Managing Welding Induced Distortion – Comparison of different computational approaches

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Background

- Accurate and reliable distortion predictions are essential for structural integrity of welded structures
  - Structural integrity analysis (Fatigue, Fracture, Buckling)
  - Manufacturing (Cutting, Forming, Joining)
  - and Assembly (Tolerances)

- Need for simplified methods for prediction of welding induced distortion
Methods for FE welding simulations for distortion predictions

- Thermo-elastic-plastic FEM simulations

- Elastic FEM based on *Inherent Strain*
  - plastic strain developed during the welding processes give rise to distortion
  - Other variants are; *Inherent deformation* and *Shrinkage force*

- This study aims to assess and compare these different approaches and validation with experimental data
What happens during welding?

Uniaxial test specimen

1. Initial condition / length

Heating
1-2. Elastic compression
To initial length

More heating
2-3. Plastic compression
To initial length

Cooling
3-4. Elastic tension
To initial length

SATOH test

\[ \varepsilon_{total} = 0 \]

\[ \sigma_{residual} = \sigma_y \]

Longitudinal stresses in the weld

**1.** Cooling

**2.** Heating

**3.** Cooling

**4.** Heating
What is inherent strain?

Three bar model

Before heat input

After cooling

After cutting

\( \Delta L \): mismatch produced by welding (inherent strain)
Classification of welding distortion

- Transverse Shrinkage
- Longitudinal Shrinkage
- Rotational Distortion
- Angular Change
- Buckling Distortion
- Longitudinal Bending
Visible strain (total strain):

\[ \varepsilon = \frac{\Delta L}{L} \]

Total strain \( \varepsilon = \) Elastic strain \( \varepsilon^e \) + Thermal strain \( \varepsilon^T \) + Plastic strain \( \varepsilon^p \) + Creep strain \( \varepsilon^c \) + Transformation strain \( \varepsilon^t \)

\[ \varepsilon = \varepsilon^e + \varepsilon^T + \varepsilon^p + \varepsilon^c + \varepsilon^t \]

Rearranging equation:

\[ \varepsilon - \varepsilon^e = \varepsilon^T + \varepsilon^p + \varepsilon^c + \varepsilon^t = \varepsilon^* \] (inherent strain)

If **Inherent Strain** is known; welding distortion can be computed by elastic analysis
Specimens and experimental set up

- **T-fillet joint with S355 steel**
  - During welding, the baseplate has been clamped in one side and in 60 mm from center of the baseplate.

- **Welding deformation measurements**
  - device is moved on the surface of the specimen and measures the deformation of some specified points both on baseplate and stiffener
Nonlinear FEA for welding simulation

- weld bead is divided into adequate number of volumes (blocks) which will be used in the implementation of the moving heat source and rapid dumping approach.

- Non-linear, temperature dependent material properties were used

![Stress extraction points](image)

![Welding direction](image)

![Distance (mm)](image)

![Longitudinal Stress (MPa)](image)
Inherent strain zone

- Determined through the non-linear FEA
  - Residual plastic strain created due plastic deformation during welding

- Good approximation; Average value of the inherent strain distribution along the weld line

- Elastic FEA may be used to predict the welding distortion when the inherent strain region and averaged magnitude is known for the particular joint.
Inherent strain approach

-Magnitude of inherent strain $\varepsilon$, consists of bending ($\varepsilon^b$) and membrane ($\varepsilon^m$)

- The inherent strain components are integrated over thickness ($t$) and the results applies on each element in the inherent strain zone,

$$\varepsilon = \varepsilon^m + \varepsilon^b$$

$$\varepsilon^m = \frac{1}{t} \int_{-\frac{t}{2}}^{\frac{t}{2}} \varepsilon dy$$
Inherent deformation approach

Integration of inherent strain over the cross section of the plate and perpendicular to welding line

-The inherent deformation may be divided into four components
  - Longitudinal shrinkage ($\delta^*_L$)
  - Transverse shrinkage ($\delta^*_T$)
  - Longitudinal bending ($\theta^*_L$)
  - Transverse bending ($\theta^*_T$)

The average value of inherent deformation components along welding length ($L_w$)

\[
\delta^*_z = \frac{1}{t} \int \varepsilon_z^* \, dx \, dy \\
\theta^*_z = \frac{1}{t} \int t\varepsilon_z^* \, dx \, dy
\]

\[
\delta^*_x = \frac{1}{t} \int \varepsilon_x^* \, dx \, dy \\
\theta^*_x = \frac{1}{t} \int t\varepsilon_x^* \, dx \, dy
\]

\[
\overline{\delta}^*_z = \frac{1}{L_w} \int_0^L \delta^*_z \, dz \\
\overline{\theta}^*_z = \frac{1}{L_w} \int_0^L \theta^*_z \, dz
\]

\[
\overline{\delta}^*_x = \frac{1}{L_w} \int_0^L \delta^*_x \, dz \\
\overline{\theta}^*_x = \frac{1}{L_w} \int_0^L \theta^*_x \, dz
\]
Elastic FEA

**Inherent deformation approach**

- Inherent deformation and inherent bending in web-flange

- Average values as straight lines
Elastic FEA

**Shrinkage force approach**

- Welding distortion can also be calculated by applying equivalent force and moments

- Applied on inherent strain zone:
  - longitudinal shrinkage force \((F_z)\)
  - longitudinal moment \((M_z)\)
  - transverse shrinkage force \((F_x)\)
  - transverse moment \((M_x)\)
Comparison of different approaches

- Transverse bending

- Longitudinal bending
Comparsion of different approaches

- Longitudinal, transverse shrinkages and angular distortion

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<thead>
<tr>
<th></th>
<th>Elastic-Plastic</th>
<th>Elastic</th>
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<tbody>
<tr>
<td></td>
<td>FEM</td>
<td>FEM</td>
</tr>
<tr>
<td>Longitudinal shrinkage (mm)</td>
<td>-0.31</td>
<td>-0.5</td>
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<tr>
<td>Transverse shrinkage (mm)</td>
<td>-0.1</td>
<td>0.25</td>
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<tr>
<td>Angular distortion (mm)</td>
<td>0.051</td>
<td>0.052</td>
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<thead>
<tr>
<th>Inherent strain</th>
<th>Inherent deformation</th>
<th>Shrinkage force</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.4</td>
<td>-0.12</td>
<td>-0.16</td>
</tr>
<tr>
<td>0.041</td>
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Conclusions

- The determination of the inherent strain distribution is essential in order to carry out the elastic FEA.
- Large variation is observed in the start and stop position of the welding, i.e. edge effects. Average value of the inherent deformation should be calculated by neglecting the results from the nodes and elements locate near the plate edges.
- It is observed that the inherent strain predicts the distortion with good accuracy as compared with the other approaches. The inherent deformation and shrinkage force requires an integration step, which will result in a poorer distortion approximation.
- Inherent strain and inherent deformation approaches are suitable to predict transverse shrinkage and transverse bending.
- Shrinkage force approach is more suitable to predict the longitudinal shrinkage and longitudinal bending.
Future work

- Further evaluation of approaches

- Application to large, real, welded structures in Construction Machinery
Thank you for your kind attention!

Questions?