Computational Weld Mechanics – Towards a simplified and cost effective approach for large welded structures

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Computational Welding Mechanics

Welding Simulation

Process simulation
- weld seam geometry
- local temperature field
- process efficiency
- process stability

Structure simulation
- global temperature field
- residual stresses
- distortions
- strength/stiffness

Material simulation
- microstructure
- phase transformation
- hardness
- hot and cold cracking

Thermal
- Weld Pool Dynamics

Microstructure
Mechanical

Interacting and coupled processes
Background

Develop FEA framework with for analysis of large complex welded structures:

• Development of an approach, *rapid dumping*, for simplified description of the welding heat source in order to decrease the CPU time.

• Investigating the influence of *thermo-mechanical material properties* of frequently used *steel grades (S355–S960)* on welding residual stresses in order to simplify the material modeling and reduce the number of material parameters in FE simulation.

• Implementation of developed simulation framework on complex welded structures, using *sub structuring* and super elements in a construction equipment vehicle

• *Validation* of the predicted residual stresses and distortions on small scale specimens and real components using X-ray diffraction techniques
Procedure for computational weld mechanics

- **Sequential analysis**: thermal analysis to obtain the temperature distributions and the subsequent elastic-plastic nonlinear mechanical analysis

- Weld bead is divided into adequate number of volumes (blocks)
  - CPU time could be reduced to 50% by using 48 blocks compared to 144
Approaches in mechanical analysis for reduction of CPU time

- **Block dumping**

  - This approach is computationally efficient but less accurate results are produced.
Approaches in mechanical analysis for reduction of CPU time

• **Gradual weld bead deposition**

  - This approach is computationally intensive but it produces more accurate results since it is much closer to reality

• **Rapid Dumping**

  - instead of using the final cooling load step for each activated block, final cooling load step is used for the center weld bead in a single load step
Approaches in mechanical analysis for reduction of CPU time

- **Sub-Structuring: small scale specimen**

  - During the welding process the region close to the heat source is highly nonlinear while remaining region in the structure behaves nearly elastic. But during the FE simulation the whole structure is treated as nonlinear model.
Approaches in mechanical analysis for reduction of CPU time

- **Sub-Structuring: large scale specimen**

  - The computational time can be reduced by using sub-structuring technique in which the linear region is condensed into a single element matrix called super element matrix and only element matrices for nonlinear portion is evaluated at the end of every equilibrium iteration during the nonlinear solution.
Validation of approaches
Longitudinal attachment with fillet welds

- **S700 MC steel grade**, Metal Cored Arc Welding (MCAW)
- Measurement of residual stresses using X-ray diffraction technique
Validation of approaches

Butt welded joint

- Single pass with grade steel ST37-2
- Measurement of residual stresses with neutron diffraction technique.

T-Fillet-welded joint

- SS 2132 with 6 mm thickness, MAG welding
- Measurement of residual stresses with x-ray diffraction technique.
Material properties
Simplifying the input parameters in welding simulations

- T-fillet joint

- Investigations are carried out on a T-fillet joint
Material properties
Simplifying the input parameters in welding simulations

- Different cases in thermal properties

<table>
<thead>
<tr>
<th>Thermal case</th>
<th>Thermal material properties</th>
<th>Heat Capacity c</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP-1</td>
<td>$k = k(T)$</td>
<td>$c = c(T)$</td>
</tr>
<tr>
<td>TP-2</td>
<td>Varying linearly between 25 °C and 1400 °C</td>
<td>Varying linearly between 25 °C and 1400 °C</td>
</tr>
<tr>
<td>TP-3</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>TP-4</td>
<td>$k = k(T)$</td>
<td>Constant</td>
</tr>
<tr>
<td>TP-5</td>
<td>Constant</td>
<td>$c = c(T)$</td>
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</table>

- Different cases in mechanical properties

<table>
<thead>
<tr>
<th>Mechanical case</th>
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<th>Yield stress $\sigma_y$</th>
<th>Coefficient of thermal expansion $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP-1</td>
<td>$E = E(T)$</td>
<td>$\sigma_y = \sigma_y(T)$</td>
<td>$\alpha = \alpha(T)$</td>
</tr>
<tr>
<td>MP-2</td>
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<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
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<td>Constant</td>
<td>$\sigma_y = \sigma_y(T)$</td>
<td>Constant</td>
</tr>
<tr>
<td>MP-4</td>
<td>Constant</td>
<td>Constant</td>
<td>$\alpha = \alpha(T)$</td>
</tr>
<tr>
<td>MP-5</td>
<td>$E = E(T)$</td>
<td>Constant</td>
<td>Constant</td>
</tr>
<tr>
<td>MP-6</td>
<td>Constant</td>
<td>$\sigma_y = \sigma_y(T)$</td>
<td>$\alpha = \alpha(T)$</td>
</tr>
<tr>
<td>MP-7</td>
<td>$E = E(T)$</td>
<td>$\sigma_y = \sigma_y(T)$</td>
<td>Constant</td>
</tr>
<tr>
<td>MP-8</td>
<td>$E = E(T)$</td>
<td>Constant</td>
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The influence of different thermal cases on temperature distributions is investigated by comparing the temperature histories.

Temperature histories at point A and B using test cases (TP 1-5) for T-fillet joint welded with S355 steel grade.
Influence of mechanical material properties

- Comparison of experimental and numerical transverse residual stresses using mechanical cases (MP 1-8) for S355 steel grade.
Influence of mechanical material properties

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<tr>
<td>MP-1</td>
<td>Young's modulus $E = E(T)$</td>
<td>$\sigma_Y = \sigma_Y(T)$</td>
<td>$\alpha = \alpha(T)$</td>
</tr>
<tr>
<td>MP-2</td>
<td>Constant</td>
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Influence of mechanical material properties

- Comparison of angular deformation predicted by different mechanical cases (MP 1-8) in T-fillet joint welded with different steel grades.
Influence of mechanical material properties

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Generalization of yield stress

- **temperature dependent yield stress** is the most important material property in the mechanical analysis. Therefore, in order to develop generalized semi-empirical expressions for temperature dependent yield stress, piece-wise linear equations are used to describe it for a wide range of steel grades.

\[
\begin{align*}
    \sigma(T) &= \sigma_{RT} + \beta_1 T & T_{RT} \leq T \leq T_{f1} \\
    \sigma(T) &= \frac{1}{(T_{f2} - T_{f1})} \left[ \sigma_{f1}(T_{f2} - T) + \beta_2 (T - T_{f1}) \right] & T_{f1} \leq T \leq T_{f2} \\
    \sigma(T) &= \frac{1}{(T_{f3} - T_{f2})} \left[ \sigma_{f2}(T_{f3} - T) + \beta_3 (T - T_{f2}) \right] & T_{f2} \leq T \leq T_{f3} \\
    \sigma(T) &= \sigma_{f3} & T_{f3} \leq T \leq T_{MT}
\end{align*}
\]

\(T_{f1}, T_{f2}\) and \(T_{f3}\) represent the temperatures at 500° C, 800° C, and 1100° C respectively.
Application to large welded structure
Bogie beam in a Volvo Articulated Hauler

Locations for residual stress measurement using X-ray diffraction tech.

Number of welds and sequences for bogie beam
Application to large welded structure
Bogie beam in a Volvo Articulated Hauler

Comparison of experimental and numerically predicted residual stresses using different approaches in bogie beam
Conclusions

- By using the rapid dumping approach for welding simulations, the CPU computational time is reduced by 90% as compared to gradual weld bead deposition.

- For assessment of welding residual stresses all of the mechanical material properties except temperature dependent yield stress can be taken as constant.

- It is important to consider the influence of solid state phase transformation in FE analysis, which will further enhance the level of accuracy of the residual stress predictions.

- The residual stresses predicted in the bogie beam structure using rapid dumping showed good agreement with measurements. The computational time could be reduced by 60% compared with gradual weld bead deposition.

- Substructuring technique using rapid dumping approach is successfully implemented on bogie beam structure. The technique has produced almost identical results and further reduced the computational time by 20% when compared with rapid dumping approach.
Thank you for your kind attention!

Questions?