Crack tip constraints in a weldment and their effect on ductile crack growth

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Outline

• Background

• Crack tip constraints in a weldment

• Ductile resistance
  – Complete Gurson model
  – Pre-strain history induced constraint

• Summary
20th European Conference on Fracture (ECF-20)

Fracture at all scales

30th June – 4th July, 2014
Trondheim, Norway

www.ecf20.no
Fracture of Iron at Nano scale

*Nano Letters, 11 (2011) 5264–5273*

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<th>0.01 K</th>
<th>100 K</th>
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<th>500 K</th>
<th>700 K</th>
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Application of fracture mechanics to offshore pipelines

From design to decommissioning

Development of procedures for testing and qualification of offshore pipelines.

Involved in development of all new fields on the Norwegian shelf since 1997
Large deformation scenarios for pipelines

Pipeline installation

On-bottom snaking

Ice loading

Earthquakes

Pipelines must in many cases be designed to withstand a given deformation or strain level – i.e. strain-based design principles should be used
Fracture mechanics for pipelines

Mismatch

Misalignment

Defect size

Difference in wall thickness

Stress-strain curves
Pipeline Steels and Weldments

- High strength and toughness
- Thickness $\rightarrow$ thin
- Diameter $\rightarrow$ large
- Large deformation
- Plasticity
- Mismatch
- Residual stresses
- Load / strain history
Transferability?

Same $K$, $J$, $\delta \rightarrow$ same stress field $\rightarrow$ same fracture probability?

- Toughness is not a unique material parameter
- Toughness is dependent on the crack tip stress field
- Crack tip stress field is not uniquely controlled by $J$, but depends on the crack tip constraint level

\[ \sigma_{ij} = \sigma_{ij}(r, \theta, K, \delta, J) \]
Crack tip Stress Field and Constraint

- J-Q formulation
- Increase of load (J)
- Independent of loading (J), only one solution!
- Fracture process zone
- HRR - solution
- Same J level!
- HRR - solution
- SENTP
- SENB
- SENTC

\[
\frac{\sigma_{yy}}{\sigma_0} = \frac{100}{0.1} N/m
\]

\[
x_N = \frac{x}{(J / \sigma_0)}
\]
Mismatch Constraint

Mismatch Material

Ref. Material

\[ J,T=0 \]

\[ \sigma_{0,2}, n \]

\[ \sigma_{0,1}, n \]

\[ m = \frac{\sigma_{0,2}}{\sigma_{0,1}} \]

\[ m = 1 \]

Stress

Strain

www.ntnu.no
Mismatch Constraint

$T=0$, $n=0.2$, opening stress

$m=0.85$

$m=1.5$

$m=2.0$

The mismatch constraint (M) is “independent” of the geometry constraint (Q)!

$\sigma_{ij}(r, \theta, J, Q, M) = \sigma_{ij}(r, \theta, J) + Q\sigma_0\tilde{f}_{ij}^Q(\theta) + M\sigma_0\tilde{f}_{ij}^M(\theta + 12\beta)$

$\beta = 0$ for $m \geq 1$

$\beta = 1$ for $m < 1$

$0.75 \leq m \leq 2.0$

$-0.6 \leq T \leq 0.5$

$-\pi/4 \leq \theta \leq \pi/2$

$1 \leq r / (J / \sigma_0) \leq 5$

Pre-strain History Induced Constraint
Pre-strain induced Constraint

- Diagram showing the effect of pre-strain on material behavior.
- Graphs illustrating the relation between CTOD and remote strain, as well as pre-strain and load (P).

CTOD 0.25r

Averaged Remote strain
**Residual Stress Constraint**

**Initial**

**Balanced**

**Introduction of crack**

Before balance

After

Liu, Zhang and Nyhus, 2007
Ren, Zhang and Nyhus, 2010
Pre-strain and Residual stress induced constraints

- CTOD-Q-R
- CTOD-Q-P
Crack tip constraints in a weldment

Constraint (Q,M,P,R)

Pre-strain (P)

Mismatch (M)

Residual Stress (R)

Ductile Fracture Mechanisms

Micro void nucleation, growth and coalescence!

Study ductile fracture must study voids!
Complete Gurson Model

Gurson Model:
Nucleation and growth

+ A physically based Coalescence Criterion

A Complete Gurson Model
Nucleation, growth and coalescence


Damage Parameter Identification

\[ \varepsilon_f = \varepsilon_f(R, f_0) \]

Modeling Ductile Crack Growth
Effect of Prestrain on Fracture

- Can we still use the equations developed for monotonically increasing load conditions?

- History independent resistance curve or material memory curve?
Pre-strain effect

Crack growth [mm]

CTOD [mm]

Prestrain 0.0
Prestrain 0.0021
Prestrain 0.0025
Prestrain 0.0034
Prestrain 0.0040

Pre-strain effect

Graphs showing CMOD [mm] vs. LOAD [kN] for BMH No. 1, BMH No. 13, BMH No. 14, BMH No. 12, BMH No. 15.
Effect of constitutive models

Experimental

Isotropic hardening

Kinematic hardening

Combined isotropic/kinematic

Physics captured better

Physics captured better

Physics not well captured
**Damage effect**

- **End of the first cycle**
- **Early stage of the re-loading**
- **End of the re-loading**
- **Un-loaded state**
Concluding Remarks

• Crack tip stress field in a pipeline steel weldment is disturbed by many factors
  – M constraint is independent of Q
  – R and P are less understood

• Pre/strain history induced constraint has a strong effect on the ductile resistance