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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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

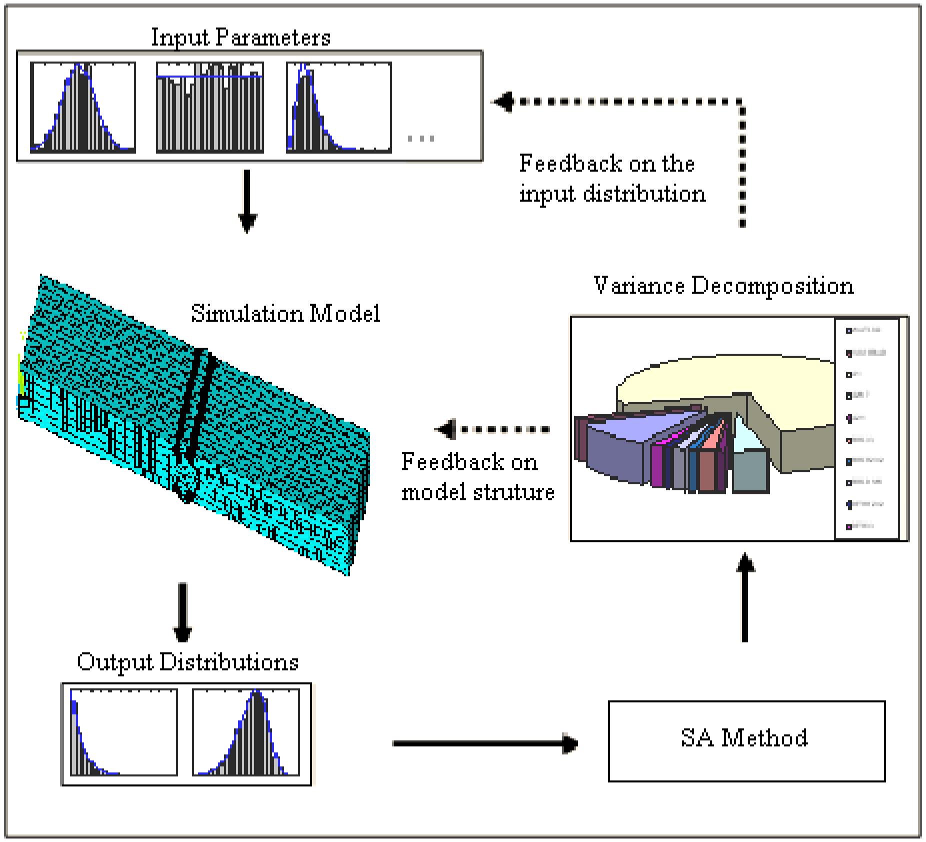
Definition

" 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

$$Y = f(X_1, X_2, X_3 \ldots X_k) = f(X)$$

Variance= Main Effect + Residual

$$V(Y) = Var_X\left[E(Y \mid x)\right] + E_X\left(Var\left[Y \mid x\right]\right)$$

Here

$$Var_X\left[E(Y \mid x)\right] = \int \left[E(Y \mid x) - E(Y)\right]^2 p_x(x)dx$$

$$E_X\left(Var\left[Y \mid x\right]\right) = \iint \left[y - E(Y \mid x)\right]^2 p_x p_{Y|x}(y)dxdy$$

$$E(Y \mid x) = \int y p_{Y|x}(y)dy$$

Variance-Based SA

- Main effect or importance measure

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

- For additive models

$$\sum_{i=1}^{n} S_i = 1$$

- For non-additive models

$$\sum_{i=1}^{n} S_i + \sum_{i=1}^{n} \sum_{j=i+1}^{n} S_{i,j} + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \sum_{k=j+1}^{n} S_{i,j,k} + \ldots + \sum \ldots . S_{i,j,k,\ldots n} = 1$$

Here

$$S_{i,j} = \frac{V[E(Y / X_i, X_j)]}{V(Y)} - S_i - S_j$$

Variance-Based SA

Total Effect

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

Or

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

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

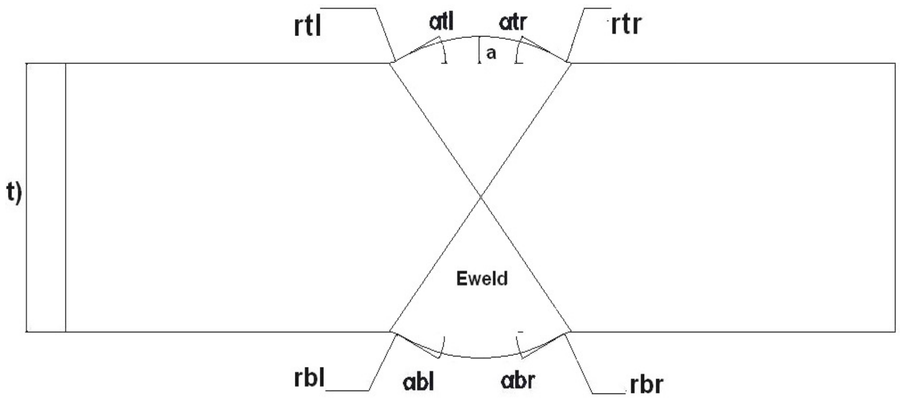


Fig (a): Double-V Butt weld

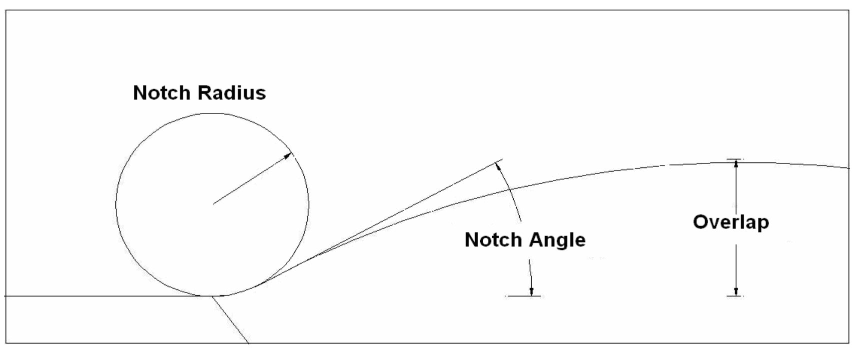


Fig (b): Top-left notch

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

Input Parameters

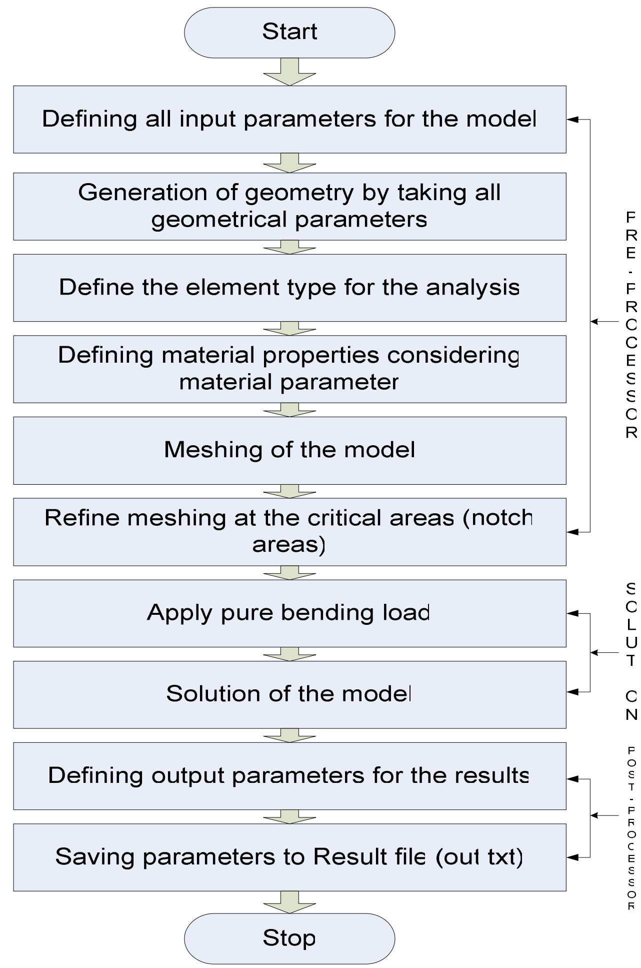
S.No	Symbol	Parameters Name	Units
1	**t**	Thickness of plate	mm
2	**a**	Overlap of weld	mm
3	**Eweld**	Young's modulus of weld pool material	MPa
4	**rtl**	Notch radius at top-left	mm
5	**rtr**	Notch radius at top-right	mm
6	**rbl**	Notch radius at bottom-left	mm
7	**rbr**	Notch radius at bottom-right	Mm
8	**αtl**	Notch angle at top-left	Degree
9	**αtr**	Notch angle at top-right	Degree
10	**αbl**	Notch angle at bottom-left	Degree
11	**αbr**	Notch angle at bottom-right	Degree

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 = αtl*(pi/180)
- KP 22 (250-0.7*s-k, s, 0) and KP 23 [250-0.7*s + k cos (αtl), s + k sin (αtl)] are generated due to fillet
  - k = rtl*tan (αtl/2) wrt. KP 4
- KP 20 (250, s + a, 0) to define overlap
- KP 25 [250+0.7*s - k cos (αtr), s + k sin (αtr)] is generated at top-right notch

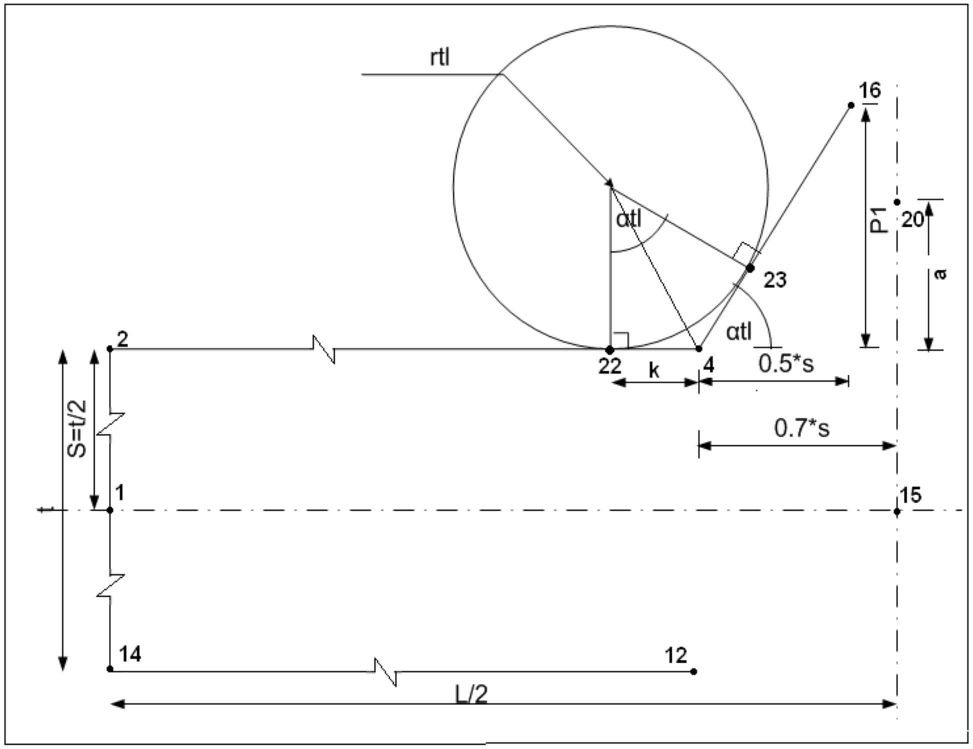


Fig: Model generation in ANSYS 9.0

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

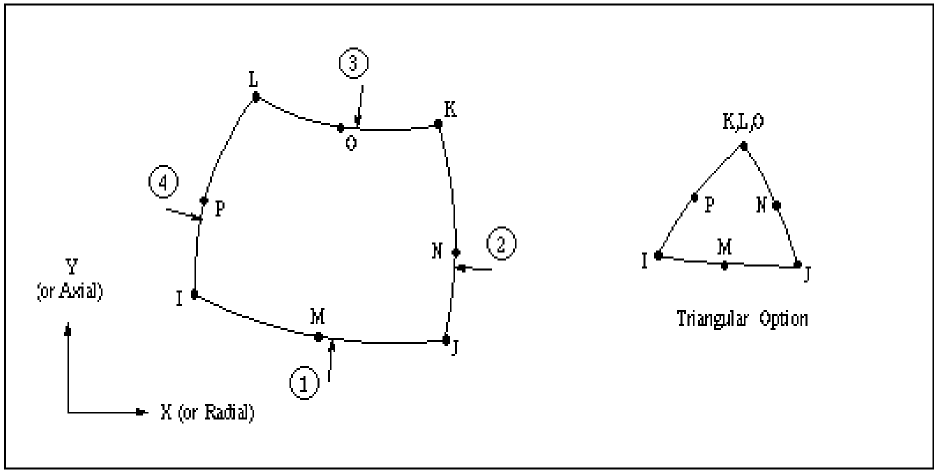


Fig: PLANE 82 geometry

Material Properties

- Elastic and Isotropic properties
- Young's Modulus and Poisson ratio

Part	Young's Modulus (E)	Poisson Ratio
Plate	206 GPa	0.3
Weld Pool	Eweld	0.3

Meshing and Loading

Meshing

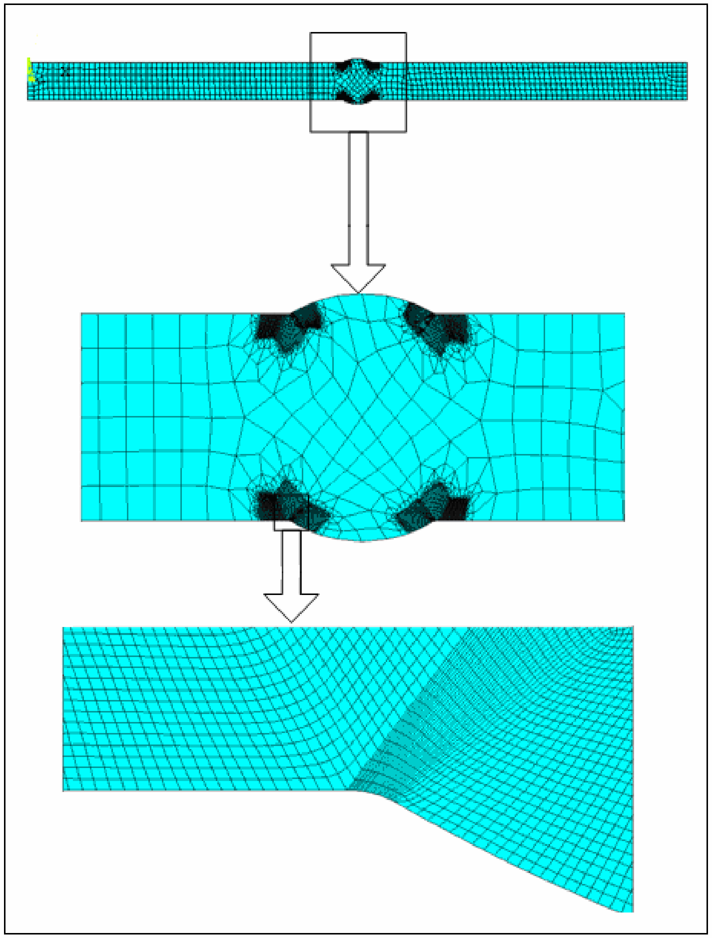
•Free Meshing

•Meshing is refined at notches

•Refinement level 4

•Depth of refinement is 0.5

•Smoothing and cleaning of the shapes



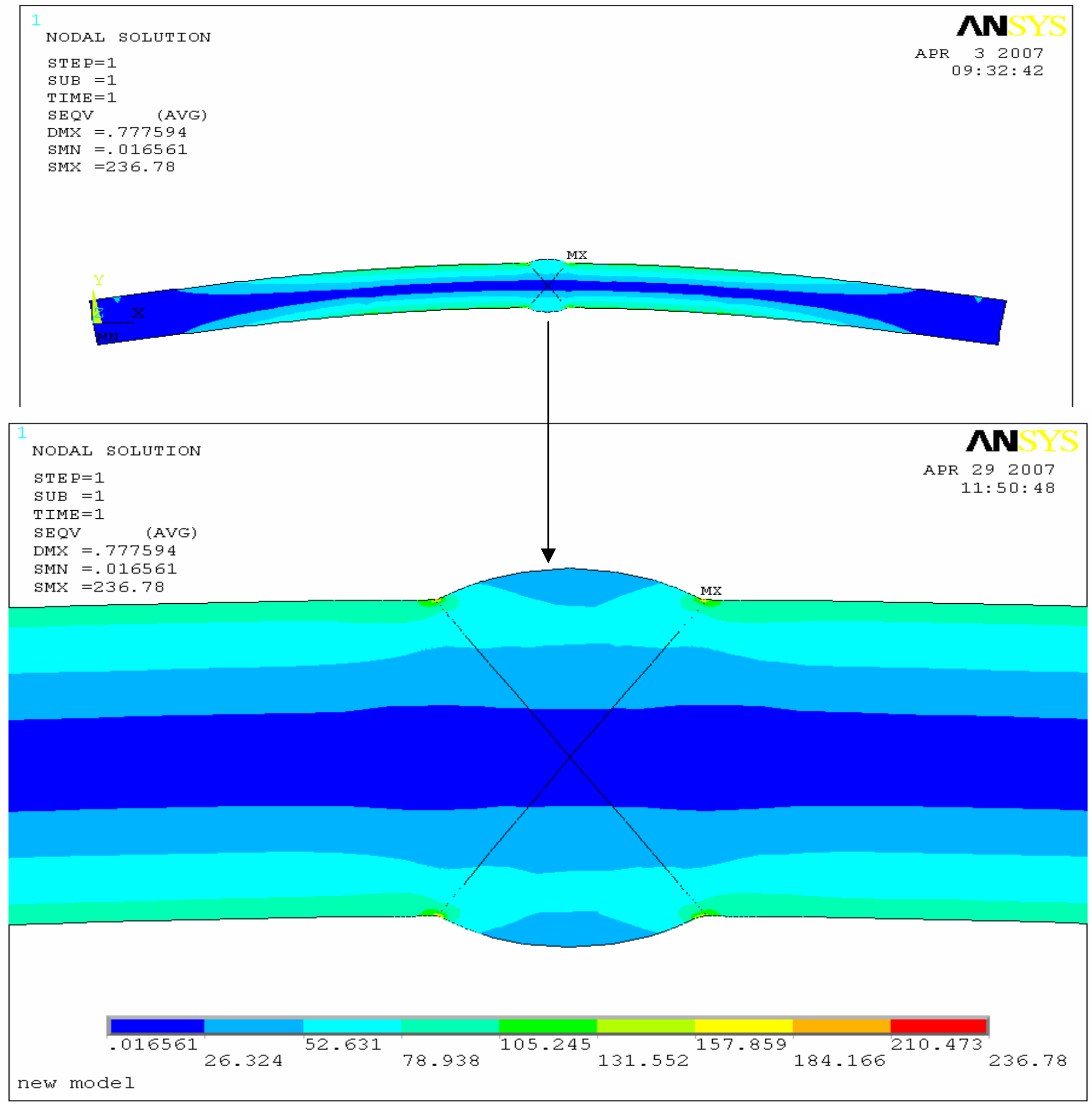
Load

•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

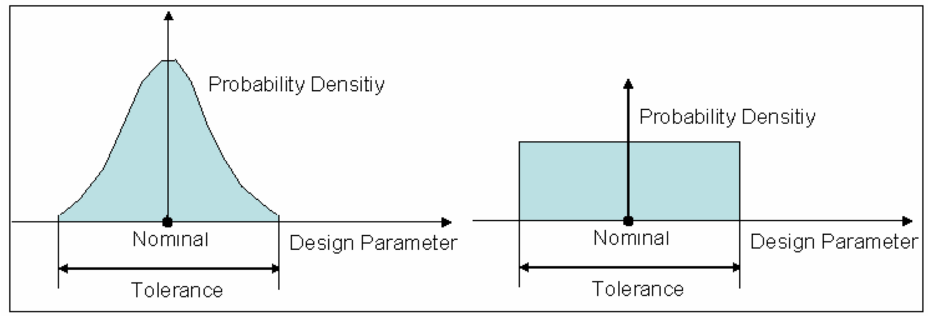
Nominal and Tolerance Value

- Normal Distribution

$$T = 6.\sigma$$

- Uniform Distribution

$$T = 2\sqrt{3}.\sigma$$



- Generalized Lambda Distribution

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

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

λ1 and λ2 are location and scale parameters and λ2 = 2/T

λ3 and λ4 jointly represents the shape of the distributions.

Input Data for the Parameters

Experimental Data

•Notch Radius distribution (input)

•Notch Angle distribution (input)

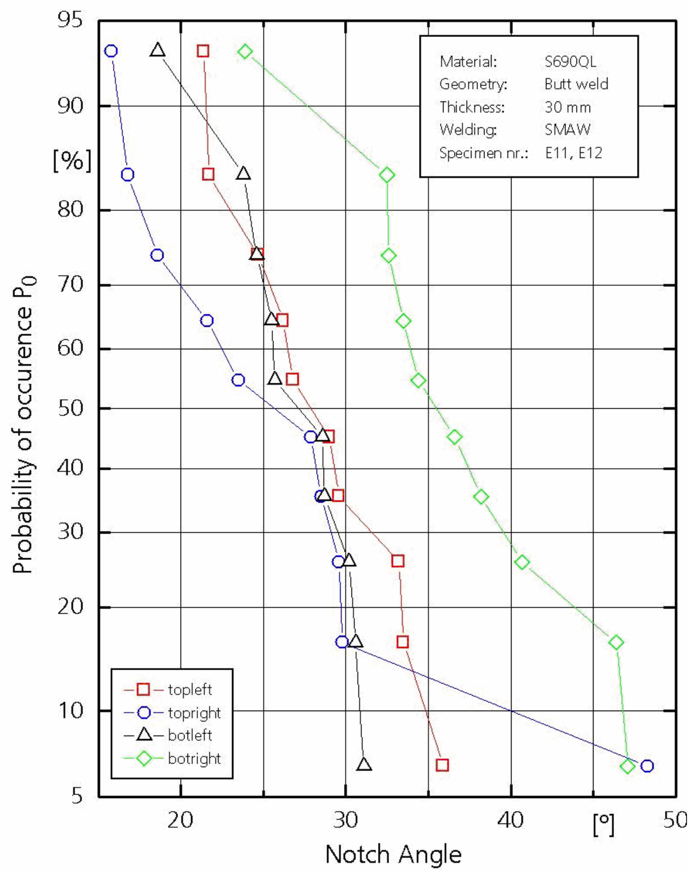
•Notch Factor distribution (output)

•Overlap value

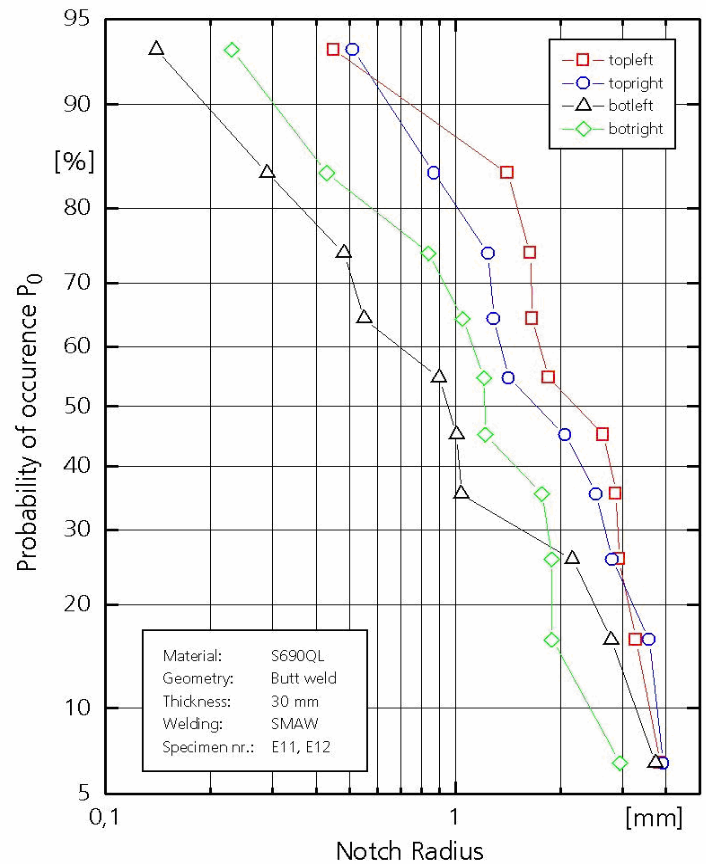
S.NO	Series	Welding procedure
1	F	Gas Metal Arc Welding (MAG)
2	AS	Submerged Arc Welding (SAW)
3	E	Shielding Metal Arc Welding (SMAW)

Thickness and Modulus of elasticity is also taken as parameter

Notch Angle Distributions



Notch Radius Distributions



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Input data for Analysis (SMAW)

Para meters	Nominal value	Tolerance value	Skewness	Kurtosis	λ_2	Distribution	Units
t	30.00	0.01	-	-	-	Uniform	mm
a	3.00	0.20	-	-	-	Normal	mm
αtl	28.65	14.50	0.09	1.84	0.138	General	degree
αtr	22.80	14.00	-0.18	1.43	0.143	General	degree
αbl	24.85	12.5	-0.77	2.86	0.160	General	degree
αbr	35.50	23.2	-0.01	2.56	0.086	General	degree
rtl	2.15	3.40	-0.15	2.16	0.588	General	mm
rtr	2.22	3.41	0.39	1.87	0.587	General	mm
rbl	1.94	3.59	0.99	2.66	0.557	General	mm
rbr	1.60	2.73	0.50	2.73	0.732	General	mm
Eweld	206000	20600	-	-	-	Normal	MPa

Design of Experiment (DOE)

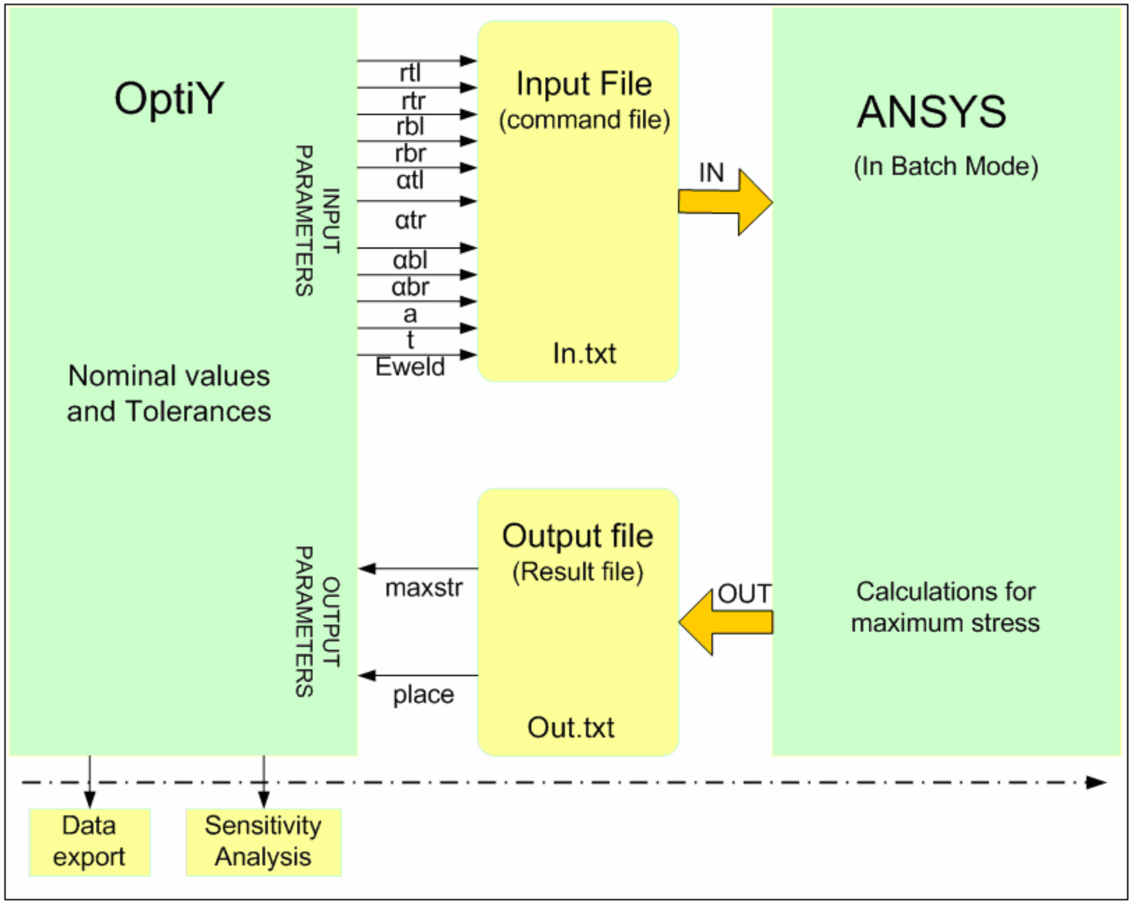
Nominal Value (Xn) and Tolerances (Tn)

- Lower limit = X_n-T_n/2
- Nominal Value = X_n
- Upper limit = X_n+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



RESULTS AND DISCUSSIONS

Design of Experiment Table

No	T_T	T_A	T_ALPHATL	T_ALPHATR	T_ALPHABL	T_ALPHABR	T_RTL	T_RTR	T_RBL	T_TBR	T_EWELD	Criteria1	Criterion2	
0	30.005	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.616	4	
1	30	3.1	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	176.997	4	
2	30	3	35.9	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.787	4	
3	30	3	28.65	29.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.711	4	
4	30	3	28.65	22.8	31.1	35.5	2.15	2.22	1.94	1.6	206000	175.248	4	
5	30	3	28.65	22.8	24.85	47.1	2.15	2.22	1.94	1.6	206000	178.319	4	11
6	30	3	28.65	22.8	24.85	35.5	3.85	2.22	1.94	1.6	206000	175.848	4	
7	30	3	28.65	22.8	24.85	35.5	2.15	3.925	1.94	1.6	206000	175.849	4	
8	30	3	28.65	22.8	24.85	35.5	2.15	2.22	3.735	1.6	206000	175.662	4	
9	30	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	2.965	206000	167.939	3	
10	30	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	216300	177.574	4	
11	29.995	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.751	4	
12	30	2.9	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	174.521	4	
13	30	3	21.4	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.938	4	
14	30	3	28.65	15.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	209.628	2	
15	30	3	28.65	22.8	18.6	35.5	2.15	2.22	1.94	1.6	206000	194.649	3	
16	30	3	28.65	22.8	24.85	23.9	2.15	2.22	1.94	1.6	206000	177.019	4	11
17	30	3	28.65	22.8	24.85	35.5	0.45	2.22	1.94	1.6	206000	220.499	1	
18	30	3	28.65	22.8	24.85	35.5	2.15	0.515	1.94	1.6	206000	223.717	2	
19	30	3	28.65	22.8	24.85	35.5	2.15	2.22	0.145	1.6	206000	268.24	3	
20	30	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	0.235	206000	252.573	4	
21	30	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	195700	174.062	4	
22	30.005	3.1	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	177.061	4	
23	30.005	3	35.9	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.54	4	
24	30.005	3	28.65	29.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.518	4	
25	30.005	3	28.65	22.8	31.1	35.5	2.15	2.22	1.94	1.6	206000	175.58	4	
26	30.005	3	28.65	22.8	24.85	47.1	2.15	2.22	1.94	1.6	206000	178.414	4	
27	30.005	3	28.65	22.8	24.85	35.5	3.85	2.22	1.94	1.6	206000	175.594	4	10
28	30.005	3	28.65	22.8	24.85	35.5	2.15	3.925	1.94	1.6	206000	175.628	4	
29	30.005	3	28.65	22.8	24.85	35.5	2.15	2.22	3.735	1.6	206000	175.578	4	
30	30.005	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	2.965	206000	167.858	3	
31	30.005	3	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	216300	177.313	4	
32	30	3.1	35.9	22.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	176.905	4	
33	30	3.1	28.65	29.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	176.904	4	
34	30	3.1	28.65	22.8	31.1	35.5	2.15	2.22	1.94	1.6	206000	176.955	4	
35	30	3.1	28.65	22.8	24.85	47.1	2.15	2.22	1.94	1.6	206000	179.374	4	
36	30	3.1	28.65	22.8	24.85	35.5	3.85	2.22	1.94	1.6	206000	177.104	4	
37	30	3.1	28.65	22.8	24.85	35.5	2.15	3.925	1.94	1.6	206000	177.049	4	9
38	30	3.1	28.65	22.8	24.85	35.5	2.15	2.22	3.735	1.6	206000	177.135	4	
39	30	3.1	28.65	22.8	24.85	35.5	2.15	2.22	1.94	2.965	206000	169.43	3	
40	30	3.1	28.65	22.8	24.85	35.5	2.15	2.22	1.94	1.6	216300	178.719	4	
41	30	3	35.9	29.8	24.85	35.5	2.15	2.22	1.94	1.6	206000	175.507	4	
42	30	3	35.9	22.8	31.1	35.5	2.15	2.22	1.94	1.6	206000	175.692	4	
43	30	3	35.9	22.8	24.85	47.1	2.15	2.22	1.94	1.6	206000	178.382	4	
44	30	3	35.9	22.8	24.85	35.5	3.85	2.22	1.94	1.6	206000	175.673	4	
45	30	3	35.9	22.8	24.85	35.5	2.15	3.925	1.94	1.6	206000	175.591	4	8
46	30	3	35.9	22.8	24.85	35.5	2.15	2.22	3.735	1.6	206000	175.575	4	
47	30	3	35.9	22.8	24.85	35.5	2.15	2.22	1.94	2.965	206000	167.428	3	
48	30	3	35.9	22.8	24.85	35.5	2.15	2.22	1.94	1.6	216300	177.494	4	
49	30	3	28.65	29.8	31.1	35.5	2.15	2.22	1.94	1.6	206000	175.211	4	
50	30	3	28.65	29.8	24.85	47.1	2.15	2.22	1.94	1.6	206000	178.232	4	
51	30	3	28.65	29.8	24.85	35.5	3.85	2.22	1.94	1.6	206000	175.75	4	
52	30	3	28.65	29.8	24.85	35.5	2.15	3.925	1.94	1.6	206000	175.61	4	7
53	30	3	28.65	29.8	24.85	35.5	2.15	2.22	3.735	1.6	206000	175.236	4	
54	30	3	28.65	29.8	24.85	35.5	2.15	2.22	1.94	2.965	206000	167.877	3	
55	30	3	28.65	29.8	24.85	35.5	2.15	2.22	1.94	1.6	216300	177.411	4	
56	30	3	28.65	22.8	31.1	47.1	2.15	2.22	1.94	1.6	206000	178.282	4	
57	30	3	28.65	22.8	31.1	35.5	3.85	2.22	1.94	1.6	206000	175.375	4	
58	30	3	28.65	22.8	31.1	35.5	2.15	3.925	1.94	1.6	206000	175.308	4	
59	30	3	28.65	22.8	31.1	35.5	2.15	2.22	3.735	1.6	206000	175.709	4	
60	30	3	28.65	22.8	31.1	35.5	2.15	2.22	1.94	2.965	206000	167.392	3	
61	30	3	28.65	22.8	31.1	35.5	2.15	2.22	1.94	1.6	216300	177.001	4	

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

$$K_t b_{utt-welds} = \left[1 - 0.156 \cdot \left(\frac{t}{r} \right)^{0.2070} \right] \cdot$$

$$\cdot \left[1 + \left(0.181 + 1.207 \cdot \sin\theta - 1.737 \cdot \sin^2\theta + 0.689 \cdot \sin^3\theta \right) \cdot \left(\frac{t}{r} \right)^{0.2919 + 0.3491 \cdot \sin(\theta + 3.2830)} \right]$$

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

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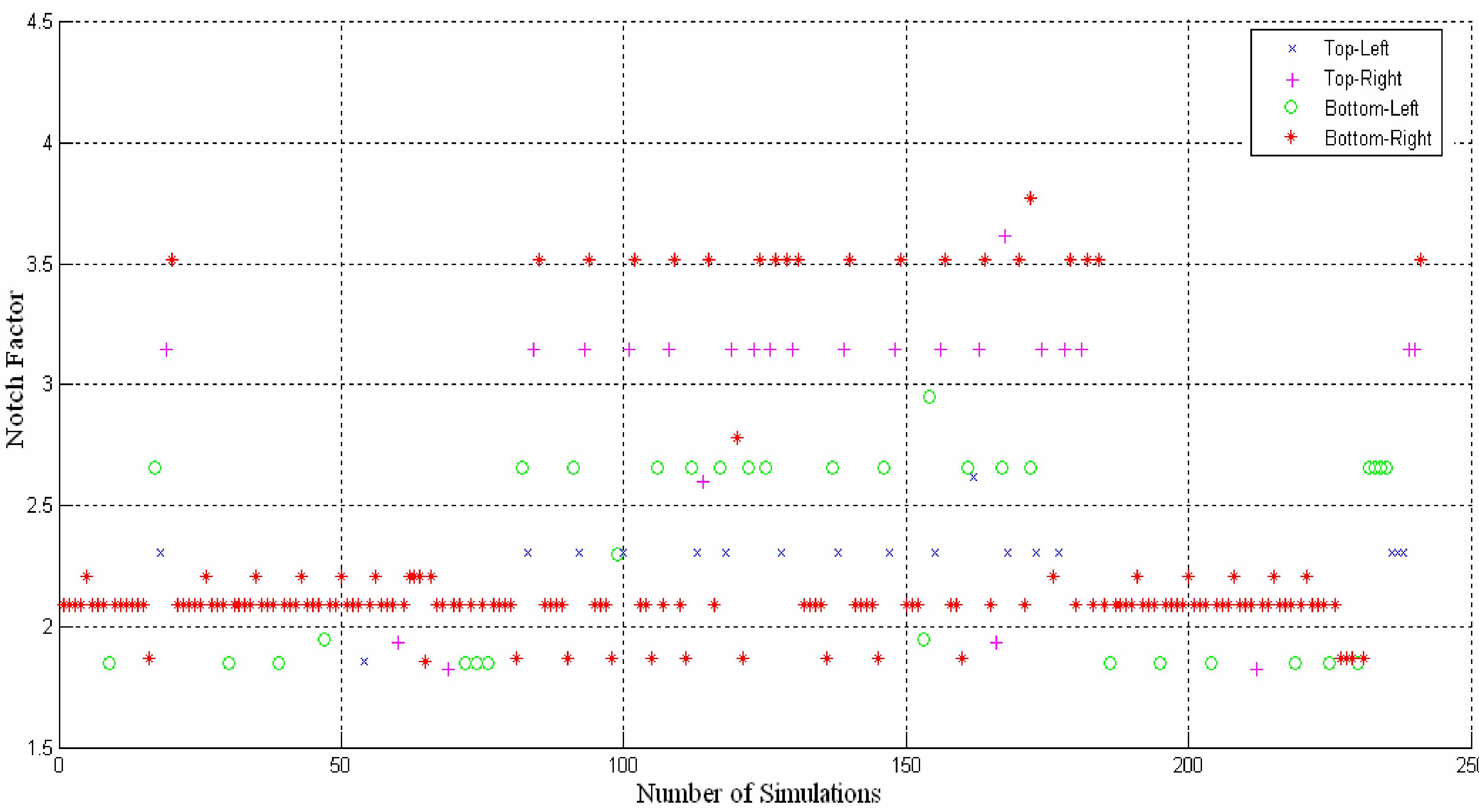
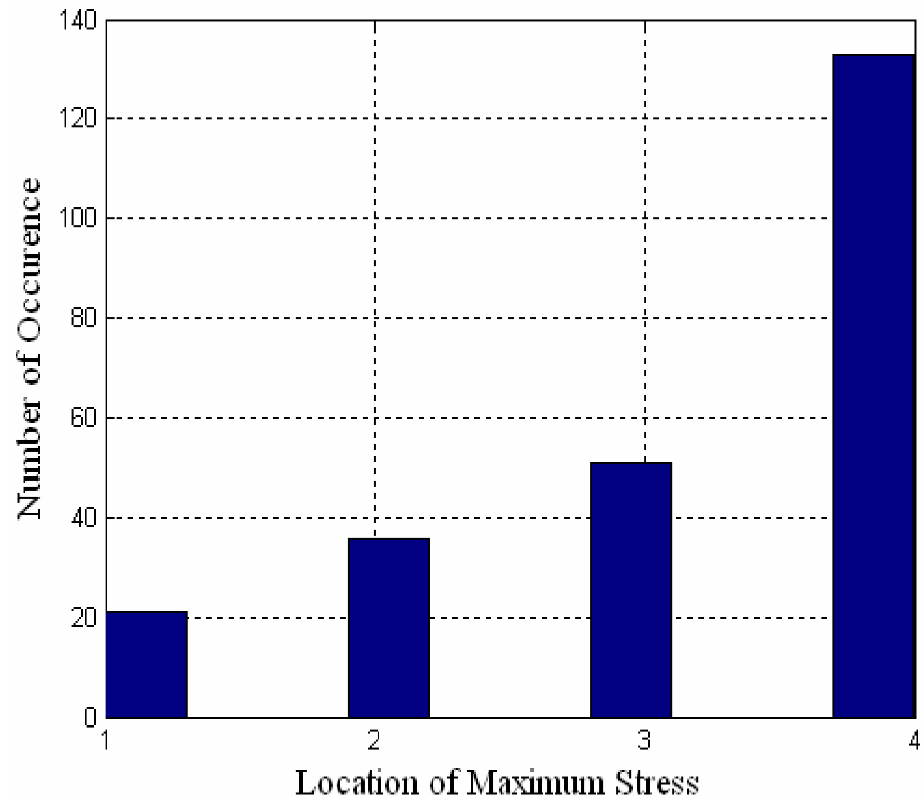


Fig: Maximum notch factor Vs Number of simulations

Contd…

- 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)

Para meters	Nominal value	Tolerance value	Skewness	Kurtosis	λ_2	Distribution	Units
t	30.00	0.01	-	-	-	Uniform	mm
a	3.00	0.20	-	-	-	Normal	mm
αtl	19.05	6.30	0.15	1.54	0.317	General	degree
αtr	12.00	6.00	-2.08	6.42	0.333	General	degree
αbl	22.95	8.10	0.09	1.95	0.247	General	degree
αbr	24.85	10.3	1.84	5.26	0.194	General	degree
rtl	0.79	1.45	1.15	2.87	1.379	General	mm
rtr	1.83	3.15	0.91	2.06	0.635	General	mm
rbl	0.50	0.79	1.35	4.25	2.532	General	mm
rbr	2.22	4.08	2.33	6.33	0.490	General	mm
Eweld	206000	20600	-	-	-	Normal	MPa

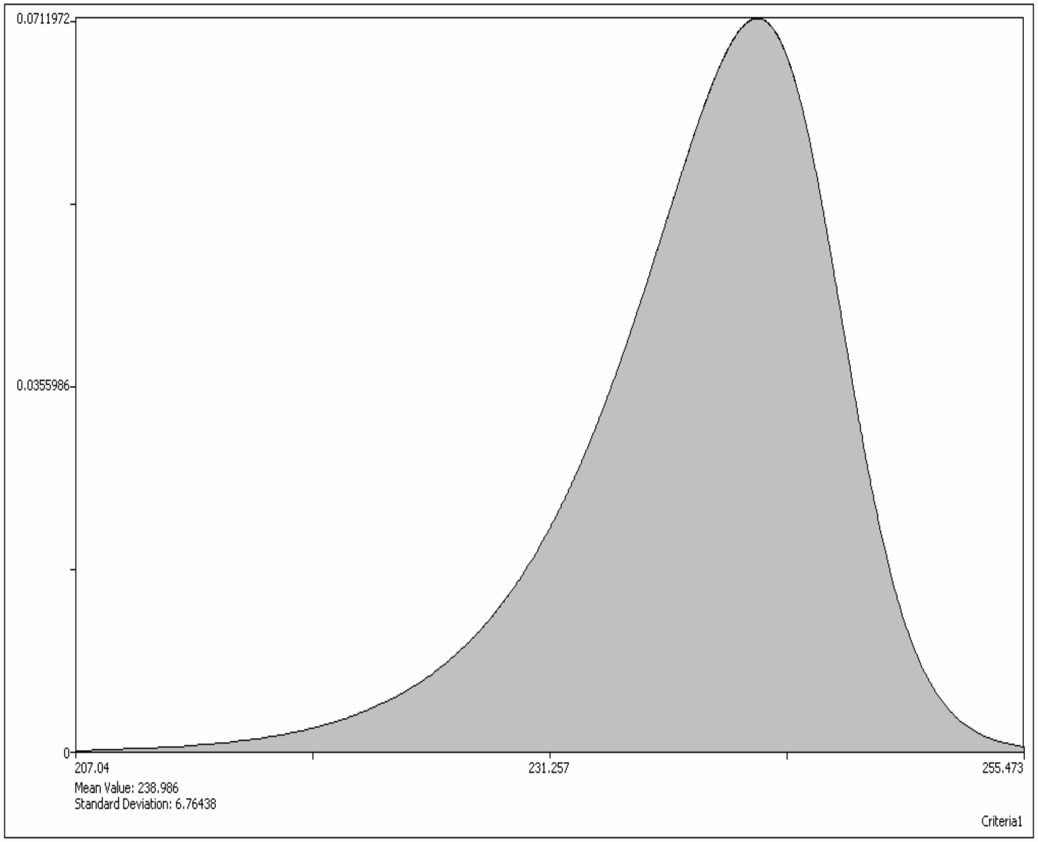
Output Distribution

Results

•The center moments of output are derivate 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, αtl , αbl, αtr, tbr αbr*.
- 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 (*αtr, rbr and αbr*) have an effect less than 0.1%.
- Deleting parameters, simulations will be 129

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

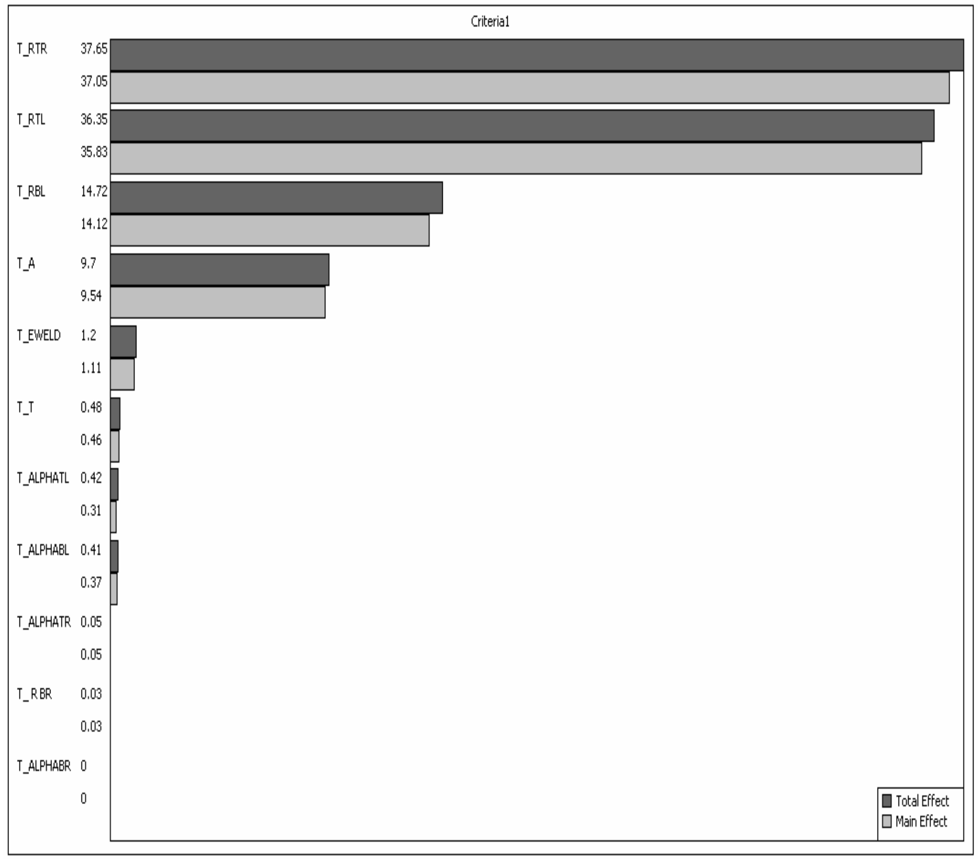


Fig: Pareto chart for maximum stress

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.

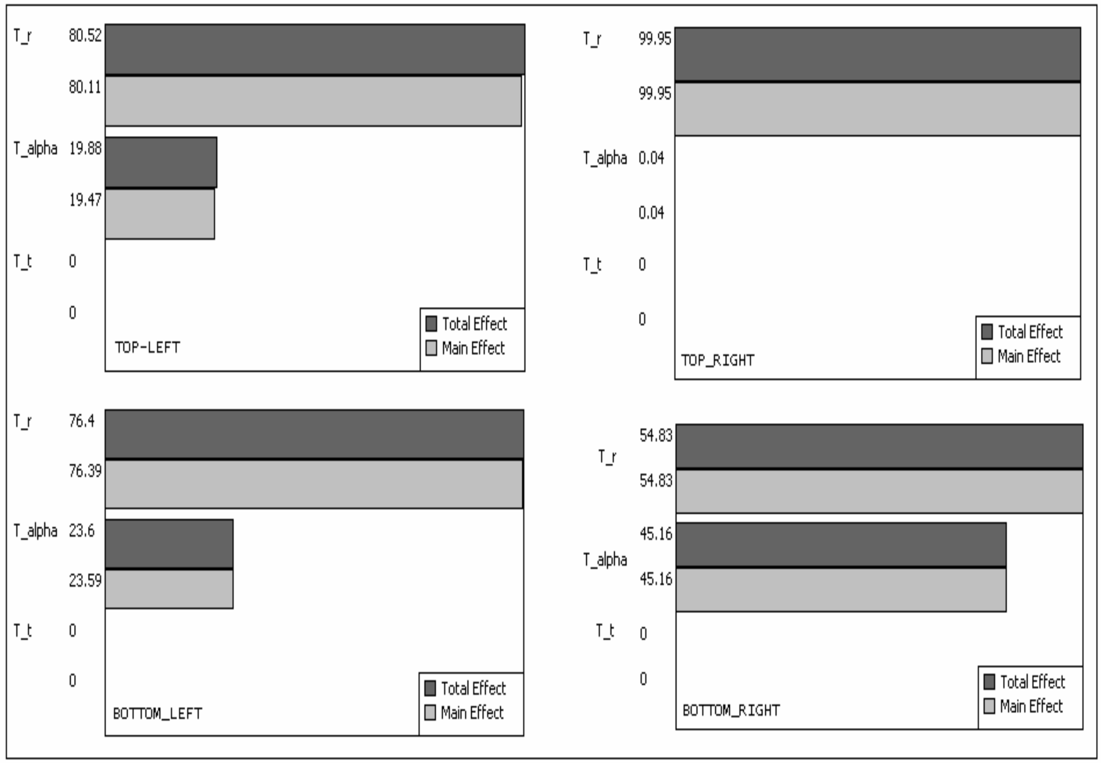
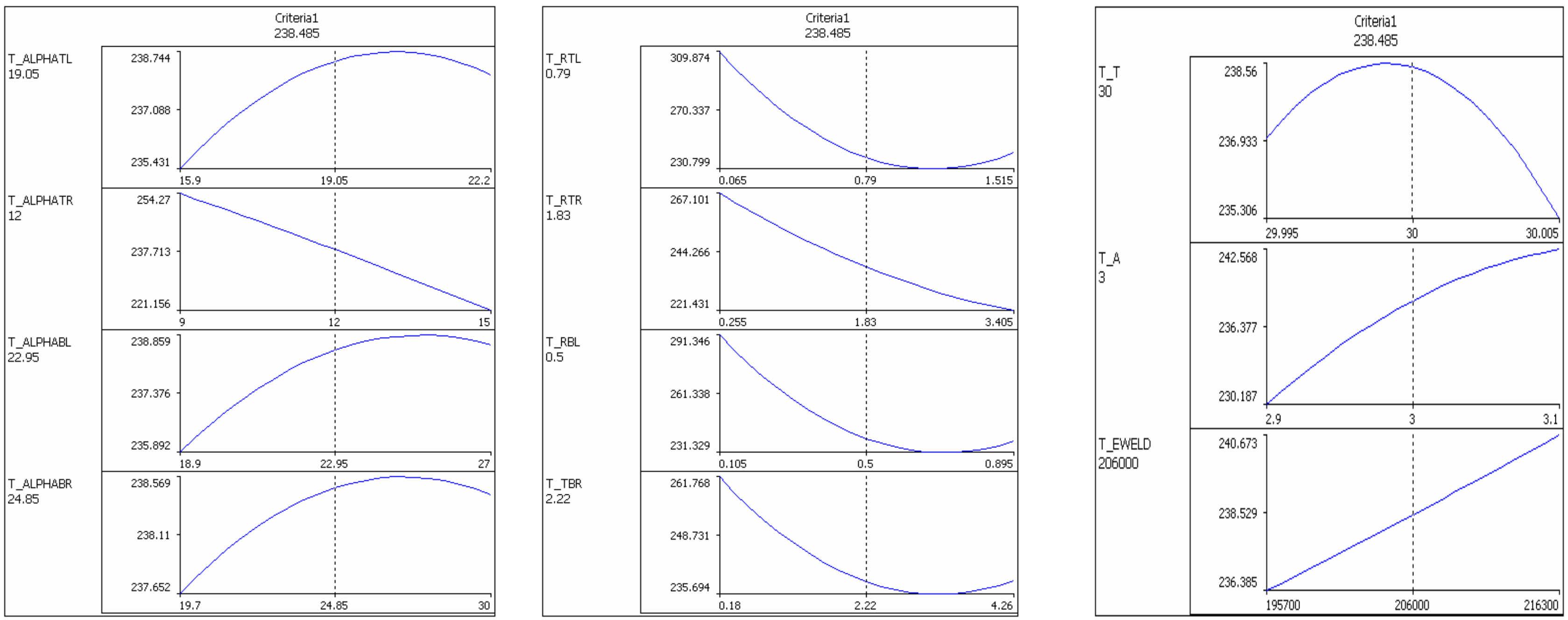


Fig: Pareto diagram for notch factor (SAW)

Section Diagrams

•Curves of approximated second order Taylor series of input parameters.

•Variation of the output for a tolerance range of the input parameter



TECHNISCHE UNIVERSITÄT DARMSTADT

Systemzuverlässigkeit und Maschinenakustik
Prof. Dr.-Ing. H. Hanselka

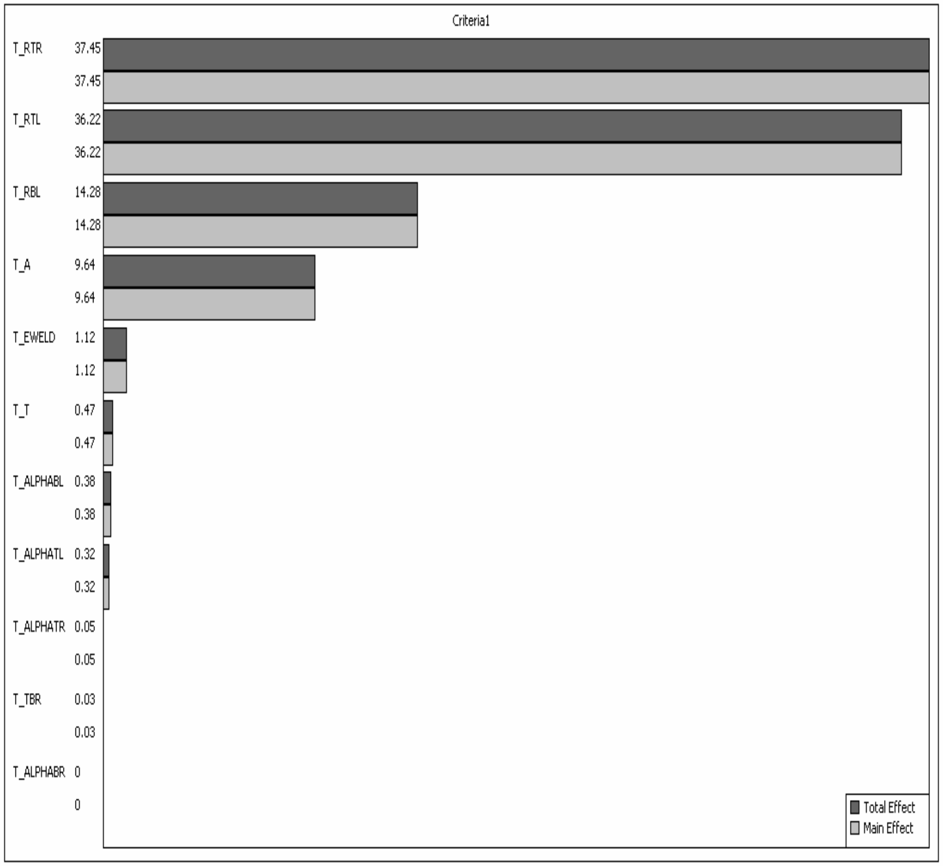
IIT ROORKEE

Reduced Second Order SA

If

$$SX_i \cong STX_i$$

- 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

SAW					
Parameters	**Second Order Analysis**		**Reduced Second Order Analysis**		**% Variation** (from total effect)
	Main Effect	**Total Effect**	**Main Effect**	**Total Effect**	
t	0.46	0.48	0.47	0.47	2.08
a	**9.50**	**9.70**	**9.64**	**9.64**	**0.62**
αtl	0.31	0.42	0.32	0.32	23.81
αtr	0.05	0.05	0.05	0.05	0.00
αbl	0.37	0.41	0.38	0.38	7.32
αbr	0.00	0.00	0.00	0.00	0.00
rtl	**35.83**	**36.35**	**36.22**	**36.22**	**0.36**
rtr	**37.05**	**37.65**	**37.45**	**37.45**	**0.53**
rbl	**14.12**	**14.72**	**14.28**	**14.28**	**2.99**
rbr	0.03	0.03	0.03	0.03	0.00
Eweld	1.11	1.20	1.12	1.12	6.67

SA of Simulation Model for SMAW

Results

•Order of the importance is *rbr, rtl, rbl, rtr, αtr, αbl, Eweld, a, αbr, t and αtl.*

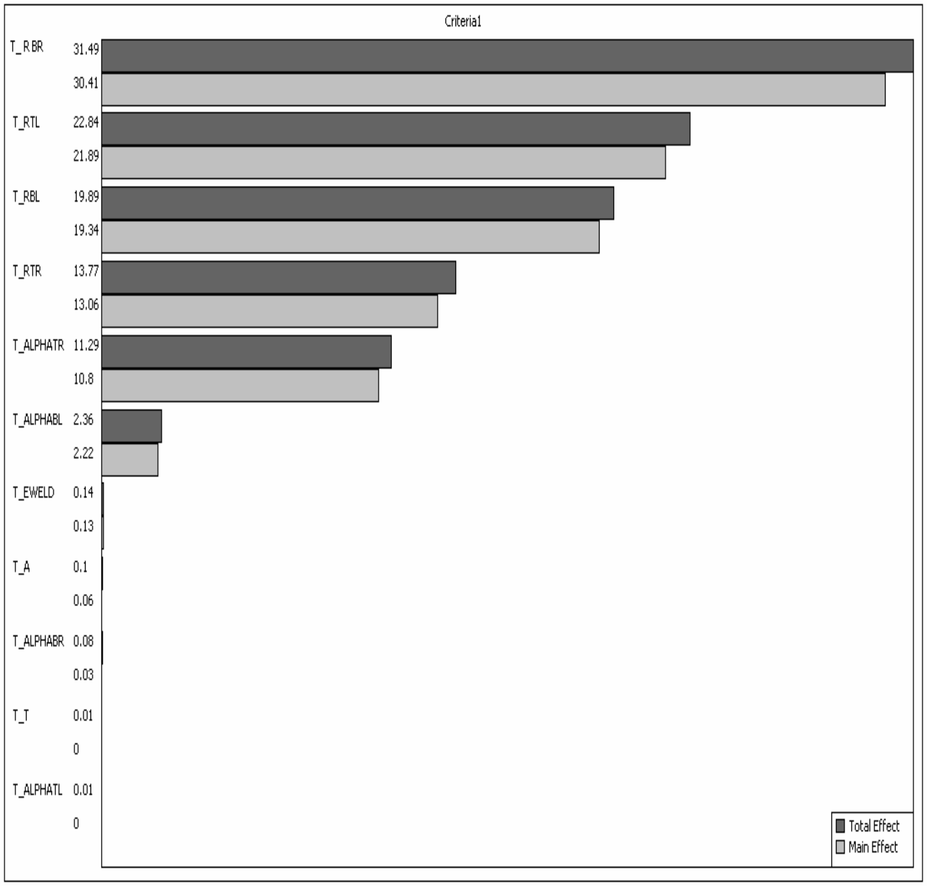
•Notch radii are the most influential parameter

•Young's modulus and overlap are not influential

•Parameters (*t, a, αtl and αbr*) have an effect less than 0.1%.

•Deleting parameters, simulations will be 99

$$\%saving = 1 - \frac{99}{243} = 59.25\%$$



SA of Simulation Model for MAG

Results

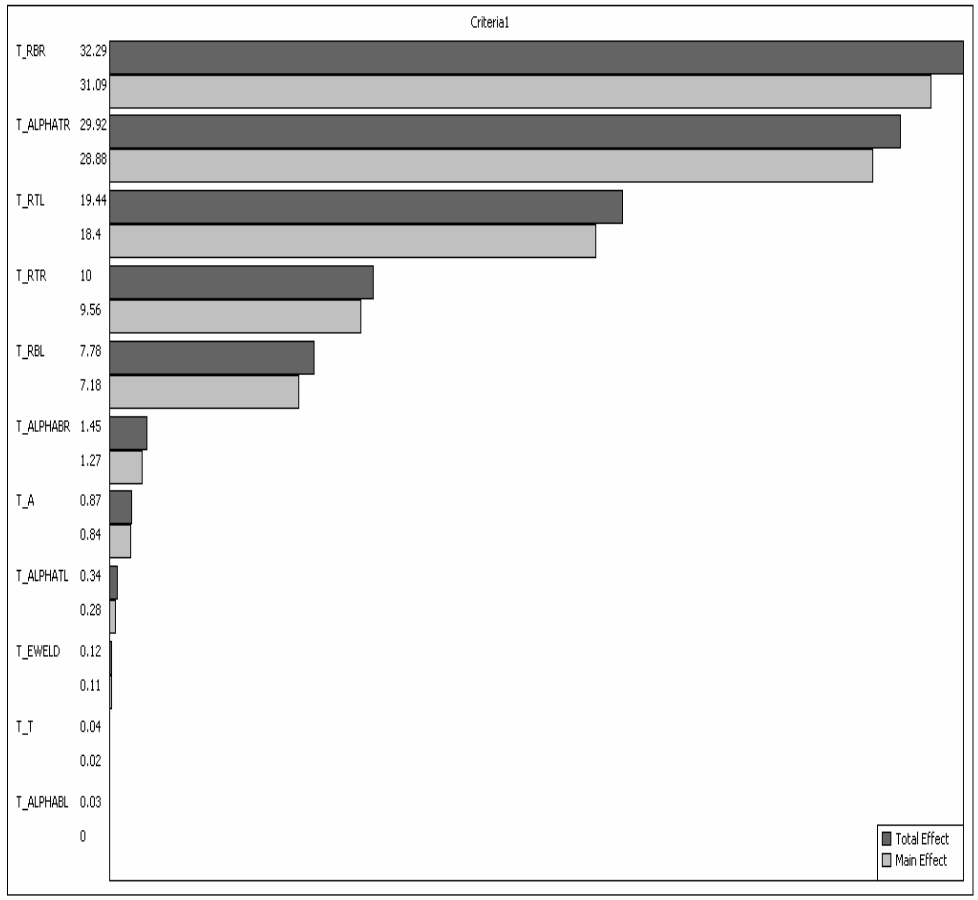
•Order of the importance is *rbr, αtr, rtl, rtr, rbl, αbr, a, αtl Eweld, t, αbl.*

•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 αbl*) have an effect less than 0.1%.

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



Conclusions and Recommendations

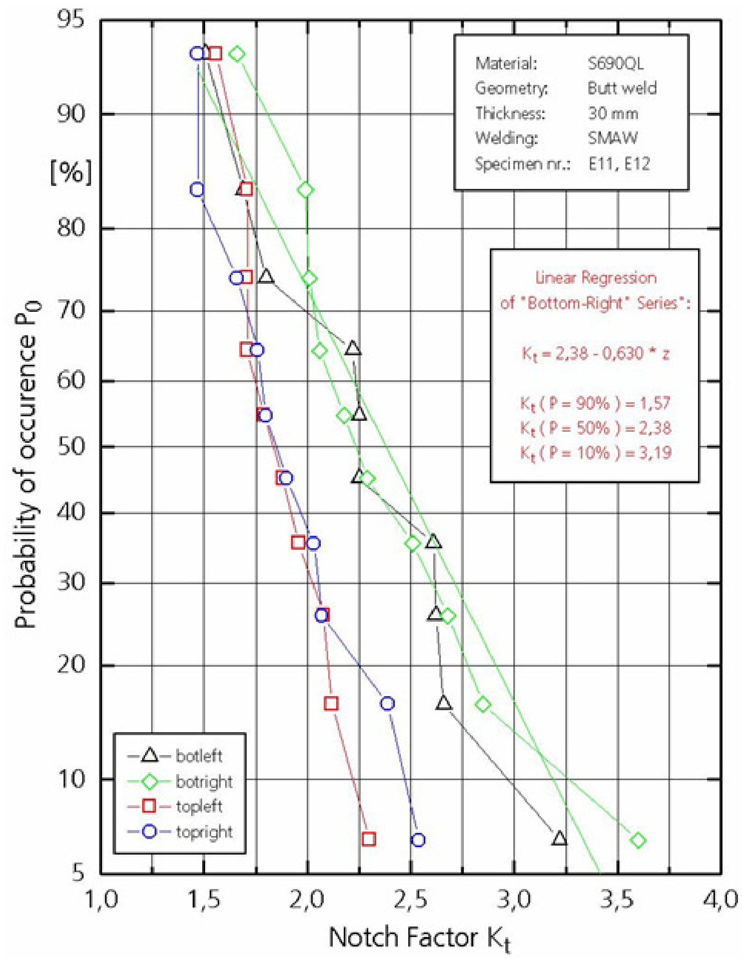
- Variance based sensitivity analysis is a powerful tool to find out the variation in the output of a model due to variations in the input parameters.
- Influential parameters found from the sensitivity analysis of finite element model are same as found from the sensitivity analysis of the Anthes, Köttgen 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 *(αtr)*, 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 *(αtr)* 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 *(Eweld)* 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



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[%]

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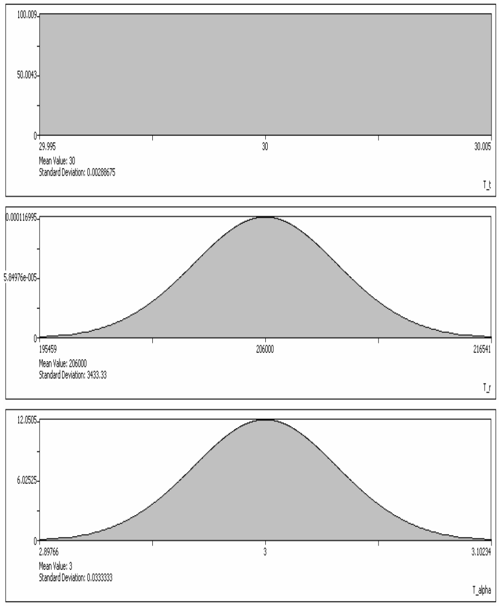
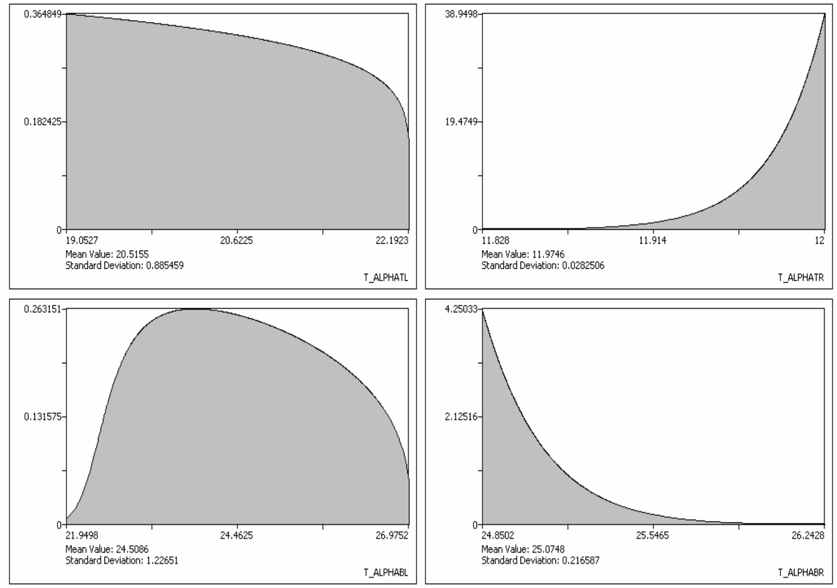
- Notch factor distributions for (SMAW) series
- The notch factor value corresponding to the probability of occurrence of 10% has been considered actually responsible of ruptures.
- Notch factor is maximum at bottom-right notch.





•Input Distribution

➢Thickness, modulus of elasticity and overlap

➢Notch Angles

➢Notch Radii