Failure and Lifetime Assessment of Welded Stainless Steel Structures via Finite Element Modeling and Variance Based Sensitivity Analysis Methods

Presented By
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Mentors

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Outline

• Concept of Sensitivity Analysis (SA)
• Variance Based SA
• Aim of the study
• Finite Element Modeling
• SA in OptiY
• Interaction of the Softwares
• SA Calculations
• Results and Discussions
• Conclusions and Recommendations
Concept of Sensitivity Analysis

Definition

“Sensitivity Analysis studies the relationships between information flowing in and out of the model”

Goals

• If the model resembles the system or process.
• Determination of factors that mostly contribute to the output variability.
• Determination of the insignificant model parameters.
• Determination of interactions of parameters
Steps Involved in SA

- Distributed input parameters
- Simulation model
- Output distributions
- Sensitivity analysis method
Classification of SA Methods

1. Screening
   • Qualitative
   • Experience required

2. Local SA
   • Quantitative method
   • Model dependent
   • Partial Derivative
   • Other parameters are constant

3. Global SA
   • Quantitative method
   • Non-linear models also
   • Other parameters are varying
Variance-Based SA

Consider a model

\[ Y = f(X_1, X_2, X_3...X_k) = f(X) \]

Variance = Main Effect + Residual

\[ V(Y) = \text{Var}_X [E(Y | x)] + E_X (\text{Var} [Y | x]) \]

Here

\[ \text{Var}_X [E(Y | x)] = \int [E(Y | x) - E(Y)]^2 p_x(x)dx \]

\[ E_X (\text{Var} [Y | x]) = \iint [y - E(Y | x)]^2 p_x p_{Y|x} (y)dx dy \]

\[ E(Y | x) = \int y p_{Y|x} (y)dy \]
Variance-Based SA

- Main effect or importance measure

\[ S_i = \frac{V[E(Y \mid X_i)]}{V(Y)} \]

- For additive models

\[ \sum_{i=1}^{n} S_i = 1 \]

- For non-additive models

\[ \sum_{i=1}^{n} S_i + \sum_{i=1}^{n} \sum_{j=i+1}^{n} S_{i,j} + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \sum_{k=j+1}^{n} S_{i,j,k} + \ldots + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \sum_{k=j+1}^{n} \sum_{l=k+1}^{n} \ldots S_{i,j,k,\ldots,n} = 1 \]

Here

\[ S_{i,j} = \frac{V[E(Y \mid X_i, X_j)]}{V(Y)} - S_i - S_j \]
Variance-Based SA

Total Effect

\[ S_{Ti} = 1 - \frac{V[E(Y \mid X_{-i})]}{V(Y)} \]

Or

\[ S_{Ti} = \frac{E[V(Y \mid X_{-i})]}{V(Y)} \]

For example

\[ S_{T1} = S_1 + S_{12} + S_{13} + S_{123} \]
\[ S_{T2} = S_2 + S_{12} + S_{23} + S_{123} \]
\[ S_{T3} = S_3 + S_{13} + S_{23} + S_{123} \]
Aim of the Study

Four notch areas
top-left, top-right, bottom-left, bottom-right

Parameters
• Overlap
• Thickness
• Notch Radii x 4
• Notch Angles x 4
• Young’s Modulus

Fig (a): Double-V Butt weld

Fig (b): Top-left notch
# Input Parameters

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Finite Element Modeling

ANSYS 9.0

Steps for finite element modeling can be divided into three parts

- Pre-processor
- Solution
- Post-processor
Inclusion of Input Parameters

• Key point (KP) 1 taken as origin
• KP 14 and KP 2 to define thickness of the plate
• KP 4 [(250-0.7*s), s, 0] to define the weld width
• KP 16 [(250-0.2*s), (s+P1), 0] to define the notch angle
  ➢ P1 = (0.5*s)*tan (beta1)
  ➢ beta1 = alpha1*(pi/180)
• KP 22 (250-0.7*s-k, s, 0) and KP 23 [250-0.7*s + k cos (alpha1), s + k sin (alpha1)] are generated due to fillet
  ➢ k = rtl*tan (alpha1/2) wrt. KP 4
• KP 20 (250, s + a, 0) to define overlap
• KP 25 [250+0.7*s - k cos (alpha1), s + k sin (alpha1)] is generated at top-right notch

Fig: Model generation in ANSYS 9.0
Element Type and Material Properties

Element Type: Plane 82

• 8-node with two degree of freedom at each node
• Tolerate irregular shapes without loss of accuracy
• Well suited for curved boundaries
• Sustain bending loads

Material Properties

• Elastic and Isotropic properties
• Young’s Modulus and Poisson ratio

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Meshing and Loading

Meshing

• Free Meshing
• Meshing is refined at notches
• Refinement level 4
• Depth of refinement is 0.5
• Smoothing and cleaning of the shapes

Load

• Pure Bending load
• KP at 1(0,0,0) and KP 8(500,0,0) are fixed to hold the plate.
Solution and post-processor

- No thermal effects
- Static analysis
- Nodal solutions for Von Mises Stress are measured.
- Notch area is the most critical area.
- Notch factor is maximum at top-right.
- Maximum value of stress is calculated.
- Output parameter
  - Maximum stress
  - Notch at which maximum stress lies
- Commands are saved in input file (in.txt)
- Output parameters are written in output file (out.txt)
SA in OptiY

Second Order Analysis

\[ f = f_0 + \sum_{j=1}^{n} \frac{\partial f}{\partial x_j}(x_j - x_0) + \frac{1}{2} \sum_{j=1}^{n} \frac{\partial^2 f}{\partial x_j^2}(x_j - x_0)^2 + \sum_{j=1}^{n-1} \sum_{k=j+1}^{n} \frac{\partial^2 f}{\partial x_j \partial x_k}(x_j - x_0)(x_k - x_0) \]

Interactions up to second order are considered

Reduced Second Order analysis

\[ f = f_0 + \sum_{j=1}^{n} \frac{\partial f}{\partial x_j}(x_j - x_0) + \frac{1}{2} \sum_{j=1}^{n} \frac{\partial^2 f}{\partial x_j^2}(x_j - x_0)^2 \]

Number of simulations required
SOA= \(2n^2+1\)= 243 simulations
RSOA=2n+1=23 simulations
Nominal and Tolerance Value

- Normal Distribution
  \[ T = 6.\sigma \]
- Uniform Distribution
  \[ T = 2\sqrt{3}.\sigma \]
- Generalized Lambda Distribution

\[
R(p) = \lambda_1 + \left[ p^{\lambda_3} - (1 - p)^{\lambda_4} \right] \frac{1}{\lambda_2}
\]

\[
f(x) = f[R(p)] = \lambda_2 \left[ \lambda_3 p^{(\lambda_3-1)} + \lambda_4 (1 - p)^{(\lambda_4-1)} \right]^{-1}
\]

\(\lambda_1\) and \(\lambda_2\) are location and scale parameters and \(\lambda_2 = 2/T\)
\(\lambda_3\) and \(\lambda_4\) jointly represents the shape of the distributions.
Input Data for the Parameters

Experimental Data

- Notch Radius distribution (input)
- Notch Angle distribution (input)
- Notch Factor distribution (output)
- Overlap value

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<td>E</td>
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Thickness and Modulus of elasticity is also taken as parameter.
Notch Angle Distributions

Notch Radius Distributions

Material: S690QL
Geometry: Butt weld
Thickness: 30 mm
Welding: SMAW
Specimen nrs.: E11, E12
## Input data for Analysis (SMAW)

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Design of Experiment (DOE)

Nominal Value (Xn) and Tolerances (Tn)
- Lower limit = $X_n - \frac{T_n}{2}$
- Nominal Value = $X_n$
- Upper limit = $X_n + \frac{T_n}{2}$

Total Number of Simulations
- Second Order Analysis
  - 242 (In DOE table) +1 (Nominal Table)
- Reduced Second Order Analysis
  - 22 (In DOE table) + 1(Nominal Table)
Interaction of the Numeric Tools

OptiY

Nominal values and Tolerances

ANSYS (In Batch Mode)

Calculations for maximum stress

Data export
Sensitivity Analysis

Input File (command file)

Input File (Result file)

r1
r1r
r2
r2b
r3
r3f
r4
r4b
Eweld
maxstr
place

Out.txt

In.txt

IIT ROORKEE
RESULTS AND DISCUSSIONS
### Design of Experiment Table

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<td>1.04</td>
<td>1.6</td>
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</tbody>
</table>
Validation of the Model

• Experiments Results
For all the series ruptures have been occurred in the sites where the highest notch factors is maximum. Notch factor is maximum at **bottom-right notch**.

• Theoretical Results
  ➢ Data is taken from the DOE
  ➢ Notch factor is calculated at four locations by Anthes, Köttgen and Seeger formula
  ➢ Maximum value is plotted

\[
K_{b \text{utt-welds}} = \left[ 1 - 0.156 \left( \frac{t}{r} \right)^{0.2070} \right] \cdot \\
\left[ 1 + \left( 0.181 + 1.207 \cdot \sin \theta - 1.737 \cdot \sin^2 \theta + 0.689 \cdot \sin^3 \theta \right) \left( \frac{t}{r} \right)^{0.2919 + 0.3491 \cdot \sin(\theta + 3.2830)} \right]
\]

➤ Maximum Notch factor is found out to be at the **bottom-right notch**
Contd…

Fig: Maximum notch factor Vs Number of simulations
• Simulation Results

- Notch at which maximum stress lies
- Location 1 is taken as top-left notch, 2 as top-right notch, 3 as bottom-left notch and 4 as bottom-right notch
- **Bottom-right notch** is found out to be the mostly stressed most of the times (133)
## Input Data to Define Parameters (SAW)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Nominal value</th>
<th>Tolerance value</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>(\lambda_2)</th>
<th>Distribution</th>
<th>Units</th>
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<tr>
<td>(t)</td>
<td>30.00</td>
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<td>Uniform</td>
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<tr>
<td>(a)</td>
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<td>(\alpha_bl)</td>
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<td>-</td>
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<td>Normal</td>
<td>MPa</td>
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</table>
Results

- The center moments of output are derived from center moments of input. From these calculated moments, the distribution density function of output is approximated.
- Mean of the output parameter (maxstr.) is 238.986 Mpa
- Standard deviation is 6.76 Mpa.
SA of Simulation Model for SAW

Results

• Order of the importance is $rtr, rtl, rbl, a, Eweld, t, atl, abl, atr, tbr, abr$.
• Notch radii are the most influential parameter.
• Young’s modulus is not very influential parameter as its total and main effect is 1.2% and 1.11% respectively.
• Overlap has a significant effect.
• Parameters ($atr, rbr, and abr$) have an effect less than 0.1%.
• Deleting parameters, simulations will be 129

$$
\text{% saving} = 1 - \frac{129}{243} = 46.9\%
$$

Fig: Pareto chart for maximum stress
SA of Notch Factor Formula

Results

• Effects of the notch radii are larger than the notch angles at all locations.
• Order of importance of notch radii is rtr, rtl, rbl and rbr.
• Parameters which influence maximum stress are same which influence the notch factor.

Fig: Pareto diagram for notch factor (SAW)
Section Diagrams

- Curves of approximated second order Taylor series of input parameters.
- Variation of the output for a tolerance range of the input parameter
Reduced Second Order SA

If

\[ SX_i \equiv STX_i \]

• Reduced second order analysis is performed
• No loss of accuracy
• Notch radius at top-right (rtr) has a highest total effect of 37.65%
# Results from SOA and RSOA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SAW</th>
<th>Reduced Second Order Analysis</th>
<th>% Variation (from total effect)</th>
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<tr>
<td>Eweld</td>
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</tr>
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</table>
Results

• Order of the importance is \( rbr, rtl, rbl, rtr, atr, abl, E_{weld}, a, abr, t \) and \( atl \).

• Notch radii are the most influential parameter.

• Young’s modulus and overlap are not influential.

• Parameters \( (t, a, atl \text{ and } abr) \) have an effect less than 0.1%.

• Deleting parameters, simulations will be 99%

\[
\% \text{saving} = 1 - \frac{99}{243} = 59.25\%
\]
SA of Simulation Model for MAG

Results

• Order of the importance is $rbr$, $atr$, $rtl$, $rtr$, $rbl$, $abr$, $a$, $atl$ $Eweld$, $t$, $abl$.

• Notch radius at bottom-right is the most influential parameter with total effect of 32.29%.

• Young’s modulus and overlap are not influential.

• Parameters ($t$ and $abl$) have an effect less than 0.1%.

$$% saving = 1 - \frac{163}{243} = 32.9\%$$
Conclusions and Recommendations

- Variance based sensitivity analysis is a powerful tool to find out the variation in the output of a model due to variations in the input parameters.
- Influential parameters found from the sensitivity analysis of finite element model are same as found from the sensitivity analysis of the Anthes, Köttgen and Seeger formula.
- Maximum stress which leads to crack initiation lies at the notch where notch factor is maximum.
- Notch radius at top-right (rtr), top-left (rtl), and bottom-left (rbl) and overlap (a) are the influential design parameters for submerged arc welding.
- Proper data should be collected for the overlap as its effect can not be ignored for submerged arc welding.
Conclusions and Recommendations

- Notch radius at bottom-right \((rtr)\), notch angle at top-right \((atr)\), notch radius at top-left \((rtl)\), top-right \((rtr)\), bottom-left \((rbl)\) are the influential design parameters for gas metal arc welding.
- Notch radius at bottom-right \((rbr)\), top-left \((rtl)\), bottom-left \((rbl)\) and top-right \((rtr)\) and notch angle at top-right \((atr)\) are the influential parameters for the shielding metal arc welding.
- Although notch angles have lower effects than notch radii, their tolerance should be controlled precisely.
- Young’s modulus \((E_{\text{weld}})\) for the weld material has negligible effect on the output variable. It can be removed from the analysis.
- Thickness of the plate has very less effect for defined range. But its effect can be ignored when the tolerance is high.
I take this opportunity to thank all the staff and colleagues for their love, support and encouragement for making my work and stay at IIT Roorkee and TU Darmstadt, a memorable one.
Notch Factor Distribution

- Notch factor distributions for (SMAW) series
- The notch factor value corresponding to the probability of occurrence of 10% has been considered actually responsible of ruptures.
- Notch factor is maximum at bottom-right notch.
• Input Distribution

- Thickness, modulus of elasticity and overlap
- Notch Angles
- Notch Radii