TRENDS IN WELDING DISTORTION ENGINEERING

Mahyar Asadi, PhD PEng IWE
Weld Engineer prepares, reviews, and assures **high-caliber instructions** for the production of welded joints.

This is usually done in accordance with applicable standard and complex instructions historically rely on the past experience.

In the modern age, Welding Engineers routinely face challenges that are not directly addressed by standards nor previous experience.
CSA W59 Clause 5.6 Control of Distortion and Shrinkage Stresses

AWS D1.1 Clause 5.20 Control of Distortion and Shrinkage

- Distortion shall be minimized
- Welding heat shall be balanced
- Program of distortion control shall be developed
- Weld shall be made in sequence such as will minimize distortion
- Restrained shall be minimized

HOW?
Controlling the Distortion in Welding

1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Adaptive Clamping
6. Adaptive Process Parameters Control
7. Sequence Design & Pattern
8. AI & ML

Finding the best sequence time and cost effective
Tack Welds and Clamping

Optimal location of tack welds?
Optimal Number of tack welds?
Optimum Interspacing?
Controlling the Distortion in Welding

1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Adaptive Clamping
6. Adaptive Process Parameters Control
7. Sequence Design & Pattern
8. AI & ML

Finding the best sequence time and cost effective
Pre-offset:

Pre-offset variables; 1) amount, 2) release time
Pre-bending: 3D-deflection, multi-pass weld (Overlay repair weld)
- Material HY80 armour steel, Corrosion resistant low alloy electrode E9016
Controlling the Distortion in Welding

1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Adaptive Clamping
6. Adaptive Process Parameters Control
7. Sequence Design & Pattern
8. AI & ML

Finding the best sequence time and cost effective
Design variables of side heating or side cooling:
1) Power
2) Size
3) Transverse offset
4) Parallel offset
Controlling the Distortion in Welding

1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Adaptive Clamping
6. Adaptive Process Parameters Control
7. Sequence Design & Pattern
8. AI & ML

Finding the best sequence time and cost effective
Adaptive Process Parameters Control

Constant Current/Speed

Adaptive Current/Speed
Controlling the Distortion in Welding

1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Adaptive Clamping
6. Adaptive Process Parameters Control
7. Sequence Design & Pattern
8. AI & ML

- Combinatorial optimization;
- \((2^n)\times n!\) possibilities

<table>
<thead>
<tr>
<th>n</th>
<th>((2^n)\times n!)</th>
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<td>9</td>
<td>1.86 (\times 10^8)</td>
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<tr>
<td>10</td>
<td>3.72 (\times 10^9)</td>
</tr>
<tr>
<td>11</td>
<td>(8.17 \times 10^{10})</td>
</tr>
</tbody>
</table>

Finding the best sequence time and cost effective
Early Joint Rigidity Approach

The welding sequence starts at the point in the structure with the highest rigidity and moves progressively toward the lowest rigidity thereby minimizing distortion.

\[
\text{Joint Rigidity} = \frac{m}{\theta}
\]

- \(m\): unit applied moment
- \(\theta\): angle of rotation per unit applied moment

By C. L. TSAI and W. T. CHENG are with The Ohio State University, Columbus, Ohio. & S. C. PARK is with Hyundai Industrial Research Institute, Korea.

The panel’s resistance to angular bending/distortion by calculating the load to return the distortion

Higher moment \(\rightarrow\) higher joint rigidity

The main practical drawback:
1) \(\theta\) is hard to define and quantify for complex shape
2) blind to weld procedure and size
3) computationally incompatible & hard for automation.
Modified Joint Rigidity Approach

The welding sequence starts at the point in the structure with the highest rigidity and moves progressively toward the lowest rigidity thereby minimizing distortion.

Joint Rigidity = 1 / D

D: Objective Deflection for given W Weld load

The panel’s resistance to angular bending/distortion by calculating the objective deflection for given weld load.

Lower D for joint’s W → higher joint rigidity

The main practical drawback:
1) If you know the objective distortion of your structure to mitigate then D is defined and quantified.
2) All weld parameters is built in Weld load.
3) Very computationally friendly and compatible for automation.
Modified Joint Rigidity Approach

• Quick Pick JRM

• Progressive JRM

• Surrogate JRM

• Evolutionary JRM
Weld Sequence Design

- Combinatorial optimization;
- \((2^n)\cdot n!\) possibilities

Initial Sequence (J I B C a F h D e K G)
Deflection = 2.4 mm

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<td>8.17 E 10</td>
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</tbody>
</table>
D value for weld “A/a” = 0.66
Max upward deflection = +0.19
Max downward deflection = -0.47
JR = 1.52
Quick Pick

“a” = 1.52  
+0.19  
-0.47  

“B” = 0.92  
+0.50  
-0.58  

“C” = 1.12  
+0.36  
-0.51  

“D” = 2.08  
+0.23  
-0.25  

“e” = 2.86  
+0.13  
-0.22  

“F” = 1.08  
+0.41  
-0.52  

“G” = 3.00  
+0.10  
-0.23  

“h” = 3.57  
-0.10  
-0.17  

“I” = 0.95  
+0.47  
-0.58  

“J” = 0.88  
+0.54  
-0.59  

“K” = 2.22  
+0.08  
-0.38  

Quick Pick

(h, G, e, K, D, a, C, F, I, B, J)

“a” = 1.52
+0.19
-0.47
6

“B” = 0.92
+0.50
-0.58
10

“C” = 1.12
+0.36
-0.51
7

“D” = 2.08
+0.23
-0.25
5

“e” = 2.86
+0.13
-0.22
3

“F” = 1.08
+0.41
-0.52
8

“G” = 3.00
+0.10
-0.23
2

“h” = 3.57
-0.10
-0.17
1

“I” = 0.95
+0.47
-0.58
9

“J” = 0.88
+0.54
-0.59
11

“K” = 2.22
+0.08
-0.38
4
Quick Pick JRM Selection of Sequence

Fast approach and well automated
“N” number of analysis (“N” is the number of weld passes)
Good for Parallel computing (Can finish in single-run CPU time)

Main Problem:
Joint rigidity does NOT remain constant and changes progressively when welds are deposited
Progressive – 1st weld

“a” = 1.52
  +0.19
  -0.47

“B” = 0.92
  +0.50
  -0.58

“C” = 1.12
  +0.36
  -0.51

“D” = 2.08
  +0.23
  -0.25

“e” = 2.86
  +0.13
  -0.22

“F” = 1.08
  +0.41
  -0.52

“G” = 3.00
  +0.10
  -0.23

“h” = 3.57
  -0.10
  -0.17

“l” = 0.95
  +0.47
  -0.58

“J” = 0.88
  +0.54
  -0.59

“K” = 2.22
  +0.08
  -0.38
Progressive – 1st weld

\[ a = 1.2 \pm 0.19 \pm 0.47 \]
\[ b = 0.12 \pm 0.13 \pm 0.47 \]
\[ c = 1.12 \pm 0.36 \pm 0.51 \]
\[ d = 2.08 \pm 0.23 \pm 0.25 \]
\[ e = 2.86 \pm 0.13 \pm 0.22 \]
\[ f = 1.08 \pm 0.41 \pm 0.52 \]
\[ g = 3.00 \pm 0.10 \pm 0.23 \]
\[ h = 3.57 \pm 0.10 \pm 0.17 \]
\[ i = 0.95 \pm 0.47 \pm 0.58 \]
\[ j = 0.88 \pm 0.54 \pm 0.59 \]
\[ k = 2.22 \pm 0.08 \pm 0.38 \]
Progressive – 2\textsuperscript{nd} weld

\[ a = 1.54 \pm 0.18 \pm 0.47 \]

\[ B = 0.93 \pm 0.50 \pm 0.58 \]

\[ C = 1.12 \pm 0.38 \pm 0.51 \]

\[ D = 2.08 \pm 0.23 \pm 0.25 \]

\[ e = 2.85 \pm 0.13 \pm 0.22 \]

\[ F = 1.08 \pm 0.41 \pm 0.52 \]

\[ G = 3.00 \pm 0.10 \pm 0.23 \]

\[ I = 1.18 \pm 0.40 \pm 0.45 \]

\[ J = 1.18 \pm 0.42 \pm 0.43 \]

\[ K = 1.96 \pm 0.15 \pm 0.36 \]

(h, ?, ?, ?, ?, ?, ?, ?, ?)

\[ h = \text{Included} \]

For all cases
Progressive – 2nd weld

For all cases

(h, G, ?, ?, ?, ?, ?, ?, ?)
Progressive – 3rd weld

\[ “a” = 1.43 \pm 0.52 \pm 0.18 \]

\[ “b” = 1.10 \pm 0.42 \pm 0.49 \]

\[ “c” = 1.23 \pm 0.40 \pm 0.42 \]

\[ “d” = 1.09 \pm 0.24 \pm 0.67 \]

\[ “e” = 2.33 \pm 0.23 \pm 0.20 \]

\[ “f” = 1.35 \pm 0.44 \pm 0.30 \]

\[ “g” = 0.33 \pm 0.10 \pm 0.23 \]

\[ “i” = 1.26 \pm 0.47 \pm 0.32 \]

\[ “j” = 1.27 \pm 0.42 \pm 0.36 \]

\[ “k” = 1.35 \pm 0.60 \pm 0.14 \]

For all cases:

\[ “h” = Included \]

\[ “g” = Included \]
Progressive – 3rd weld

"a" = 1.43
+0.52
-0.18

"b" = 1.10
+0.29
-0.49

"c" = 1.23
+0.40
-0.42

"d" = 1.09
+0.24
-0.67

"e" = 2.33
+0.23
-0.20

"f" = 1.35
+0.44
-0.30

"g" = 0.33
+0.10
-0.23

"h" = Included

"G" = Included
For all cases

"j" = 1.27
+0.45
-0.66

"k" = 1.35
+0.60
-0.14

(h, G, e, ?, ?, ?, ?, ?, ?, ?)

U, U2 (CSYS-1)

+6.561e-01
+6.100e-01
+5.005e-01
+3.950e-01
+2.875e-01
+1.800e-01
+7.250e-02
+3.500e-02
-1.425e-01
-3.500e-01
-3.575e-01
-4.650e-01
-5.725e-01
-6.800e-01
Progressive JRM Selection of Sequence

(h, G, e, K, F, a, D, B, C, I, J)

Longer calculation time but well automated

\(\frac{N(N+1)}{2} - 1\) number of analysis ("N" is the number of weld passes)

**Main Problem:**

Blind to counter balancing effect of pairs
**Surrogate Selection of Sequence**

**Counter balancing pairs**

- Pair (b, c)
  - “b” = 1.08
    - +0.50
    - -0.58
  - “c” = 0.89
    - +0.36
    - -0.51

- Pair (i, j)
  - “i” = 1.05
    - +0.47
    - -0.58
  - “j” = 1.13
    - +0.54
    - -0.59
Surrogate Selection of Sequence

Training set for machine learning

\[
\begin{align*}
\text{ADCb} & \quad \text{DaBC} & \quad \text{Bdac} & \quad \text{abDc} \\
dcba & \quad bCdA & \quad cAdB & \quad cBDA \\
\text{ABcD} & \quad \text{CaDB} & \quad bcad & \quad \text{DbAC} \\
\text{CAbd} & \quad \text{BaCD} & \quad \text{Acdb} & \quad \text{dCBA}
\end{align*}
\]

Sequence (????)

Machine-Learned Meta-Model

Displacement

\[X_1, X_2, X_3, \ldots X_n\]
\[Y_1, Y_2, Y_3, \ldots Y_n\]
\[Z_1, Z_2, Z_3, \ldots Z_n\]

\(2^4 \cdot 4! = 384\) possible sequences
Surrogate Selection of Sequence

FEM

Surrogate

\[ R'_1(c_1) \]

cdAb

Training set for machine learning

- ADCb
- DaBC
- Bdac
- abDc
- dcba
- bCdA
- cAdB
- cBDA
- ABcD
- CaDB
- bcad
- DbAC
- CAbd
- BaCD
- Acdb
- dCBA
Surrogate Selection of Sequence

FEM

Surrogate

cdAb

R'(c₁)

R'₁(c₁) + R''₂(c, d)

Training set for machine learning

ADCb  DaBC  Bdac  abDc

dcba  bCda  cAdB  cBDA

ABcD  CaDB  bcad  DbAC

CAbd  BaCD  AcdB  dCBA
Surrogate Selection of Sequence

FEM

Surrogate

\[ R'(c_1) \]

\[ R'(c_1) + R''_2(c, d) \]

\[ R'(c_1) + R''_2(c, d) + R''_3(C, d, A) \]

cdAb

Training set for machine learning

<table>
<thead>
<tr>
<th>Training set</th>
<th>ADCb</th>
<th>DaBC</th>
<th>Bdac</th>
<th>abDc</th>
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<tr>
<td>dcba</td>
<td>bCdB</td>
<td>cAdB</td>
<td>cBDA</td>
<td></td>
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<tr>
<td>ABCD</td>
<td>CaDB</td>
<td>bcad</td>
<td>DbAC</td>
<td></td>
</tr>
<tr>
<td>CAbd</td>
<td>BaCD</td>
<td>Acdb</td>
<td>dCBA</td>
<td></td>
</tr>
</tbody>
</table>
Surrogate Selection of Sequence

FEM

Surrogate

\[ R'_1(c_1) \]

\[ R'_1(c_1)+R''_2(c, d) \]

\[ R'_1(c_1)+R''_2(c, d)+R'''_3(C, d, A) \]

\[ R'_1(c_1)+R''_2(c, d)+R'''_3(C, d, A)+R'''_3(D, a, B) \]

Training set for machine learning

- ADCb
- DaBC
- Bdac
- abDc
- dcba
- bCda
- cAdB
- cBDA
- ABcD
- CaDB
- bcad
- DbAC
- CAbd
- BaCD
- Acdb
- dCBA
Surrogate Selection of Sequence

FEM

Surrogate

cdAb

Training set for machine learning

- ADCb
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- Bdac
- abDc
- dcba
- bCda
- cAdB
- cBDA
- ABcD
- CaDB
- bcad
- DbAC
- CAbd
- BaCD
- AcdB
- dCBA

- R'_1(c_1)
- R'_1(c_1)+R''_2(c, d)
- R'_1(c_1)+R''_2(c, d)+R''_3(C, d, A)
- R'_1(c_1)+R''_2(c, d)+R''_3(C, d, A)+R''_3(D, a, B)
- R'_1(c_1)+R''_2(c, d)+R''_3(C, d, A)+R''_3(D, a, B)+R'_4(b_4)
Surrogate Selection of Sequence

Training set for machine learning (61 scenarios)

DHBaCkjiFEg   bjkagHfcdEi   JaIkFCdGhEB
fJICGDEaBhk   ejKaFBghDci   AcgFDjEHibK   ...
hFlaGjDCEB   KHCDAlEJfgb   kFjiGEdachEb
CEbkgJdaffh   fhGEjIBdaKC   HeKbIgadJfC
  :

$2^{11111} = 8.17 \times 10^{10}$ possible sequences
Surrogate Selection of Sequence

Machine-Learned Meta-Model

Sequence (?????????????)

Displacement

$X_1, X_2, X_3, \ldots X_n$

$Y_1, Y_2, Y_3, \ldots Y_n$

$Z_1, Z_2, Z_3, \ldots Z_n$

$2^{11}11! = 8.17 \times 10^{10}$ possible sequences
Surrogate Selection of Sequence

(G, e, b, j, c, l, f, a, D, h, k)

Longer calculation time but well automated

4-6N number of analysis (“N” is the number of weld passes)

Main Problem:
Fidelity of meta-model reduces for larger number of weld passes.
Evolutionary Surrogate Selection of Sequence

Training set for machine learning (61 scenarios)
DHBaCkjiFeg  bjkgHfcdeI  JaIkFChGbEB
fJICGDEaBhk  cjKaFBghDci  AcgFDjEHIbK
hFklaGjDCBE  KHCDAleJfgb  kFjiGEdacHb
CEbkgJdaflh  fhGEjIBdaKC  HeKbIgadJfC

Wise extend of training set for machine learning

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<th>Sequence</th>
<th>objective</th>
<th>Score</th>
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<td>GlobDijhflk</td>
<td>0.999</td>
<td>0.597</td>
</tr>
<tr>
<td>2</td>
<td>jehbDjGefk</td>
<td>0.939</td>
<td>0.556</td>
</tr>
<tr>
<td>3</td>
<td>GbjiGfdBik</td>
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<td>4</td>
<td>jehbDjGladk</td>
<td>1.061</td>
<td>0.550</td>
</tr>
<tr>
<td>5</td>
<td>leehGdGhikC</td>
<td>0.947</td>
<td>0.478</td>
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<td>6</td>
<td>TrehjijDgik</td>
<td>1.118</td>
<td>0.513</td>
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<td>7</td>
<td>bchjDjGefk</td>
<td>1.310</td>
<td>0.595</td>
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<td>TrehjijDgik</td>
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<td>0.521</td>
</tr>
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<td>0.514</td>
</tr>
<tr>
<td>10</td>
<td>aBjiGvDhikC</td>
<td>1.273</td>
<td>0.540</td>
</tr>
</tbody>
</table>
Deflection = 0.98 ~ 1 mm

(i, d, e, f, J, H, g, a, b, c, K)

Longer calculation time but well automated
Continuous improvement, can always try to deliver a better solution.

Main Problem:
Almost endless,
Some engineering judgment is required to guide and stop the evolution
Weld Sequence Selection Option

- **Initial (Intuitive best) Sequence**
  
  \( (J, I, B, C, a, F, h, D, e, K, G) \)
  
  Distortion = **2.4 mm**

- **Quick JRM (For tight, quick, or behind schedule/budget)**
  
  \( (h, G, e, K, D, a, C, F, I, B, J) \)
  
  Distortion = **1.9 mm**
  
  Time: Preparation, post analysis, CPU time ~ 2 day schedule
  
  Number of analysis = 11 + 3 repeats due to human error
  
  Cost to client ~ CAN$ 1,800

- **Progressive JRM (For a normal schedule/budget)**
  
  \( (h, G, e, K, F, a, D, B, C, I, J) \)
  
  Distortion = **1.5 mm**
  
  Time: Preparation, post analysis, CPU time ~ 5 days schedule
  
  Number of analysis = 65 + 14 repeats due to human error
  
  Cost to client ~ CAN$ 3,300

- **Surrogate ML (For tight tolerance)**
  
  \( (G, e, b, j, c, l, f, a, D, h, k) \)
  
  Distortion = **1.1 mm**
  
  Time: Preparation, post analysis, CPU time ~ 10 days schedule
  
  Number of analysis = 61 + 20 repeats due to human error
  
  Cost to client ~ CAN$ 8,000

- **Evolutionary ML (For repetitive work and mass production)**
  
  \( (i, d, e, f, J, H, g, a, b, c, K) \)
  
  Distortion = **<1 mm**
  
  Time: Preparation, post analysis, CPU time ~ one evolution per day schedule
  
  Number of analysis = open
  
  Cost to client ~ additional CAN$ 1,500 per day (one evolution)
Controlling the Distortion in Welding

1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Adaptive Clamping
6. Adaptive Process Parameters Control
7. Sequence Design & Pattern
8. AI & ML

- Combinatorial optimization;
- \((2^n)xn!\) possibilities

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Finding the best sequence time and cost effective
Wrap-up

Weld Engineering Is Now Practically Feasible
To Go Beyond Standards
Wrap-up

Weld Engineering Is Now Practically Feasible
To Go Beyond Standards

With thanks to the team
• Majid Kashani
• Mohamad Mohseni
• Michael Fernandez
• Ghazi Alsorouji