Experimental–Numerical Evaluation of Ductile Tearing Resistance and Tensile Strain Capacity of Biaxially Loaded Pipelines

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Matthias Verstraete was in Gent
Kazan, Tatarstan, Russia
City
Matthias Verstraete was in Kazan
Girth welds unavoidably contain defects
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ECA methods predict maximum allowable defect dimensions
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Pipelines can be subjected to severe deformations during operation
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Biaxial loading originates from longitudinal straining and internal pressure

\[ L_0 \]
Biaxial loading originates from longitudinal straining and internal pressure.
Biaxial loading originates from longitudinal straining and internal pressure

\[ \text{strain} = \varepsilon = \frac{L_1 - L_0}{L_0} \]
Biaxial loading originates from longitudinal straining and internal pressure

\[ \text{strain} = \varepsilon = \frac{L_1 - L_0}{L_0} \]
ECA methods predict maximum allowable defect dimensions
ECA methods predict maximum allowable defect dimensions

- Applied Strain
- Internal Pressure
- Loading Conditions
  - Strain Based Engineering Critical Assessment
  - Max. Defect Dimensions
ECA methods predict maximum allowable defect dimensions
How to evaluate tearing resistance?

Sent & MWP testing

Strain based

Fracture mechanics based

Critical assessment

Relation between CWP and full pipe?

Experiment based

Numerous variables correction functions

Methods results scatter
Behaviour of crack needs to be well characterized

initial crack — blunting — crack initiation — ductile tearing
Behaviour of crack needs to be well characterized

initial crack — blunting — crack initiation — ductile tearing
Behaviour of crack needs to be well characterized

initial crack — blunting — crack initiation — ductile tearing
Behaviour of crack needs to be well characterized

initial crack — blunting — crack initiation — ductile tearing
Crack opening and crack extension used to characterize crack behaviour
Crack opening and crack extension used to characterize crack behaviour

Crack Tip Opening Displacement (CTOD)
Crack opening and crack extension used to characterize crack behaviour

Crack Tip Opening Displacement (CTOD)

crack growth ($\Delta a$)
Tearing resistance describes relation between CTOD and crack growth
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Crack Tip Opening Displacement (CTOD)

Crack growth ($\Delta a$)
Tearing resistance describes relation between CTOD and crack growth.

Crack Tip Opening Displacement (CTOD)

\[ \Delta \text{a} \]

Crack growth (\( \Delta \text{a} \))
How to evaluate tearing resistance?

Fracture mechanics based

Strain based engineering critical assessment

Experiment based

Relation between CWP and full pipe? Numerous variables correction function methods results scatter
Need for representative specimen to evaluate the defect tolerance
Need for representative specimen to evaluate the defect tolerance
Need for representative specimen to evaluate the defect tolerance
Two types of wide plate specimens are commonly considered:

- **Curved Wide Plate (CWP)**
- **Medium Wide Plate (MWP)**
CWP is limited to uniaxial loading in contrast to biaxial loading in pipe

- full scale test
- wide plate test
CWP is limited to uniaxial loading in contrast to biaxial loading in pipe

full scale test

wide plate test

relationship?
fracture mechanics based

How to evaluate tearing resistance?

STRAIN BASED ENGINEERING CRITICAL ASSESSMENT

experiment based

Relation between CWP and full pipe?
Tearing resistance describes the relation between CTOD and crack growth.

Crack Tip Opening Displacement (CTOD)

crack growth ($\Delta a$)

tearing resistance

$\Delta a$
STRAIN BASED ENGINEERING CRITICAL ASSESSMENT

fracture mechanics based

How to evaluate tearing resistance?

specimens methods results

experiment based

Relation between CWP and full pipe?
MWP specimen still requires large testing capacities
Different possibilities for small scale testing

**SENB**
- loaded in bending
- traditionally used (standardized)
- known conservatism

**SENT**
- loaded in tension
- no experience (no standards)
- similarity in crack tip stress fields
Need for small scale specimen to evaluate the tearing resistance
Two tests for evaluation of tearing resistance

Medium Wide Plate (MWP)

SENT
How to evaluate tearing resistance?

Specimens

SENT & MWP testing

Methods

Relation between CWP and full pipe?

Results

Strain based engineering critical assessment

Fracture mechanics based experiment based
Two methods for measuring CTOD

$\delta_5$ method*

*SENT only

double clip gauge method (DCG)
Two methods for measuring CTOD

δ₅ method*

*SENT only

double clip gauge method (DCG)

clip gauge 1

clip gauge 2
CTOD as the displacement of two points around the crack tip
Deformation evaluation based on images of deforming specimen

3D view through the use of two synchronized cameras

~25°
Deformation evaluation based on images of deforming specimen

3D view through the use of two synchronized cameras

~25°
Random speckle pattern required on the surface of the specimen

- White background
- Black spray
- High contrast pattern

SENT specimen
Strain evaluation based on images of deforming specimen
DIC allows to extract full field strain distribution
DIC allows evaluating displacements and strains

**longitudinal displacement**

$u$

- 3.0 mm
- 1.5 mm
- 0.0 mm

**longitudinal strain**

$\varepsilon_{xx}$

- 10.0%
- 5.0%
- 0.0%

**transverse strain**

$\varepsilon_{yy}$

- 0.0%
- -5.0%
- -10.0%
CTOD as the displacement of two points around the crack tip
Two methods for measuring CTOD

$\delta_5$ method*

*SENT only

double clip gauge method (DCG)
CTOD measurement at crack tip not always possible
CTOD measurement at crack tip not always possible
Knives attached to specimen for measuring opening at two different heights
Knives attached to specimen for measuring opening at two different heights
Knives attached to specimen for measuring opening at two different heights
Knives attached to specimen for measuring opening at two different heights

\[ V_1 @ h_1 \]
Knives attached to specimen for measuring opening at two different heights

\[ V_2 @ h_2 \]

\[ V_1 @ h_1 \]
Knives attached to specimen for measuring opening at two different heights

\[ \text{CTOD} = f(V_1, V_2, h_1, h_2, a_0) \]
Knives attached to specimen for measuring opening at two different heights
Two methods for measuring CTOD

$\delta_5$ method*

*SENT only

double clip gauge method (DCG)
Both CTOD measurement methods yield comparable results.
How to evaluate tearing resistance?

specimens: SENT & MWP testing
methods: CTOD, DCG or $\delta_5$
results: scatter

Relation between CWP and full pipe?

experiment based

fracture mechanics based

STRAIN BASED ENGINEERING CRITICAL ASSESSMENT
Two methods for measuring crack extension

Unloading Compliance*

Direct Current Potential Drop

*SENT only
Two methods for measuring crack extension

Unloading Compliance

Direct Current Potential Drop

*SENT only

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Stiffness differs between shallow and deep cracked specimens

springs

soft spring

rigid spring

5 kg

5 kg
Stiffness differs between shallow and deep cracked specimens

**springs**
- soft spring
- rigid spring

**cracks**
- large crack
- small crack

5 kg
5 ton
Stiffness decreases if crack extends
Stiffness decreases if crack extends

force (F)

Crack Mouth Opening Displacement (CMOD)

CMOD
Stiffness decreases if crack extends

\[ \text{Compliance} = C = \frac{\Delta \text{CMOD}}{\Delta F} \]
Line pipe steels deform plastically
Elastic unloading cycles required to evaluate the stiffness

\[\text{Compliance} = C = \frac{\Delta CMOD}{\Delta F}\]
How to relate measured signal to crack size?

measured signal

compliance

CMOD

transfer function

analytical

crack extension

Δa

CMOD
Two methods for measuring crack extension

Unloading Compliance*

Direct Current Potential Drop

*SENT only
Ohm’s law: current relates to potential drop

\[ I = \text{constant} \]

\[ R \]
Ohm’s law: current relates to potential drop

\[ I = \text{constant} \]
Ohm’s law: current relates to potential drop

\[ V = I \times R \]

constant
Ohm’s law: current relates to potential drop

\[ I = \text{constant} \]

\[ V = I \times R \]
Crack growth increases the electrical resistance

\[ V = I \times R \]

\[ I = \text{constant} \]

\[ 2R \]

\[ \text{constant} \]
Crack growth increases the electrical resistance

\[ I = \text{constant} \]

\[ V = I \times R \]

\[ 2R \]

\[ 24.0 \]

\[ 0.002 \]
Crack growth increases the electrical resistance

\[ I = \text{constant} \]

\[ V = I \times R \]

\[ I = \text{constant} \]

\[ V = 24.0 \]

\[ I = 0.004 \]
How to relate measured signal to crack size?

- measured signal
- crack extension

transfer function

- analytical (literature)
- finite element analysis
Two methods for measuring crack extension

Unloading Compliance*

Direct Current Potential Drop

*SSENT only

[Graphs showing F vs CMOD and relative potential drop vs relative crack depth]
Two methods for measuring crack extension

Unloading Compliance*

Direct Current Potential Drop

*SSENT only
How to evaluate tearing resistance?

specimens
SENT & MWP testing

methods
CTOD, DCG or $\delta_5$
$\Delta a$
UC or PD

results

experiment based

Relation between CWP and full pipe?

fracture mechanics based

Strain based engineering critical assessment
Lot of testing required for strain based ECA methods

- natural scatter
- crack depth
- notch orientation
- specimen type
Repeating test on specimen with identical properties does not yield identical results
Repeating test on specimen with identical properties does not yield identical results
Repeating test on specimen with identical properties does not yield identical results

![Graph showing CTOD vs Δa with ±0.15 mm uncertainty]

CTOD [mm] vs Δa [mm] with a ±0.15 mm uncertainty.
Lot of testing required for strain based ECA methods

- natural scatter
- crack depth
- notch orientation
- specimen type

Theoretically identical specimens yield different curves.
Tearing resistance decreases with increasing notch depth

\[CTOD \ [\text{mm}]\]

\[\Delta a \ [\text{mm}]\]

- \(a_0 = 3.0 \ \text{mm}\)
- \(a_0 = 6.0 \ \text{mm}\)
- \(a_0 = 9.0 \ \text{mm}\)
Lot of testing required for strain based ECA methods

- natural scatter: theoretically identical specimens yield different curves
- crack depth: tearing resistance is not a material property
- notch orientation
- specimen type
Notch orientation has a strong influence on the tearing resistance
Notch orientation has a strong influence on the tearing resistance
Notch orientation has a strong influence on the tearing resistance
Lot of testing required for strain based ECA methods

- natural scatter: theoretically identical specimens yield different curves
- crack depth: tearing resistance is not a material property
- notch orientation: welds are strongly heterogeneous
- specimen type
Wide plate specimens yield higher tearing resistance
Lot of testing required for strain based ECA methods

- natural scatter: theoretically identical specimens yield different curves
- crack depth: tearing resistance is not a material property
- notch orientation: welds are strongly heterogeneous
- specimen type: MWP less conservative, SENT suitable, cheaper alternative
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Fracture mechanics based

How to evaluate tearing resistance?

Specimens
SENT & MWP testing

Methods
CTOD
DCG or $\delta_5$
$\Delta a$
UC or PD

Results
scatter

Relation between CWP and full pipe?

Strain based engineering critical assessment

Experiment based
CWP is limited to uniaxial loading in contrast to biaxial loading in pipe.
How to evaluate tearing resistance?

Specimens: SENT & MWP testing

Methods:
- CTOD
- DCG or δ₅
- Δa
- UC or PD

Results: scatter

Relation between CWP and full pipe?

Methods

Results
Finite element study performed to study relationship between CWP and pipe specimens

- moment of failure
- test matrix
- simulations
Two failure modes are experimentally observed

![Diagram showing failure at the crack]

- Material A
- Material B
- Weld
Two failure modes are experimentally observed

failure at the crack

<table>
<thead>
<tr>
<th>Material A</th>
<th>Weld</th>
<th>Material B</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε_{xx} [%]</td>
<td>6.0</td>
<td>3.0</td>
</tr>
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</table>

failure remote from crack

<table>
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<tr>
<th>Material A</th>
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</thead>
<tbody>
<tr>
<td>ε_{xx} [%]</td>
<td>25.0</td>
<td>12.5</td>
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failure at the crack

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Two failure modes are experimentally observed

$$\varepsilon_{\text{max}} = \frac{\varepsilon_1 + \varepsilon_2}{2}$$
Finite element study performed to study relationship between CWP and pipe specimens

- moment of failure
- test matrix
- simulations

failure characterized by critical global strain ($\varepsilon_{\text{max}}$)
Large number of parameters influence failure behaviour

\[ \text{stress } \sigma \]

\[ \text{strain } \varepsilon \]
Large number of parameters influence failure behaviour
Large number of parameters influence failure behaviour

**Mismatch**
- Overmatch (strong weld)
- Undermatch (weak weld)

**Misalignment**
- Misalignment (e)
Large number of parameters influence failure behaviour

mismatch

overmatch (strong weld)  undermatch (weak weld)

e =0.0 mm  e = 1.6 mm

misalignment
Large number of parameters influence failure behaviour

**mismatch**
- overmatch (strong weld)
- undermatch (weak weld)

**misalignment**
- $e = 0.0 \text{ mm}$
- $e = 1.6 \text{ mm}$

**defect size**
Large number of parameters influence failure behaviour

- **Mismatch**
  - Overmatch (strong weld)
  - Undermatch (weak weld)

- **Misalignment**
  - $e = 0.0$ mm
  - $e = 1.6$ mm

- **Defect size**
  - $a = 2.0$ mm
  - $a = 5.0$ mm

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Finite element study performed to study relationship between CWP and pipe specimens

- **moment of failure**: failure characterized by critical global strain
- **test matrix**: large number of parameters have a potential influence
- **simulations**
Finite element study performed to study relationship between CWP and pipe specimens

- Moment of failure: failure characterized by critical global strain
- Test matrix: large number of parameters have a potential influence
- Simulations: same failure modes can be detected
How to evaluate tearing resistance?

- fracture mechanics based

- How to evaluate tearing resistance?

- specimens
  - SENT & MWP testing

- methods
  - CTOD
  - DCG or $\delta_5$
  - $\Delta a$
  - UC or PD

- results
  - scatter

- experiment based

- Relation between CWP and full pipe?

- methods
  - numerous variables

- results
Comparison between pressurized pipes and CWP specimens

\[ \frac{\varepsilon_{\text{max}} \mid \text{pressurized pipe}}{\varepsilon_{\text{max}} \mid \text{CWP specimen}} \]
Comparison between pressurized pipes and CWP specimens

\[ \frac{\varepsilon_{\text{max}} \mid \text{pressurized pipe}}{\varepsilon_{\text{max}} \mid \text{CWP specimen}} = f(\text{misalignment}; \text{mismatch}; \text{crack size}; \text{Y/T-ratio}) \]
Comparison between pressurized pipes and CWP specimens

\[ \frac{\varepsilon_{\text{max}} | \text{pressurized pipe}}{\varepsilon_{\text{max}} | \text{CWP specimen}} = f(\text{misalignment}; \text{mismatch}; \text{crack size}; Y/T-\text{ratio}) \]

significant scatter
Comparison between pressurized pipes and CWP specimens

\[
\frac{\varepsilon_{\text{max}} \mid \text{pressurized pipe}}{\varepsilon_{\text{max}} \mid \text{CWP specimen}} = f(\text{misalignment; mismatch; crack size; } Y/T\text{-ratio})
\]

significant scatter
lower bound = safe
= conservatism
How to evaluate tearing resistance?

- fracture mechanics based

Experiment based

Relation between CWP and full pipe?

Specimens
- SENT & MWP testing

Methods
- CTOD
- DCG or $\delta_5$
- $\Delta a$
- UC or PD

Results
- scatter

Methods
- numerous variables

Results
- correction function
Testing remains crucial for Strain-Based ECA

- **analytical procedures**
  - experimental evaluation of tearing resistance through SENT testing
  - tearing resistance is not a material property and affected by scatter of material properties

- **experimental procedures**
  - CWP testing can be used in combination with established correction functions to evaluate defect acceptance
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