Task 6 - Safety Review and Licensing
On the Job Training on Stress Analysis

F.M. with Finite Element analysis - Wall Elliptical crack, Sub-Clad semielliptical crack and Elastic-Plastic calculation of the J parameter (ANSYS Workbench/ Apdl)

Davide Mazzini – Ciro Santus

Pisa (Italy)
June 15 – July 14, 2015
Table of content

Content

• Calculation example of a wall subsurface Elliptical crack
• The effect of the cladding properties on a semielliptical sub-clad surface crack, ANSYS Workbench
• $J$ parameter calculation with ANSYS Workbench with Elastic-Plastic material
Definition of the problem

Half model (symmetry), with an elliptical shape crack

\[ t = 25 \text{ mm} \]
\[ W = 60 \text{ mm} \]
\[ h = 30 \text{ mm} \]
\[ 2a = 15 \text{ mm} \]
\[ 2c = 30 \text{ mm} \]
\[ \sigma_0 = 100 \text{ MPa} \]
Solution with Tetrahedrons mesh

Solution accurate, however tetrahedrons not ok for the CINT command

Refinement at the two most significant points
Solution with Hexahedrons mesh

The model is divided into solids for keep Hexahedrons mesh near the crack front
Mesh options

The Hex dominant option works with this toroid shape

Pisa, June 15 – July 14, 2015
Solution

ANSYS Workbench

Symmetry boundary up to the crack front

Accurate solution

Pisa, June 15 – July 14, 2015
CINT, SIFS calculation

Coordinate systems introduced in Workbench then useful for the CINT calculation in ANSYS Apdl
CINT, SIFS calculation

Coordinate systems 12

Coordinate systems 13
CINT, SIFS calculation

\[ \text{eps} = 0.05 \]

\begin{verbatim}
csys, 12
nsel, s, loc, y, 0.0
nsel, r, loc, x, -eps, eps
nsel, r, loc, z, -0.8, 0.8
esel, s, type, , 4
nsle, u
\end{verbatim}

\begin{verbatim}
csys, 13
nsel, s, loc, y, 0.0
nsel, r, loc, x, -eps, eps
nsel, r, loc, z, -0.8, 0.8
esel, s, type, , 4
nsle, u
\end{verbatim}

\begin{verbatim}
cm, CRACK_TIP_NODE_CM_2, node
alls
\end{verbatim}

\begin{verbatim}
cm, CRACK_TIP_NODE_CM_3, node
alls
\end{verbatim}
CINT, SIFS calculation

- Unreliable values at the boundary of the crack front
- Outer contours interact with the boundary of the toroid volume
ANSYS Apdl command in the Workbench environment

```
eps = 0.05

Csys, 12
nsel, s, loc, y, 0.0
nsel, x, loc, x, -eps, eps
nsel, x, loc, z, -0.8, 0.8
nsel, s, type, 4
nsel, u
cm, CRACK Tip NODE CM_2, node all
alls
csys, 13
nsel, s, loc, y, 0.0
nsel, x, loc, x, -eps, eps
nsel, x, loc, z, -0.8, 0.8
nsel, s, type, 4
nsel, u
cm, CRACK Tip NODE CM_3, node all
alls
C*** CIN1 with SIFs options
cin1, new, 2
cin1, type, sif
s
s

preint, 2, , K1
preint, 3, , K1
```
Results verification through handbook

\[
\begin{align*}
2a &= 15 \text{ mm} \\
2c &= 30 \text{ mm} \\
\sigma_0 &= 100 \text{ MPa}
\end{align*}
\]

\[
K_1 = f_m^A \sigma_0 \sqrt{\pi a} = 492 \text{ MPa} \sqrt{\text{mm}}
\]

\[
K_1 (\text{ANSYS Wb, 3D}) = 475 \text{ MPa} \sqrt{\text{mm}}
\]

Ok! possible effect of the limited width

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
2a/t & e/t=0 & e/t=0.15 & e/t=0.3 \\
\hline
0 & 0.638 & 0.000 & 0.638 & 0.191 & 0.638 & 0.383 \\
0.2 & 0.649 & 0.087 & 0.659 & 0.286 & 0.694 & 0.509 \\
0.4 & 0.681 & 0.182 & 0.725 & 0.411 & - & - \\
0.6 & 0.739 & 0.296 & 0.870 & 0.509 & - & - \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
2a/t & e/t=0 & e/t=0.15 & e/t=0.3 \\
\hline
0 & 0.824 & 0.000 & 0.824 & 0.247 & 0.824 & 0.494 \\
0.2 & 0.844 & 0.098 & 0.862 & 0.350 & 0.932 & 0.668 \\
0.4 & 0.991 & 0.210 & 0.987 & 0.526 & - & - \\
0.6 & 1.014 & 0.355 & 1.332 & 0.866 & - & - \\
\hline
\end{array}
\]
Content

• Calculation example of a wall subsurface Elliptical crack

• The effect of the cladding properties on a semielliptical sub-clad surface crack, ANSYS Workbench

• $J$ parameter calculation with ANSYS Workbench with Elastic-Plastic material
Sub-clad surface semielliptical crack

The model

Sub-clad defect

Crack only on the wall part
**Sub-clad surface semielliptical crack**

The model

Hide a body to pick any other surface behind

Create the surface semielliptical crack through the usual steps
Sub-clad surface semielliptical crack

The model

The attachment between the wall and the clad cannot be continuous across the entire surface.

A circle can give a dimension of the discontinuity between the two parts.
SIF results

First result can be obtained without any connection between the two parts.
Sub-clad surface semielliptical crack

SIF results

Then calculation is repeated with connection outside the circle.
Sub-clad surface semielliptical crack

SIF results

Finally the full surface connection can be activated, after imposing plastic properties of the clad.

Clad Elastic-Plastic properties
Sub-clad surface semielliptical crack

SIF results

Finally the full surface connection can be activated, after imposing plastic properties of the clad.
Sub-clad surface semielliptical crack

SIF result comparison

Which one is the most realistic result?

\[ K_1 = 510 \text{ MPa} \sqrt{\text{mm}} \]

\[ K_1 = 426 \text{ MPa} \sqrt{\text{mm}} \]

\[ K_1 = 369 \text{ MPa} \sqrt{\text{mm}} \]
Table of content

Content

• Calculation example of a wall subsurface Elliptical crack
• The effect of the cladding properties on a semielliptical sub-clad surface crack, ANSYS Workbench
• $J$ parameter calculation with ANSYS Workbench with Elastic-Plastic material
CT specimen example

**J** parameter as an option of the Wb automatic Crack tool

Elastic calculation – Relation between $K_I$ and $J$

---

\[ K_I(\text{ANSYS}) = 782 \text{ MPa} \sqrt{\text{mm}} \quad J(\text{ANSYS}) = 2.786 \text{ mJ/mm}^2 \]

Conversion, validation: \( E = 200000 \text{ MPa}, \nu = 0.3 \)

\[ J = \frac{K_I^2}{E'} = 2.782 \text{ mJ/mm}^2 \quad \text{OK!} \]
CT specimen example

Elastic-Plastic steel, *Bilinear Isotropic Hardening*

![Graph showing stress-strain relationship for elastic-plastic steel with bilinear isotropic hardening](image)

<table>
<thead>
<tr>
<th>Outline of Schematic A2: Engineering Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

| 12 | Bilinear Isotropic Hardening            |
| 13 | Yield Strength                          | 500 MPa  |
| 14 | Tangent Modulus                         | 5000 MPa  |
Elastic-Plastic steel, *Bilinear Isotropic Hardening*
Elastic-Plastic steel, *Bilinear Isotropic Hardening*

Same load $P$, Elastic-Plastic material:

$$J(\text{ANSYS}) = 2.748 \text{ mJ/mm}^2$$

Previous (just Elastic):

$$J(\text{ANSYS}) = 2.786 \text{ mJ/mm}^2$$

$\Delta\% = -1.4\%$
**CT specimen example**

Elastic-Plastic steel, *Bilinear Isotropic Hardening*

Same load $P$, Elastic-Plastic material: $K_{I(II,III)}$ is also calculated, though theoretically not available (just the output of CINT,SIFS command)

$K_1(\text{ANSYS}) = 800 \text{ MPa}\sqrt{\text{mm}}$

Previous (just Elastic):

$K_1(\text{ANSYS}) = 782 \text{ MPa}\sqrt{\text{mm}}$

$\Delta\% = 2.3\%$
Small Scale Yielding

$K_1$ and $J$ similar values, with respect to the previous just elastic calculation, due to the very small plastic region.
CT specimen example

Increasing load – Multiple time step simulation
Increasing load – Multiple time step simulation

Non linear analysis – iterative solution
Increasing load – Multiple time step simulation

Increasingly discrepancy of $K_I$ with respect to $J$

<table>
<thead>
<tr>
<th>Elastic-Plastic, ANSYS Workbench</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_Y$, MPa</td>
<td>$B$, mm</td>
</tr>
<tr>
<td>500</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$P$, kN</th>
<th>$K_I$, MPa mm$^{0.5}$</th>
<th>$J$, mJ/mm$^2$</th>
<th>$K_I$, from $J$</th>
<th>Delta %</th>
<th>$B_{min}$ for Pl. Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>800</td>
<td>2.748</td>
<td>777</td>
<td>-2.9</td>
<td>6.0 =&gt; Pl. Strain</td>
</tr>
<tr>
<td>20</td>
<td>1969</td>
<td>11.25</td>
<td>1572</td>
<td>-25.2</td>
<td>24.7 =&gt; Pl. Stress</td>
</tr>
<tr>
<td>30</td>
<td>3712</td>
<td>27.32</td>
<td>2450</td>
<td>-51.5</td>
<td>60.0 =&gt; Pl. Stress</td>
</tr>
<tr>
<td>40</td>
<td>6269</td>
<td>56.85</td>
<td>3535</td>
<td>-77.4</td>
<td>124.9 =&gt; Pl. Stress</td>
</tr>
</tbody>
</table>

Unreliable \[\uparrow\] \[\uparrow\] \[\uparrow\] Reliable \[\uparrow\] Equivalence
Increasing load – Multiple time step simulation

Plastic region size

\[
P = 10 \text{ kN} \quad B = 12 \text{ mm}
\]

\[
B_{\text{min}} = 2.5 \left( \frac{K_1}{S_Y} \right)^2 = 6.0 \text{ mm}
\]

→ Plane strain

\[
r_p = \frac{1}{3\pi} \left( \frac{K_1}{S_Y} \right)^2 = 0.26 \text{ mm}
\]
Increasing load – Multiple time step simulation

Plastic region size

\[ P = 40 \text{ kN} \quad B = 12 \text{ mm} \]

\[ B_{\text{min}} = 2.5 \left( \frac{K_1}{S_Y} \right)^2 = 124.9 \text{ mm} \]

\[ \Rightarrow \text{Plane stress} \]

\[ r_p = \frac{1}{\pi} \left( \frac{K_1}{S_Y} \right)^2 = 15.9 \text{ mm} \]

LEFM validity for Pl. Stress not satisfied:

\[ a = 30 \text{ mm} < \frac{4}{\pi} \left( \frac{K_1}{S_Y} \right)^2 = 57.9 \text{ mm} \]

Load \ll 80\% of fully plastic value

Ok the use of \( J \)