ON THE STRUCTURAL INTEGRITY ASSESSMENT OF HETEROGENEOUS WELDED JOINT

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December 2012, Fraunhofer IWM Freiburg, Germany
MOTIVATION

- Repair welding are common in practice
- Repair welds are heterogeneous!
- What is their limit loads?
- How to consider this heterogeneity for structure integrity assessment?
CONSIDERED PROBLEM

- “I” shape butt welded joint
- Repaired weld – heterogeneous joint
- Three point bend specimen - bending loading common in structures

- FINITE ELEMENT ANALYSIS
- EXPERIMENTS
Three point bend specimen – butt welded “I” welded joint

Problem complexity – idealizations and simplifications:

- part of repaired butt welded joint idealized with rectangular shape
- crack positioned in the middle of the weld
- HAZ is not considered
- even share of „overmatch” (WM1) and „undermatch” (WM2) part of weld
- elastic properties - constant

![Diagram of the welded joint](image)
**FINITE ELEMENT ANALYSIS**

**VERIFICATION OF FE MODEL**

- Slip line field
- Homogeneous specimen:

\[
F_{\text{YB}} = \beta \cdot \frac{\sigma_{\text{YB}} \cdot B(W-a)^2}{\sqrt{3} \cdot S/2}
\]

\[
\beta = \begin{cases} 
1,125 + 0,892 \cdot x - 2,238 \cdot x^2 & \text{za } 0 < x = a/W \leq 0,172 \\
1,199 + 0,096 \cdot x & \text{za } 0,172 < x < 1 
\end{cases}
\]

* Y.J. Kim, K.H. Schwalbe, Compendium of yield load solutions for strength mis-matched DE (T), SE (B) and C (T) specimens, Engineering Fracture Mechanics, (2001), 68, 1137–1151.
Weld material with higher yield strength than base material - overmatch:

\[
F_{YM} = \min \left( \left( \frac{F_{YM}}{F_{YB}} \right)_1, \left( \frac{F_{YM}}{F_{YB}} \right)_2 \right)
\]

Net section of base material yields before weld material:

\[
\left( \frac{F_{YM}}{F_{YB}} \right)_1 = \beta_b \cdot \frac{1}{\beta} \left( \frac{a}{W} \right)^2
\]

\[
\beta_b = 4,5557 - 3,6072 \left( 2 - \frac{H}{W} \right) + 1,3095 \left( 2 - \frac{H}{W} \right)^2 - 0,1818 \left( 2 - \frac{H}{W} \right)^3
\]

Yield zones spreads through both materials:

\[
\left( \frac{F_{YM}}{F_{YB}} \right)_2 = \begin{cases} 
M & \text{for } 0 \leq \psi \leq \psi_1 \\
A + B \cdot \frac{\psi_1}{\psi} - C \left( \frac{\psi_1}{\psi} \right)^M & \text{for } \psi_1 \leq \psi
\end{cases}
\]

* Y.J. Kim, K.H. Schwalbe, Compendium of yield load solutions for strength mis-matched DE (T), SE (B) and C (T) specimens, Engineering Fracture Mechanics, (2001), 68, 1137–1151.
**FINITE ELEMENT ANALYSIS**

**VERIFICATION OF FE MODEL**

Numerical 2D model – plain strain – ANSYS software
- Modeled ½ of specimen – symmetry
- Key points
- Systematically varied half width of weld $H$ and crack length $a$
- Isoparametric 8-node finite elements
- 1847 finite elements and 5690 nodes
- Crack tip – element size 100 $\mu$m

![Diagram of numerical verification model](image)
FINITE ELEMENT ANALYSIS

VERIFICATION OF FE MODEL

Numerical 2D model – plain strain – ANSYS software
- Force load – yielding whole net section of welded joint
- Small force increment – precise yield load determination
- Material linear-elastic almost ideal plastic
- Yield criterion – von Mises

![Graph showing stress-strain curve with key points labeled](image)

Keypoints of FE model:
- Practically ideally plastic
- Keypoints: a = 0.1W, 0.2W, 0.3W, 0.4W, 0.5W
- Symmetry line

Numerical verification model
FINITE ELEMENT ANALYSIS

VERIFICATION OF FE MODEL

\[
\frac{F_{YM}}{F_{YB}}
\]

Comparison of numerical results to slip line field solution

Slip line field solutions

Numerical results

\[
(W-a)/H
\]
**FINITE ELEMENT ANALYSIS**

**VERIFICATION OF FE MODEL**

\[
\frac{F_{YM}}{F_{YB}}
\]

Comparison of numerical results to slip line field solution

- **Slip line field solutions**
- **Numerical results**

\[(W-a)/H\]
FINITE ELEMENT ANALYSIS

- Geometric parameters – parameter of numerical model - unchanged
- Change in material properties

Keypoints of FE model

Crack in WM1-OM
Crack in WM2-UM
Numerical model of heterogeneous welded joint
### Finite Element Analysis

Required number of numerical simulations for analysis of heterogeneous welded joint

<table>
<thead>
<tr>
<th>$M_2$</th>
<th>$M_1$</th>
<th>1,19</th>
<th>1,5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha/W$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>$W/2$</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$W/4$</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$W/8$</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$W/16$</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$W/24$</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

$M_1$ – 3 levels, $M_2$ – 3 levels, $\alpha/W$ – 5 levels, $H$ – 5 levels

225 combinations $\times 2 = 450$ simulations
Stress distribution in heterogeneous welded joint with crack positioned in “overmatch” part of weld
(a/W=0.5, H=W/8)
FINITE ELEMENT ANALYSIS

Regression analysis results with coefficients of second order polynomial function \((R^2 = 0.853)\) for crack in overmatch material (WM1)

<table>
<thead>
<tr>
<th></th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C)</td>
<td>0.90467</td>
</tr>
<tr>
<td>(M_1)</td>
<td>0.18539</td>
</tr>
<tr>
<td>(M_2)</td>
<td>-0.30892</td>
</tr>
<tr>
<td>(a/W)</td>
<td>1.07910</td>
</tr>
<tr>
<td>(H)</td>
<td>-0.09146</td>
</tr>
<tr>
<td>((a/W)^2)</td>
<td>-1.91433</td>
</tr>
<tr>
<td>(H^2)</td>
<td>0.00207</td>
</tr>
<tr>
<td>(M_1 \cdot a/W)</td>
<td>-0.51386</td>
</tr>
<tr>
<td>(M_1 \cdot H)</td>
<td>0.02609</td>
</tr>
<tr>
<td>(M_2 \cdot a/W)</td>
<td>1.21194</td>
</tr>
<tr>
<td>(M_2 \cdot H)</td>
<td>0.06139</td>
</tr>
<tr>
<td>(a/W \cdot H)</td>
<td>-0.09577</td>
</tr>
</tbody>
</table>

- Statistical analysis – software STATISTICA
- Analysis of variance – all factors all significant
- Regression analysis – analysis of variance of regression model – second order model
\[
\frac{F_{YM}}{F_{YB}} = 0,90467 + 0,18539 \cdot M_1 - 0,30892 \cdot M_2 + 1,0791 \cdot (a/W) - 0,09146 \cdot H - \\
- 1,91433 \cdot (a/W)^2 + 0,00207 \cdot H^2 - 0,51386 \cdot M_1 \cdot (a/W) + 0,02609M_1 \cdot H + \\
+ 1,21194 \cdot M_2 \cdot (a/W) + 0,06139 \cdot M_2 \cdot H - 0,09577 \cdot (a/W) \cdot H.
\]

- crack in "overmatch" material \((M_1)\)
Regression analysis results with coefficients of second order polynomial function ($R^2 = 0.916$) for crack in undermatch material (WM2)

<table>
<thead>
<tr>
<th>Term</th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>1.02213</td>
</tr>
<tr>
<td>$M_1$</td>
<td>0.12708</td>
</tr>
<tr>
<td>$M_2$</td>
<td>0.19979</td>
</tr>
<tr>
<td>$a/W$</td>
<td>-1.02879</td>
</tr>
<tr>
<td>$H$</td>
<td>-0.12510</td>
</tr>
<tr>
<td>$M_1^2$</td>
<td>-0.11012</td>
</tr>
<tr>
<td>$(a/W)^2$</td>
<td>1.14417</td>
</tr>
<tr>
<td>$H^2$</td>
<td>0.00122</td>
</tr>
<tr>
<td>$M_1 \cdot a/W$</td>
<td>0.50305</td>
</tr>
<tr>
<td>$M_1 \cdot H$</td>
<td>0.04560</td>
</tr>
<tr>
<td>$M_2 \cdot a/W$</td>
<td>-0.53766</td>
</tr>
<tr>
<td>$M_2 \cdot H$</td>
<td>0.04002</td>
</tr>
<tr>
<td>$a/W \cdot H$</td>
<td>0.09722</td>
</tr>
</tbody>
</table>
\[
\frac{F_{YM}}{F_{YB}} = 1.02213 + 0.12708 \cdot M_1 + 0.19979 \cdot M_2 - 1.02879 \cdot (a/W) - 0.1251 \cdot H - \\
- 0.11012 \cdot M_1^2 + 1.14417 \cdot (a/W)^2 + 0.00122 \cdot H^2 + 0.50305 \cdot M_1 \cdot (a/W) + \\
+ 0.0456 \cdot M_1 \cdot H - 0.53766 \cdot M_2 \cdot (a/W) + 0.04002 \cdot M_2 \cdot H + 0.09722 \cdot (a/W) \cdot H
\]

- crack in "undermatch" material \((M_2)\)
FINITE ELEMENT ANALYSIS

\[ H = \frac{W}{24} \]

Crack in overmatched material (WM1)  –  Crack in undermatched material (WM2)
Crack in overmatched material (WM1) — Crack in undermatched material (WM2)
FINITE ELEMENT ANALYSIS

Crack in overmatched material (WM1) – Crack in undermatched material (WM2)
FINITE ELEMENT ANALYSIS

\( \alpha/W = 0.1 = \text{konst.} \quad i \quad H = W/24 = \text{konst.} \)

\( M_2 < 1 \) undermatch mismatch factor

\[ M_2 = \frac{R_{c,UM}}{R_{c,BM}} < 1 \]

\( M_1 > 1 \) overmatch mismatch factor

\[ M_1 = \frac{R_{e,OM}}{R_{e,BM}} > 1 \]

Crack in overmatched material (WM1) – Crack in undermatched material (WM2)

a)
Yield load ratio in dependence on strength of mismatch factor of weld materials ($a/W_i H=\text{const.}$) with crack in overmatched part of weld ($a/W=0.1$)

Yield load ratio in dependence on strength of mismatch factor of weld materials ($a/W_i H=\text{const.}$) with crack in undermatched part of weld ($a/W=0.1$)
Yield load ratio in dependence on strength of mismatch factor of weld materials \(\alpha/W_i H=\text{const.}\)

with crack in overmatched part of weld \(\alpha/W = 0.5\)

Yield load ratio in dependence on strength of mismatch factor of weld materials \(\alpha/W_i H=\text{const.}\)

with crack in undermatched part of weld \(\alpha/W = 0.5\)
A high-strength low-alloy HSLA steel HT 50, was base metal (BM).

Two different tubular wires were selected for the welding over-and under-matched (OM and UM) configurations.

A Flux Cord Arc Welding (FCAW) procedure was applied.

The welding procedure is usually used for repair welding or for weld joints where possibly cold hydrogen assisted cracking can appear.

Welding arrangement (2H=10 mm)
Cross-section with notch position in overmatched weld metal

Note: Such a welded joint exhibits locally different microstructures causing local variations:
- of the yield strength,
- the strain hardening exponent, and
- the Young’s modulus.

The assessment of the material inhomogeneity term can be essential to understand the fracture resistance of the welded joint!
Toughness of the base material and weld materials with mismatch factors $M_1 = 1.19$ and $M_2 = 0.86$ (according to *)

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Material</th>
<th>$J_{mat}$ N/mm</th>
<th>$K_{mat}$ MPa m$^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a/W=0.1$</td>
<td>Base material (NIOMOL 490)</td>
<td>669</td>
<td>386</td>
</tr>
<tr>
<td>$B=W=25$ mm</td>
<td>Weld material (FITUB 75)</td>
<td>171.5</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>Weld material (VAC 60)</td>
<td>604</td>
<td>370</td>
</tr>
</tbody>
</table>

Mechanical properties of the base material and weld materials with mismatch factors $M_1 = 1.19$ and $M_2 = 0.86$

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_{p0.2}$ MPa</th>
<th>$R_m$ MPa</th>
<th>$E$ GPa</th>
<th>$KV$ $J$</th>
<th>$\sigma$ MPa</th>
<th>$n$ -</th>
<th>$\alpha$ -</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material (NIOMOL 490)</td>
<td>545</td>
<td>648</td>
<td>202</td>
<td>$\geq 60$ J on $-60$ °C</td>
<td>516</td>
<td>0,08915</td>
<td>0,96486</td>
<td></td>
</tr>
<tr>
<td>Weld material (FITUB 75)</td>
<td>648</td>
<td>744</td>
<td>184</td>
<td>$\geq 40$ J on $-60$ °C</td>
<td>607</td>
<td>0,09431</td>
<td>0,94434</td>
<td>1,19</td>
</tr>
<tr>
<td>Weld material (VAC 60)</td>
<td>469</td>
<td>590</td>
<td>206</td>
<td>$\geq 80$ J on $-60$ °C</td>
<td>436</td>
<td>0,10462</td>
<td>0,97326</td>
<td>0,86</td>
</tr>
</tbody>
</table>

SINTAP ASSESSMENT - EXAMPLE

SINTAP procedure (Level 2B – FAD approach) – function $f(L_r)$ is defined

$$f(L_r) = \left[1 + 0,5 \cdot L_r^2\right]^{\frac{1}{2}} \cdot \left[0,3 + 0,7 \cdot e^{-\mu_M L_r^6}\right] \text{ za } 0 \leq L_r \leq 1$$

$$f(L_r) = f(L_r=1) \cdot L_r^{\frac{(N_M-1)}{2N_M}} \text{ za } 1 \leq L_r \leq L_r^{\text{max}}$$

$$\mu_M = \min \left\{ \frac{F_{YM}}{F_{YB}} - 1 \right\} / \mu_W + \left( M - \frac{F_{YM}}{F_{YB}} \right) / \mu_B$$

$$\mu_W = \min \left\{ 0,001 \cdot \frac{E_W}{R_{p0,2,W}} \right\}$$

$$\mu_B = \min \left\{ 0,001 \cdot \frac{E_B}{R_{p0,2,B}} \right\} \text{ 0,6}$$

$$N_M = \frac{M - 1}{\left( \frac{F_{YM}}{F_{YB}} - 1 \right) / N_W + \left( M - \frac{F_{YM}}{F_{YB}} \right) / N_B}$$

$$N_B = 0,3 \cdot \left[ 1 - \frac{R_{p0,2,B}}{R_{m,B}} \right]$$

$$L_r^{\text{max}} = 0,3 \cdot \left[ 1 + \frac{0,3}{0,3 - N_M} \right]$$

$$N_W = 0,3 \cdot \left[ 1 - \frac{R_{p0,2,W}}{R_{m,W}} \right]$$

Modification due to heterogeneity - the weld material properties - material containing crack
SINTAP ASSESSMENT - EXAMPLE

SINTAP procedure (Level 3B) – FAD and CDF approach

$$f_2(L_r) = \left[ \frac{E \varepsilon_{ef,M}}{L_r \sigma_{Y,M}} + \frac{L_r^2 \sigma_{ref,M}}{2E \varepsilon_{ef}} \right]^\frac{1}{2} \; \text{za} \; 0 \leq L_r \leq L_r^{\text{max}}$$

$$J = J_{el} \left[ f \left( L_r \right) \right]^{-2}$$

$$J_{el} = \frac{K^2}{E'}$$

Plain strain

$$E' = \frac{E}{1 - \nu^2}$$

Plane stress

$$E' = E$$

$$\sigma_{Y,M} = \frac{F_{YM}}{F_{YB}} \sigma_{YM}$$

$$M = M(\varepsilon_p) = \frac{\sigma_W}{\sigma_B}$$

$$\sigma_{ref,M}(\varepsilon_p) = \frac{1}{(M - 1)} \left[ \left( \frac{F_{YM}}{F_{YB}} - 1 \right) \sigma_{ref,W}(\varepsilon_p) + \left( M - \frac{F_{YM}}{F_{YB}} \right) \sigma_{ref,B}(\varepsilon_p) \right]$$

$$\sigma_f,M = \frac{F_{YW}(\varepsilon_p)}{F_{YB}} \sigma_B(\varepsilon_p)$$

$$\sigma_Y = \frac{F_{YW}}{F_{YB}} \sigma_{YB}$$

$$L_r^{\text{max}} = \frac{\sigma_f,M}{\sigma_{Y,M}}$$

Plain strain

$$E' = \frac{E}{1 - \nu^2}$$

Plane stress

$$E' = E$$
Determination of critical force using SINTAP procedure (Level 2B – FAD approach) of homogeneous weld with mismatch factor ($M_1=1,19$ and $M_2=0,86$) and heterogeneous weld for $a/W=0,1$ and $H=W/2$
Determination of critical force using SINTAP procedure (Level 2B – CDF approach) of homogeneous weld with mismatch factor ($M_1=1.19$ and $M_2=0.86$) and heterogeneous weld for $a/W=0.1$ and $H=W/2$
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### SINTAP ASSESSMENT - EXAMPLE

<table>
<thead>
<tr>
<th>Description of welded joint</th>
<th>SINTAP Level</th>
<th>Critical force, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous welded joint - weld material WM1 ($M_1 = 1.19$)</td>
<td>2B</td>
<td>107.3</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>120.9</td>
</tr>
<tr>
<td>Homogeneous welded joint - weld material WM2 ($M_2 = 0.86$)</td>
<td>2B</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>91.4</td>
</tr>
<tr>
<td>Heterogeneous welded joint - weld materials WM1 and WM2 ($M_1 = 1.19$ and $M_2 = 0.86$) with crack in WM1</td>
<td>2B</td>
<td>94.1</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>101.5</td>
</tr>
<tr>
<td>Heterogeneous welded joint - weld materials WM1 and WM2 ($M_1 = 1.19$ and $M_2 = 0.86$) with crack in WM2</td>
<td>2B</td>
<td>104.2</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>110.1</td>
</tr>
<tr>
<td>Homogeneous joint - just base material (BM)</td>
<td>2B</td>
<td>103.4</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>103.4</td>
</tr>
</tbody>
</table>

- Critical value of load – is largest for homogeneous OM weld, and smaller for homogeneous UM weld
- Critical forces of heterogeneous welded joint are within maximal (OM) and minimal (UM) values
- Heterogeneous welded joint with crack in UM → OM shows higher loading capacity compared to weld with crack in OM → UM
SINTAP ASSESSMENT – EXAMPLE

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</tr>
<tr>
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<td>3B</td>
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</tr>
<tr>
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<td>2B</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td><strong>91.4</strong></td>
</tr>
<tr>
<td>Heterogeneous welded joint - weld materials WM1 and WM2 ($M_1=1.19$ and $M_2=0.86$) with crack in WM1</td>
<td>2B</td>
<td>94,1</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td><strong>101,5</strong></td>
</tr>
<tr>
<td>Heterogeneous welded joint - weld materials WM1 and WM2 ($M_1=1.19$ and $M_2=0.86$) with crack in WM2</td>
<td>2B</td>
<td>104,2</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td><strong>110,1</strong></td>
</tr>
<tr>
<td>Homogeneous joint - just base material (BM)</td>
<td>2B</td>
<td>103,4</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td><strong>103,4</strong></td>
</tr>
</tbody>
</table>

- SINTAP analysis on Level 3 confirms analysis on Level 2
- Analysis on Level 3 – less conservative assessment
- Values of critical forces for all combinations are higher than values obtained using Level 2 assessment
A single specimen method for the crack tip opening displacement (CTOD) testing, (BS 7448 [6] and the GKSS $\delta_5$ testing procedure). ($\delta_5$ is measured over a gauge length of 5 mm at the specimen side surfaces at the position of the fatigue pre-crack tip).

The CTOD tests were performed at RT (+24 °C) under displacement control (1 mm/min).

The load (F), the load point displacement, the crack mouth opening displacement (CMOD), and the $\delta_5$ were recorded.
EXPERIMENTS
Crack tip in the overmatch weld metal (spec. Vs2)!
EXPERIMENTS

Crack tip in the undevermatch weld metal (spec. Ns9)!
The load (F_y), is limit load for heterogeneous welded joint!
MODEL vs. EXPERIMENTS

CRACK IN OVERMATCHED PART OF WELD

Comparison of experiment results to predicted results obtained by statistical analysis of FEM results for cracks in overmatched part of heterogeneous weld

- $F_{pr}$ – prediction yield load, kN
- $F_{exp}$ – max. load obtained by experiments, kN

- $M_1 = 1.19$
- $M_2 = 0.86$
- $B = 25$ mm
- $W = 25$ mm

$0.44 < a/W < 0.5$ mm
EXPERIMENTS

The load (Fy), is limit load for heterogeneous welded joint!
Comparison of experiment results to predicted results obtained by statistical analysis of FEM results for cracks in undermatched part of heterogeneous weld.

- $F_{pr}$ – prediction yield load, kN
- $F_{exp}$ – yield load obtained by experiments, kN

Material properties:
- $M_1 = 1.19$
- $M_2 = 0.86$
- $B = 25$ mm
- $W = 25$ mm
- $0.26 < a/W < 0.35$ mm
CONCLUSION

• Limit load value is largest for homogeneous OM weld, and smaller for homogeneous UM weld

• Limit load of heterogeneous welded joint are within maximal and minimal values of homogeneous OM and UM, respectively

• Heterogeneous welded joint with crack in UM→OM shows higher loading capacity compared to OM → UM
CONCLUSION

• SINTAP analysis on Level 3 confirms analysis on Level 2

• Analysis on Level 3 – less conservative assessment

• Values of Limit loads for all combinations are higher than values obtained using Level 2 assessment
CONCLUSION

• Implementation of yield load solutions of heterogeneous welded joints provide less conservative results than just standard approach by SINTAP Level 2 or Level 3 without consideration of weld heterogeneity

• Yet yield load solutions of heterogeneous welded joints are still enough conservative compared to experimental results
THANK YOU FOR YOUR ATTENTION!

The authors want to thank the GKSS Research Center Geesthacht, Germany for the support in CTOD testing and Marie Curie Fundation for posdoc fellowship for N. Gubeljak in years 2000-2001!
ON THE STRUCTURAL INTEGRITY ASSESSMENT OF HETEROGENEOUS WELDED JOINT

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December 2012, Fraunhofer IWM Freiburg, Germany