A Hybrid Digital-Twin Platform for Sequence Design in Welded Structures

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**General Distortion Control Plan**

**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

This is generally follow the general guide/references/recommendation and/or complex instructions historically rely on the past experience.
1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Sequence Design & Pattern
6. Adaptive Clamping
7. Adaptive Process Parameters Control
8. AI & ML
1. Tack Welds and Clamping
2. Pre-Bending / Pre-offset
3. Side Heating/Fast Cooling
4. Mathematical modeling
5. Sequence Design & Pattern
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Weld Sequence Design

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

<table>
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<tr>
<th>n</th>
<th>((2^n)\times n!)</th>
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Initial Sequence
(J I B C a F h D e K G)
Deflection = 2.4 mm
Artificial Neural Network (ANN)

Sequence

Machine-Learned Meta-Model

Displacement

\(X_1, X_2, X_3, \ldots X_n\)

\(Y_1, Y_2, Y_3, \ldots Y_n\)

\(Z_1, Z_2, Z_3, \ldots Z_n\)

\(2^{11} \times 11! = 81.7 \text{ Bn possible sequences}\)
Physics-Guided Mach. LRn (PGML)

Weld Resemblance

A set of sequence with high likelihood of resemblance (61 Scenarios)

- DHBaCkjiFEg
- bjkagHfcdEi
- JaIkFCdGhEB
- fJICGDEaBhk
- ejKaFBghDci
- AcgFDjEHlbK
- ...  
- hFkIaGjDCBE
- KHCDAlEJfgb
- kFjiGEdacHb
- CEBkgJdafih
- fhGEjIBdaKC
- HeKbiGadJfC

Each weld occurs at least once at every location

Each pair occurs at least once in the sequence

\[ 2^{11} \times 11! = 81.7 \text{ Bn possible sequences} \]
Welds Position

Weld Resemblance

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

Reference point 1

Reference point 2

Displacement

$X_1, X_2, X_3, \ldots X_n$

$Y_1, Y_2, Y_3, \ldots Y_n$

$Z_1, Z_2, Z_3, \ldots Z_n$

$2^{11} \times 11! = 81.7 \text{ Bn possible sequences}$
\[ \theta_1 = \cos \left( \frac{p_1 - p_2}{|p_1 - p_2|} \right) \]
\[ \theta_2 = \sin \left( \frac{p_1 - p_2}{|p_1 - p_2|} \right) \]

\[ 2^{11} \times 11! = 81.7 \text{ Bn possible sequences} \]
2^{11} \times 11! = 81.7 \text{ Bn possible sequences}
Training set for machine learning (61 scenarios)

DHBaCkjfEg  bjkagHfcdEi  JaIkJFdGhEB
fJICGDEaBhk  ejKaFBghDci  AcgFDjEHiKb  ...
hFkIaGjDCBE  KHCDAlJeJfgb  kFjiGEdacHb
CEbkgIdafHl  fhGEjIBdaKC  HeKbIgadJfC

Displacement

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

$2^{11} \times 11! = 81.7 \text{ Bn possible sequences}$
ANN Validation

ML-Shadow  FEM

Training set for machine learning

DHBaCkjiFEg  bjkagHfcdeI  JaIkFCdGhEB
fJICGDEaBhk  ejKaFBghDci  AcgFDjEHIbK
hFkIaGjDCBE  KHCDAlIejfgb  kFjiGEdacHb
CEbkgJdaflh  fhGEjIBdaKC  HeKblGadJfC

fGHaJDcEKbi
ANN Validation

ML-Shadow  FEM

Training set for machine learning

fGHaJDCeKbi
ANN Validation

ML-Shadow | FEM

Training set for machine learning

DHBaCkjiFEg   bjkagHfcdEi   JaIkFCdGhEB
fJICGDEaBhk   ejKaFBghDci   AcgFDjEHbK
hFkIaGjDCBE   KHCDAlJeJgb   kFjiGEdacHb
CEbkgJd aflh   fhGEjIBdaKC   HeKbIgadJfC

\[
fGHaJDcEKbi\]
ANN Validation

Training set for machine learning

- DHBaCkjiFEg
- fJICGDEaBhk
- hFkIaGjDCBE
- CEbkgJdaflh

- bjkagHfcdEi
- ejKaFBghDci
- KHCDAlJeJfgb
- fhGEjIBdaKC

- JaIkFCdGhEB
- AcgFDjEHibK
- kFjiGEdacHb
- HeKblgadJfC

- fGHaJDcEKbi

Diagram of a structural model with various components labeled A, B, C, D, E, F, G, H, I, and K.
ANN Validation

ML-Shadow | FEM
---|---
\text{fGHaJ}
\text{fGHaJD}
\text{fGHaJDc}
\text{fGHaJDcE}

ML-Shadow | FEM
---|---
\text{fGHaJDCk}
\text{fGHaJDCkB}
\text{fGHaJDCKbi}
Cool Down
Machine-Learned Meta-Model

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

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

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

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

Deflection = 1.1 mm
**Evolution of Model**

Deflection = 1.1 mm

Deflection = 0.98 ~ 1 mm
**Weld Sequence Design Approach**

- **Initial (Intuitive best) Sequence**
  - (J, I, B, C, a, F, h, D, e, K, G)
  - Distortion = 2.4 mm
  - Number of analysis = 5

- **Meta Model (ANN)**
  - (G, e, b, j, c, l, f, a, D, h, k)
  - Distortion = 1.1 mm
  - Number of analysis = 4N – 6N (Parallel)

- **Evolutionary DT**
  - (For repetitive work and mass production)
  - (i, d, e, f, J, H, g, a, b, c, K)
  - Distortion = <1 mm
  - Number of analysis = Open
Constructing a Responsive Digital Twin of Manufacturing Processes is Now Practical Even if No Data to Start.
Constructing a Responsive Digital Twin of Manufacturing Processes is Now Practical Even if No Data to Start.

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