Cost-effective precracking of Charpy V-notch specimens for fracture toughness testing by using a piezo-electric actuator

Johan Schuurmans, Marc Scibetta
NMS-SMT

jschuurm@sckcen.be
Outline

- Introduction
- Precracking requirements
- Piezo precracking
- Validation
- “Piezomatic” in hotcell
- Precracking cost
- Conclusions
Havilland Comet – world’s first jet airliner

“Plane broke apart in mid flight” - 1954
After the fuselage was subjected to less than 400 cycles, cracks began to appear around the edges of the cabin's windows

Cause: cracks were created around the rivets in the planes thin aluminum skin around the square windows at assembly

“Boeing reports 'cracks' in factory Dreamliner planes” – Reuters - March 2014
© SCK•CEN 2014

Introduction

- “The discovery of the cracks at Doel’s Unit 3 by the use of a new ultrasound measuring technique, sent a nervous ripple through the international nuclear industry.” – Bellona – August 2012

- “after being out of service for 10 months, both reactors could be restart safely” – Electrabel – June 2012

- “Extension of the shutdown of Doel 3 nuclear power station ... the reactor will not be restarted until all results are in” – Electrabel – August 2012
Introduction

- “fracture toughness is a property which describes the ability of a material containing a crack to resist further fracture” – Wiki

- Standard Test Method for Measurement of Fracture Toughness
- “Experience has shown that it is practically impossible to obtain a reproducible, sharp, narrow notch using conventional manufacturing techniques that will simulate a natural crack well enough to provide a satisfactory fracture toughness result. All specimens shall be precracked in fatigue” – ASTM E1820
Introduction

\[ \sigma_{\text{local}} = \frac{K}{\sqrt{2\pi r}} \times f(\text{geometry}) \]
Precracking requirements

\[
P_i = \frac{Bb_0^2 \sigma_Y}{2S}
\]

\[
P_f = 0.7 P_{\text{max}}^T
\]

\[
a_f - a^* \geq 1.3 \text{ mm}
\]

**E1820-99**

\[
K_i = \frac{\sigma_{YS}^f}{\sigma_{YS}^T} (0.063 \sigma_{YS}^f)
\]

\[
K_f = 0.6 \frac{\sigma_{YS}^f}{\sigma_{YS}^T} K_F
\]

\[
a_f - a^* \geq 1.3 \text{ mm (wide notch)}
\]

\[
a_f - a^* \geq 0.6 \text{ mm (narrow notch)}
\]

**E1921-97**

\[
K_i = 0.00013 E
\]

\[
K_f = 0.000096 \frac{\sigma_{YS}^f}{\sigma_{YS}^T} E
\]

\[
a_f - a^* \geq 0.6 \text{ mm}
\]

**E1921-13**

\[
K_i = 25 \text{ MPa}\sqrt{m}
\]

\[
K_f = \begin{cases} 
15 \text{ MPa}\sqrt{m} & \text{for } T_T < T_f \\
20 \text{ MPa}\sqrt{m} & \text{for } T_T \geq T_f 
\end{cases}
\]

\[
a_{p1} = \frac{1}{3\pi} \left( \frac{K_i}{\sigma_{YS}} \right)^2
\]

\[
a_{p2} = \frac{1}{3\pi} \left( \frac{K_f}{\sigma_{YS}} \right)^2
\]

\[
a_f - a_{p2} \geq 0.2 \text{ mm}
\]
The force values must be limited to keep the maximum stress intensity during precracking well below the material fracture toughness measured during the subsequent test.

- Requirements became more stringent over time
- Precracking procedure differ between standards
- Accurate control of the precracking process is essential
Piezo-precracking

Piezoelectric effect

Stroke-force diagram

10

Copyright © 2014 SCK•CEN
Piezo-precracking

- **Advantages**
  - High operating frequency (kHz)
  - Compact
  - “Low-cost”

- **Disadvantages**
  - Limited stroke (order 100 µm)
  - Performance is determined by the combined characteristics of the actuator and the attached mechanics
    - Very stiff design!
  - Large drive current at high frequency (capacitive nature)
  - Possibility of overheating → good thermal management
    - Low thermal conductivity PZT
    - Airgap between stack and casing
  - Brittle nature PZT material (vulnerable to tensile stress)
Piezo-precracking

Basic Operation piezo-precracking machine

- piezo-actuator
- cartridge
- (mini)-PCCV specimen
- loadcell
- LVDT
- pusher
- tray

Compliance method

\[ C = \frac{\Delta d}{\Delta P} \]
Validation

PCCV specimens

<table>
<thead>
<tr>
<th>Type</th>
<th>PCCV</th>
<th>Criterion</th>
<th>Plane-sided</th>
<th>Side grooved</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>10</td>
<td>0.45 ≤ a/W ≤ 0.55</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>W</td>
<td>10</td>
<td>a_f</td>
<td>5.046</td>
<td>5.115</td>
</tr>
<tr>
<td>a_N</td>
<td>3</td>
<td>σ</td>
<td>0.060</td>
<td>0.0887</td>
</tr>
<tr>
<td>Material</td>
<td>20NiMoCr2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>E1921-13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a_f</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K_i</td>
<td>17.5</td>
<td>MPa√m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K_f</td>
<td>18</td>
<td>MPa√m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_i</td>
<td>75</td>
<td>Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_f</td>
<td>100</td>
<td>Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) ASTM 1820
   i = 1,2,...,9

(2) ISO 12135
   i = 2,3,...,8
   a_1 = (a_1+a_9)/2
Reconstituted PCCV specimens

<table>
<thead>
<tr>
<th>Type</th>
<th>PCCV (reconstituted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>10 mm</td>
</tr>
<tr>
<td>W</td>
<td>10 mm</td>
</tr>
<tr>
<td>(a_N)</td>
<td>3 mm</td>
</tr>
<tr>
<td>Material</td>
<td>20NiMoCr2</td>
</tr>
<tr>
<td>Number</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard</th>
<th>E1921-13</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_f)</td>
<td>5 mm</td>
</tr>
<tr>
<td>(K_i)</td>
<td>17.5 MPa/(\sqrt{m})</td>
</tr>
<tr>
<td>(K_f)</td>
<td>18 MPa/(\sqrt{m})</td>
</tr>
<tr>
<td>(f_i)</td>
<td>75 Hz</td>
</tr>
<tr>
<td>(f_f)</td>
<td>100 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Plane-sided</th>
<th>Side grooved</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 ≤ (a/W) ≤ 0.55</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>(a_f)</td>
<td>5.126</td>
<td>5.207</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>0.071</td>
<td>0.084</td>
</tr>
<tr>
<td>(</td>
<td>a_i-a</td>
<td>≤ 0.05 B)</td>
</tr>
<tr>
<td>(</td>
<td>a_i-a</td>
<td>≤ 0.1 a)</td>
</tr>
<tr>
<td>(K_f)</td>
<td>18.79</td>
<td></td>
</tr>
<tr>
<td>(\sigma)</td>
<td>0.408</td>
<td></td>
</tr>
</tbody>
</table>

(1) ASTM 1820
\[i = 1,2,\ldots,9\]
(2) ISO 12135
\[i = 2,3,\ldots,8\]
\[a_1 = (a_1+a_9)/2\]
## Mini-PCCV specimens

<table>
<thead>
<tr>
<th>Type</th>
<th>mini-PCCV</th>
<th>Criterion</th>
<th>Plane-sided</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>3 mm</td>
<td>$0.45 \leq a/W \leq 0.55$</td>
<td>OK</td>
</tr>
<tr>
<td>W</td>
<td>4 mm</td>
<td>$a_f = 1.917$</td>
<td></td>
</tr>
<tr>
<td>a_N</td>
<td>1 mm</td>
<td>$\sigma = 0.057$</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>20NiMoCr2</td>
<td>$</td>
<td>a_i-a</td>
</tr>
<tr>
<td>Number</td>
<td>7</td>
<td>$</td>
<td>a_i-a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K_f = 16.66$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma = 0.435$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard</th>
<th>E1921-13</th>
<th>$a_f = 2$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_i$</td>
<td>18 MPa/\sqrt{m}</td>
<td></td>
</tr>
<tr>
<td>$K_f$</td>
<td>18 MPa/\sqrt{m}</td>
<td></td>
</tr>
<tr>
<td>$f_i$</td>
<td>150 Hz</td>
<td></td>
</tr>
<tr>
<td>$f_f$</td>
<td>200 Hz</td>
<td></td>
</tr>
</tbody>
</table>

(1) ASTM 1820
   $i = 1,2,\ldots,9$

(2) ISO 12135
   $i = 2,3,\ldots,8$
   $a_1 = (a_1+a_9)/2$
“Piezomatic” in hot cell

- Ease of operation
- Compact design
- Low maintenance
- Light weight
## Comparison precracking cost

<table>
<thead>
<tr>
<th>Fixed cost</th>
<th>Hydraulic testbench</th>
<th>Resonant machine</th>
<th>Piezomatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>29.03</td>
<td>4.97</td>
<td>3.87</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>3.37</td>
<td>0.43</td>
<td>0.27</td>
</tr>
</tbody>
</table>

### Variable cost

<table>
<thead>
<tr>
<th></th>
<th>Hydraulic testbench</th>
<th>Resonant machine</th>
<th>Piezomatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>27.00</td>
<td>0.18</td>
<td>0.09</td>
</tr>
<tr>
<td>Labour [min]</td>
<td>15</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total [€]</strong></td>
<td><strong>59.40</strong></td>
<td><strong>5.58</strong></td>
<td><strong>4.23</strong></td>
</tr>
</tbody>
</table>

(*) Labour and overhead not included
Conclusions

- Very compact design
- Fast precracking (100 to 200 Hz)
- Various PCCV specimens sizes
- High degree of automation
  - Meets the ASTM E1921-13 precracking requirements
  - High accuracy and reproduceability of crack length
  - Easy to operate
- Suited for use in hotcell environment
- Low cost-of-ownership
- Very competitive precracking cost per specimen
The presented work is partially funded by Tractebel Engineering. Their support is greatly appreciated.