Effect of loading rate and crack geometry on the fracture behaviour of precracked Charpy specimens

Results from recent PCC-Testing
Hans-Jakob Schindler
Mat-Tec AG Winterthur, Switzerland
Dietmar Kalkhof
Swiss Federal Nuclear Safety Inspectorate (HSK), Switzerland
Conrad Zurbuchen, Hans-Werner Viehrig
Forschungszentrum Dresden, Germany
Contents

• Background
• Dynamic effects on transition behaviour
• Effect of in-plane constraints (crack-length)
• Estimation of local strain rates
• Estimation of tensile properties from PCC-tests
• Estimation of KJd from classical CVN-test data
• Discussion and preliminary conclusions
Background

- PCC-Specimens for aging surveillance of Swiss Nuclear Power plants since 1975
- HSK AN 425 as a testing guideline for PCC-specimens since 1978
- Scientific progress and several corresponding revisions AN 425 since
- Related international activities on PCC-testing: DVM, ESIS TC5, ISO, ASTM
- Question: Static vs. dynamic testing
- Current Project to evaluate the use of PCC-specimens in aging surveillance
Purpose of HSK AN 425

- Providing a guideline for PCC-testing, that enables a simple, automated, user-independent evaluation of key-data
- More specific than ESIS-TC5/ISO procedure
- Defining the minimum requirements of PCC-testing
- Ensures that data suitable for RPV- fracture analysis are delivered
- Applicability not only to aging surveillance of RPV, but also to other metallic components where toughness is an issue
Core Elements of AN 425

Constraint-correction:

\[ J_{0.2td/\text{con}} = \frac{J_{0.2td}}{c_{\text{con}}} \]

\[ c_{\text{con}}(a_0) = \begin{cases} 
1 + 9 \cdot (0.5 - \frac{a_0}{W})^2 & \text{für } 0.275 < \frac{a_0}{W} < 0.5 \\
1 & \text{für } \frac{a_0}{W} \geq 0.5
\end{cases} \]
Aim of the current research project

Motivation:
Efficient testing crucial for long term operation:
- How to get maximum information on toughness behaviour from a limited amount of testing material?

Open questions concerning:
- Effect of loading rate, in-plane constraints (crack-length), out of-plane constraints (size), notch/crack radius on transition behaviour
- Capability of MC to cope with these effects
- Advantages/disadvantages of dynamic and static testing of PCC-specimens
Test Material

Original RPV-steel 22NiMoCr3–7

Tensile properties:

Charpy transition curve:

Reference temperature acc. E1921: \( T_0 = -75^\circ \)
Effect of loading rate on $T_0$

Temperature shift due to loading rate $1.2 - 2.4$ m/s: $\Delta T = 73^\circ$
Effect of crack-length on $T_0$

Quasistatic loading:

- $T_{0/0.5w} = -86^\circ C$
- $T_{0/0.3w} = -76^\circ C$

Dynamic loading:

- $T_{0/0.5w} = -13.8^\circ C$
- $T_{0/0.3w} = -12.1^\circ C$

No (or even reversed) effect of crack-length $a/W=0.3$
(compared with $a/W=0.5$)

Out-of-plane constraints insufficient?
Transition behaviour dynamic vs. static

Dynamic:
- Loss of constraints
- + adiabatic effects
- + loss of strain rate

Static:
- Loss of constraints

Impact tests: Sharp rise of $K_{jd}$ at ca. 100 MPam$^{.5}$

Related effect: „cleavage gap“
Cleavage gap

„Cleavage J-R-Curves“ from a german DVM-round robin

Cleavage J-R-Curve for CVN specimens

Cleavage J-R-Curve for precracked specimens

Cleavage J-R-Curve for EDM-notched specimens

ASTM Workshop on PCC-Testing

16. 10. 2008, St Louis
### Representative strain rates

<table>
<thead>
<tr>
<th>Type</th>
<th>Formula</th>
<th>Typical values for CVN-specimens, 5m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM-Draft</td>
<td>$\dot{\varepsilon} = \frac{\sigma_{ys}}{E \cdot t_f}$</td>
<td>$= 5/s$</td>
</tr>
<tr>
<td>Smooth beam, elastic</td>
<td>$\dot{\varepsilon} = \frac{2k \cdot S}{2B \cdot W^2 E} \cdot v_0$</td>
<td>$= 30/s$</td>
</tr>
<tr>
<td>Smooth beam, plastic hinge</td>
<td>$\dot{\varepsilon} = \frac{2}{S} \cdot v_0$</td>
<td>$= 120/s$</td>
</tr>
<tr>
<td>CVN-notched, elastic</td>
<td>$\dot{\varepsilon} = \frac{\alpha \cdot 2k \cdot S}{2B \cdot W^2 E} \cdot v_0$</td>
<td>$= 180/s$</td>
</tr>
<tr>
<td>CVN-notched, plastic</td>
<td>$\dot{\varepsilon} = \frac{\alpha \cdot 2}{S} \cdot v_0$</td>
<td>$= 800/s$</td>
</tr>
<tr>
<td>EDM- notch, length a, notch radius $\rho=0.1$mm,</td>
<td>$\dot{\varepsilon} = \frac{\eta \cdot (W-a)}{\rho \cdot S} \cdot v_0$</td>
<td>$= 5000/s$</td>
</tr>
<tr>
<td>Deep crack, length a</td>
<td>$\dot{\varepsilon} = \frac{\eta \cdot \sigma_{ys} \cdot (W-a)}{J \cdot S} \cdot v_0$</td>
<td>$= 600000/J /s$</td>
</tr>
</tbody>
</table>
Estimation of tensile properties from impact bending tests

\[ \sigma_{yd} = \frac{C \cdot S}{(W - a_0)^2 B_N} \left( \frac{F_m + F_{gy}}{2} \right) \]

C: "Constraint factor"

From quasi-static SENB-testing, side-grooved specimens:

- Precracked, a/W=0.3: C=0.64
- Precracked, a/W=0.5: C=0.67
- EDM 0.1 mm, a/W=0.3: C=0.62
- EDM 0.1 mm, a/W=0.5: C=0.67

Comparison with CVN-data

CVN, ISO-tup:

C = 0.738
Comparison between CVN and PCCVN

C dependent on crack/notch length and eventually striker geometry
Rate effects on plastic flow stress

Data collapse to one curve, if flow stress is represented as a function of $T \cdot \log \frac{C_\varepsilon}{\dot{\varepsilon}}$

General shape:

$$\sigma_{yd}(T, \dot{\varepsilon}) = \begin{cases} 
\sigma_y(T, \dot{\varepsilon}) & \text{for } \dot{\varepsilon} \leq \dot{\varepsilon}_{qs} \\
\sigma_i + \sigma_0 \cdot \exp\left(-T \cdot \log \frac{C_\varepsilon}{\dot{\varepsilon}}\right) & \text{for } \dot{\varepsilon} > \dot{\varepsilon}_{qs}
\end{cases}$$

$\sigma_i$, $\sigma_0$, $C_\varepsilon$, $\dot{\varepsilon}_{qs}$ : to be determined by fitting tensile test data
Determination of open parameters by fitting

Quasi-static strength to be on the same straight line as the increased strain rates!

Increased strain rates to be on the same curve as the static values!

\[ \dot{\varepsilon}_{qs} \approx 2.5 \cdot 10^{-3} / s \]

\[ C_\varepsilon = 1 \cdot E6 \]

Charpy data to be on the same curve as the tensile data!

Representative strain rate of a CVN-test

\[ \dot{\varepsilon}_{CVN} \approx 400 / s \]
Estimation of KJc from Charpy-data

Semi-analytical relation for upper shelf + upper transition data (Schindler, ASTM STP 1380, 1999):

Empirical relation to estimate $T_0$ (Sreenivasan et al., Int. J. Fr. 2004):

$$K_{JCV} = \sqrt{\frac{5.20 \cdot A_g \cdot KV \cdot E}{1 - 1.47 \cdot \frac{KV}{R_m} \cdot (1 - V^2)}}$$

$$T_0[^\circ C] \approx 0.534 \cdot T_{0CVN[^\circ C]} - 76.18$$

$\approx -85^\circ C$
Comparison between $K_{Jcd}$ and $K_{JC\nu N}$ estimated from Charpy data
Estimation of Percentage of ductile fracture

Available formulas:

(a) \[ \% \text{shear} = \left(1 - \frac{F_{bf} - F_a}{F_m}\right) \times 100 \]

(b) \[ \% \text{shear} = \left(1 - \frac{F_{bf} - F_a}{F_m + (F_m - F_{c})}\right) \times 100 \]

(c) \[ \% \text{shear} = \left(1 - \frac{F_{bf} - F_a}{F_m + k(F_m - F_{c})}\right) \times 100 \] with \( k \approx 0.5 \)

(d) \[ \% \text{shear} = \left[1 - \sqrt{\frac{F_{c}}{F_m}} + 2 \left(\frac{F_{bf}}{F_m} - \frac{F_a}{F_m}\right)\right] \times 100 \]

(e) \[ \% \text{shear} = \left(1 - \frac{F_{bf} - F_a}{0.5(F_{c} + F_m)}\right) \times 100 \]
Discussion and Preliminary Conclusions

• Tendentially higher $T_0$ for $a/W=0.3$ than for $a/W=0.5$
  
  Either out-of-plane-Constraints not sufficient, or they do not play a crucial role in cleavage fracture

• Determination of yield stress and UTS from instrumented Charpy should be further specified

• EDM-notch of width 0.1mm) causes a temperature shift of ca. 40°
  
  Correction (preferably on y-axis, not temperature shift)

• Slope of transition increases with loading rate
  
  Correction (preferably on y-axis, not temperature shift)
Estimation of $T_0$ from an insufficient set of small-specimen test data

Regression line from invalid cleavage data

- Measured cleavage data
- Measured upper shelf data

50% p.o.f. MC

$K_{jc}$-validity limit E 1820

$K_{jc}$-validity limit E 1921

$J_c$-validity limit E 1820

$T_{jc}$ $T_0$ $T$