta}{2} \right) \sin \left( \frac{\theta}{2} \right) \cos \left( \frac{3\theta}{2} \right) + O \left( r^{\frac{1}{2}} \right) \]

[Ben Amara, 2015]
Physical meaning of the T-stress

- [Moustabchir, 2012]
- [Sobotka, 2011]
Estimation of the T-stress value during RDF

Remote biaxial stress state of the material:

\[ \sigma_t = \sigma_h = \frac{Pr}{t} \]

\[ \sigma_a = \frac{Pr}{2t} \]

Aimed normalized T-stress in the range of -0.4

\[ \eta = \frac{\sigma_a}{\sigma_h} = \frac{1}{2} \]

[Shlyannikov, 2014]
Advantages and drawbacks

Advantages

• Recommended and standardized by ISO 22889 and ASTM E2472
• Local measurement
• Existing standard (ASTM E3039) for its determination without optical measurement for the DWTT which might be extended to other methods
• Numerical methods exist to use it as a criterion for simulation

Drawbacks

• Potential variability in the measured angle and potential difficulty at high rate.
Measurement of the fracture resistance: CTOA

Parameters potentially influencing the CTOA

- Crack length
  - Edge effects have an influence on the CTOA
- Specimen thickness
  - Influence is not clear: Full thickness specimens should be used
- Loading conditions
  - Influence is not clear: Quantitative comparison of the loading conditions is required
- Loading rate / crack speed
  - Influence is not clear: further investigations are required

The CTOA is a convenient quantity to measure the fracture resistance. Its sensitivity to the loading conditions still needs to be quantified properly.

[Shibanuma, 2008]
[Shibanuma, 2018]
[Wang, 2012]
[Shuai, 2015]
[Pussegoda, 2000]
[Yu, 2015]
List of non-subjective criteria for the reference methods

• Crack propagation at a remote stress below the yield stress of the material
  • No generalized plastic deformation of the ligament before the onset of crack propagation

• Normalized T-stress at the crack tip
  • Value in the range of ~ -0.4

• Full pipe line material thickness

• Unstable or high-rate crack propagation

• Force measurement is possible

• CTOA measurement is possible
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<td>[Corre, 2020]</td>
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**MDCB/MCT: Modified Double Cantilever Beam / Compact tension**

<table>
<thead>
<tr>
<th>Method</th>
<th>T-stress</th>
<th>Full thickness</th>
<th>Unstable/ High-rate crack propagation</th>
<th>Force measurement</th>
<th>CTOA measurement</th>
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<tr>
<td>Remote stress</td>
<td>✔️</td>
<td>✔️</td>
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- **T-Stress**: No complete study available in the literature. Negative values obtained by Ben Amara. Sensitivity analysis on the specimen geometry and loading conditions required.

- **Full thickness**: No tests conducted so far but theoretically possible using welded loading blocks.

[Shterenlikht, 2004]
### IPS: In-Plane Stretching

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<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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- **T-Stress:** No study available in the literature. Sensitivity analysis on the specimen geometry and loading conditions required.

- **Unstable/High-rate crack propagation:** No proof of tests at high velocities have been realized. Due to the similar dimensions of the specimens with the MDCB, high-rate tests should be possible.
### Evaluation of the reference test methods

**CCS: Center Crack Specimen**

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<th>Unstable/High-rate crack propagation</th>
<th>CTOA measurement</th>
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<tr>
<td><img src="#" alt="Checkmark" /></td>
<td><img src="#" alt="Cross" /></td>
<td><img src="#" alt="Checkmark" /></td>
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- Remote stress deformation
- Unstable/High-rate crack propagation: Difficult due to the large specimen dimensions.

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![Graph](image1.png)

- [Simonsen, 2004](#)

![Graph](image2.png)

- [Sherry, 1995](#)
### WLDCB: Wedge Loaded Double Cantilever Beam

**Evaluation of the reference test methods**

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<tr>
<td>✓</td>
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- **T-Stress:** Values of normalized T-stress in the range of 0.8 due to the compressive force applied by the wedge.
- **Unstable/High-rate crack propagation:** Unstable crack propagation likely not possible due to the large plastic domain of the linepipe steels.
- **Force measurement:** The opening force applied on the DCB can only be determined indirectly.

[Hahn, 1974]

[Shlyannikov, 2014]
### Evaluation of the reference test methods

**USETT: Unstable Single Edge Tensile Test**

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- **Remote stress**: Values of remote stress expected to be higher than the yield stress.
- **Unstable/High-rate crack propagation**: Unstable crack propagation likely not possible due to the large plastic domain of the linepipe steels. High rate crack propagation should be possible.

[Corre, 2020]
Evaluation of the reference test methods

DWTT/BS-DWTT: Drop Weight Tear Test/Back-Slot Drop Weight Test

Remote stress

T-S be

CTOA measurement

needs to

[Sherry, 1995]

[Yu, 2015]
## Evaluation of the reference test methods

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A two step strategy is suggested:

• Ensure the transferability of the measured values of CTOA between different specimen geometries and thus between lab and full-scale using the T-stress as criterion.
  ➢ For example: 3 tests: 2 different tests designed with equivalent values of T-stress and one designed to exhibit a different T-stress.
  ➢ It should be possible to quantify, using DIC, the real stress or strain state close to the crack tip in the plastically deformed specimen.

• Evaluate the sensitivity of the CTOA to the loading rate and set basis for an industrial process based on a T-stress optimized BS-DWTT.
Conclusion and perspectives

- The loss of validity of the BTCM for high toughness steels is due to the measurement of an inappropriate value of the fracture resistance in the CVN test

- Necessity to quantify precisely the biaxial stress state at the crack tip
  - The “T-stress” has been proposed as a criterion to compare the stress states at the crack tip induced by different reference methods

- The CTOA has been identified as a convenient quantity to measure the fracture resistance
  - The sensitivity of the CTOA to the loading conditions has been evaluated and needs to be further investigated
The 6 reference test methods have been evaluated using non-subjective criteria
- The MDCB/MCT, IPS and BS-DWTT/DWTT have been selected for further investigations

A strategy has been proposed to enable determining the most appropriate method to measure a relevant value of fracture resistance for high toughness steels

Investigations should be conducted to determine how the measured CTOA should be used in the design of the pipelines
Thank you for your attention.