Welding Engineering Services
Beyond the Standard

Simulation/Digital Twins/Distortion Control/Fitness for Services
Options after Crack Detected

- Replace
- Retire
- Repair
- Rerate
- Revisit

FFS & ECA
API 579 / BS7910

ENERGY & INDUSTRY DIVISION
Fitness for Service — Level 3

- Level 1  
  - Screening Assessment.
- Level 2  
  - Basic Fracture Mechanics Analysis.
- Level 3  
  - Advanced Computational Fracture Mechanics.
Fatigue — Butt Weld
Fatigue — Butt Weld

1. Crack grows or not
2. If safely NO, leave it
3. If yes, rerating
4. If cannot rerate, how long
5. Expect a leak-before-break
6. Safe Life and SII.
1. Crack grows or not
2. If safely NO, leave it
3. If yes, rerating
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5. Expect a leak-before-break
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Thermal Fatigue – Rev. Eng. Loading

Lower Vessel Locking Tension Screw Assembl

Trunnion Ring
Symmetry Condition
Vessel Shell
Inner Bracket

In Service Top
NORTH →
In Service Bottom

Tap Side LVL

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• Safe Life: 21 months
• SII not beyond 6 months
• Rerate vessel at temp < 330 °C
• Report immediately if the inspection detects crack depth of 40 mm or more
Creep - Failure in Steam Generators

Service condition is at high pressure (125 psi) & high temperature (550 C) around the clock
Creep - Failure in Steam Generators

ASME Boiler and Pressure Vessel Code B 31.3

Service condition is at high pressure (125 psi) & high temperature (550 C) around the clock
Creep - Failure in Steam Generators

Design 1  Design 2  Design 3  Design 4

ENERGY & INDUSTRY DIVISION
Creep - Failure in Steam Generators
Creep - Failure in Steam Generators

Design 1

Design 2

Design 3

Design 4
**Welding Engineering Niche**

**Standard Requirements** *(AWS D1.1, CSA W59,...)*
- 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

Generally following:
- the general guide/references/recommendation.
- complex instructions historically rely on the experience.
1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Sequence Design & Pattern
5. Adaptive Clamping
6. Adaptive Process Parameters Control
7. Mathematical modeling
8. Artificial Intelligence & Machine Learning
Combinatorial Optimization
$(2^N) \times N!$ Possibilities

<table>
<thead>
<tr>
<th>N</th>
<th>$(2^N) \times N!$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8</td>
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<tr>
<td>3</td>
<td>48</td>
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<tr>
<td>4</td>
<td>384</td>
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<tr>
<td>5</td>
<td>3840</td>
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<tr>
<td>6</td>
<td>46080</td>
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<td>7</td>
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<td>8</td>
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<tr>
<td>9</td>
<td>1.86E+8</td>
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<tr>
<td>10</td>
<td>3.72E+9</td>
</tr>
<tr>
<td>11</td>
<td>8.17E+10</td>
</tr>
</tbody>
</table>

Complexity of combinatorial optimization
WELDING SEQUENCE DESIGN

Initial Sequence
(J I B C a F h D e K G)
Deflection = 2.4 mm
“a” = 0.66
+0.19
-0.47

“b” = 1.08
+0.50
-0.58

“c” = 0.89
+0.36
-0.51

“d” = 0.48
+0.23
-0.25

“e” = 0.35
+0.13
-0.22

“f” = 0.93
+0.41
-0.52

“g” = 0.33
+0.10
-0.23

“h” = 0.28
-0.10
-0.17

“i” = 1.05
+0.47
-0.58

“j” = 1.13
+0.54
-0.59

“k” = 0.45
+0.08
-0.38
“a” = 0.66
  +0.19
  -0.47

“b” = 1.08
  +0.50
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  -0.38
$a = 0.65 + 0.18 - 0.47$

$b = 1.08 + 0.50 - 0.58$

$c = 0.89 + 0.38 - 0.51$

$d = 0.48 + 0.23 - 0.25$

$e = 0.35 + 0.13 - 0.22$

$f = 0.93 + 0.41 - 0.52$

$g = 0.33 + 0.10 - 0.23$

$h = \text{Included For all cases}$

$i = 0.85 + 0.40 - 0.45$

$j = 0.85 + 0.42 - 0.43$

$k = 0.51 + 0.15 - 0.36$
Welding Sequence Design - JRM

\( a = 0.65 \) 
\( +0.18 \)
\( -0.47 \)

\( b = 1.08 \)
\( +0.50 \)
\( -0.58 \)

\( c = 0.89 \)
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\( +0.40 \)
\( -0.45 \)

\( i = 0.85 \)
\( +0.42 \)
\( -0.43 \)

\( j = 0.85 \)
\( +0.15 \)
\( -0.36 \)

\( k = 0.51 \)
\( +0.15 \)
\( -0.36 \)

"h" = Included
For all cases
Welding Sequence Design - JRM

- "a" = 0.70
  +0.52
  -0.18

- "b" = 0.91
  +0.42
  -0.49

- "c" = 0.81
  +0.40
  -0.42

- "d" = 0.92
  +0.24
  -0.67

- "e" = 0.43
  +0.23
  -0.20

- "f" = 0.74
  +0.44
  -0.30

- "g" = Included
  For all cases

- "h" = Included
  For all cases

- "i" = 0.79
  +0.47
  -0.32

- "j" = 0.79
  +0.42
  -0.36

- "k" = 0.74
  +0.60
  -0.14
Welding Sequence Design - JRM

"a" = 0.70
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  +0.60
  -0.14

"h" = Included
For all cases
Click “Run” to weld the given sequence

- A report is generated upon job completion; format given in following pages
\[ \frac{N(N+1)}{2} \] -1 number of analysis ("N" is the number of weld passes)

**Main Problem:**
Blind to counter balancing effect of pairs
Counter balancing effect from the block sequence of 3 weld passes or more

Evolutionary algorithm like genetic algorithm that can continue as long as resources available and there is an appetite to improve the sequence

Block sequence (c, b, e)

Block sequence (i, j, h)
Welding Seq. Design - Surrogate

Displacement
$X_1, X_2, X_3, ... X_n$
$Y_1, Y_2, Y_3, ... Y_n$
$Z_1, Z_2, Z_3, ... Z_n$

$2^4 \cdot 4! = 384$ possible sequences
Welding Seq. Design - Surrogate

Training set for machine learning

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

Sequence (?????)

Meta-Model

Displacement

- $X_1$, $X_2$, $X_3$, ..., $X_n$
- $Y_1$, $Y_2$, $Y_3$, ..., $Y_n$
- $Z_1$, $Z_2$, $Z_3$, ..., $Z_n$

$2^4 \times 4! = 384$ possible sequences
Welding Seq. Design - Surrogate

FEM

Surrogate

\( R'(c_1) \)

\( \text{cdAb} \)

Training set for machine learning

- ADCb
- DaBC
- Bdac
- abDc
- dcba
- bCdA
- cAdB
- cBDA
- ABcD
- CaDB
- bcad
- DbAC
- CAbd
- BaCD
- Acdb
- dCBA
Welding Seq. Design - Surrogate

FEM          Surrogate

\[ R'(c_1) + R'_{2}(c_2) \]

Training set for machine learning

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WELDING SEQ. DESIGN - SURROGATE

**FEM**

**Surrogate**

**cdAb**

Training set for machine learning

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

\[ R'_1(c_1) + R''_2(c, d) + R''_3(C, d, A) \]
FEM | Surrogate | cdAb | Training set for machine learning
---|---|---|---

\( R'_1(c_1) \)

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

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

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

ADCb DaBC Bdac abDc
dcba bCda cAdB cBDA
ABcD CaDB bcad DbAC
CAbd BaCD AcdB dCBA
Welding Seq. Design - Surrogate

FEM

Surrogate

**cdAb**

Training set for machine learning

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

\[
R'_1(c_1) + R''_2(c, d) + R''_3(C, d, A) + R''_3(D, a, B) + R'_{4(b_4)}
\]
Training set for machine learning (61 scenarios)

$2^{1111} = 8.17 \times 10^{10}$ possible sequences

Sequence (????????????)
Welding Seq. Design - Surrogate

Machine-Learned Meta-Model

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

Training set for machine learning (61 scenarios)

2^{1111} = 8.17 \times 10^{10} \text{ possible sequences}

Wise extend of training set for machine learning

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

GA

Low Fidelity Selections
Deflection = 1.1 mm

Deflection = 0.98 ~ 1 mm
Click “Run” to weld the given sequence.

- A report is generated upon job completion; format given in following pages.
Distortion control portfolio

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

- **Quick JRM** (For quick schedule/ limited budget)
  (h, G, e, K, D, a, C, F, I, B, J)  
  Distortion = 1.9 mm  
  Number of analysis = N (parallel)

- **Progressive JRM** (For a normal schedule/budget)
  (h, G, e, K, F, a, D, B, C, I, J)  
  Distortion = 1.5 mm  
  Number of analysis = N(N+1)/2-1 (partial parallel)

- **Surrogate ML** (For tight tolerance)
  (G, e, b, j, c, I, f, a, D, h, k)  
  Distortion = 1.1 mm  
  Number of analysis = 4N – 6N (Parallel)

- **Evolutionary ML** (For repetitive work and mass production)
  (i, d, e, f, J, H, g, a, b, c, K)  
  Distortion = <1 mm  
  Number of analysis = open
Different overlay patterns to build a machine learning model for node distortion prediction
Welding overlay
DeepWeld
AI framework
Welding Pattern Design — AI & ML

Complex model

DeepWeld

stiffeners
WELDING PATTERN DESIGN – AI & ML

Overlay Pattern

ML Prediction

FEA Simulation
Welding Pattern Design – AI & ML

stiffeners

DeepWeld

Complex model

www.deepweld.com
HAZ-Softening Assessment