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MAGNA POWERTRAIN

FEMFAT User Meeting 2007

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Fatigue Assessment of Welded Structures Based on Nodal Forces

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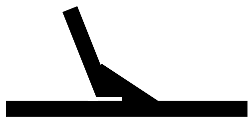
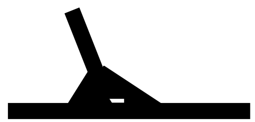
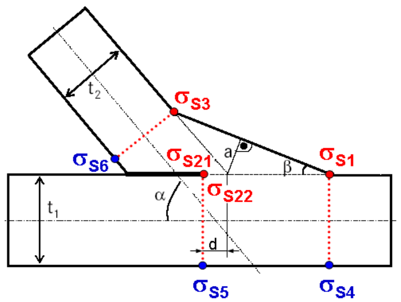
Contents

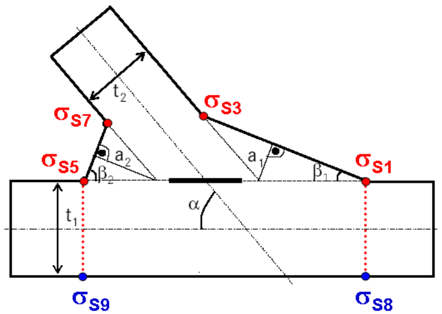
Joint Type in Consideration

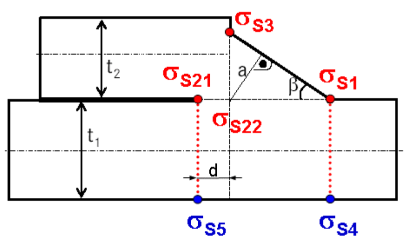
Y/T-Joint		Overlap Joint	Butt Joint
Single Fillet	Double Fillets		

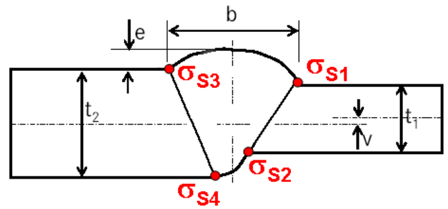












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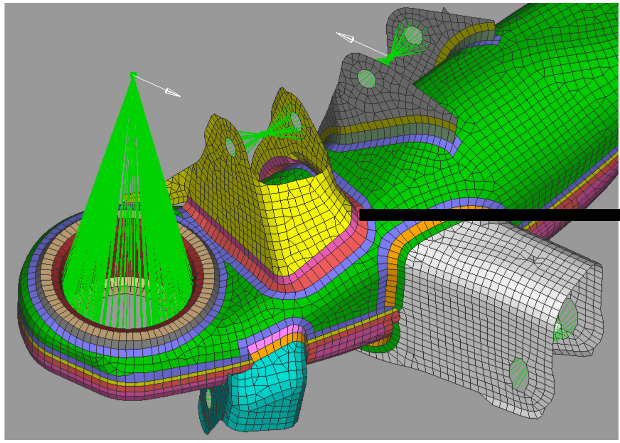
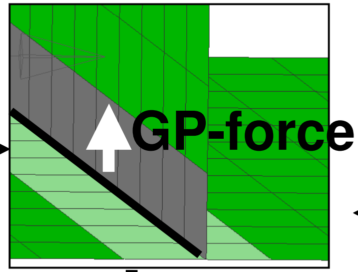
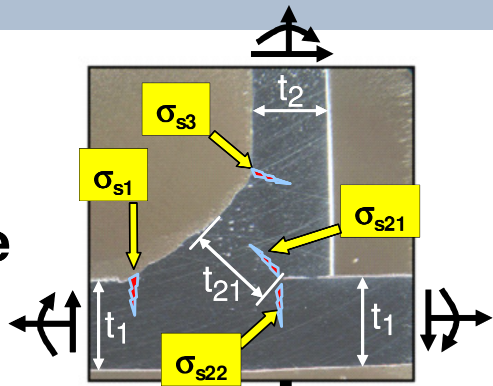
Principle of SSZ/MSZ Method







$$\text{Line force} = \frac{\text{Nodal force (GP-force)}}{\text{Element length}}$$

$$\sigma_{SSZ} = \frac{\text{Line force}}{\text{Sheet thickness}}$$

$$\sigma_{MSZ} = \sigma_{SSZ} \cdot \text{Notch factor}$$

Procedure:
1) Identification of weld line
2) Definition of critical locations
3) Determination of line forces
4) Calculation of structural stresses
5) Estimation of notch stresses

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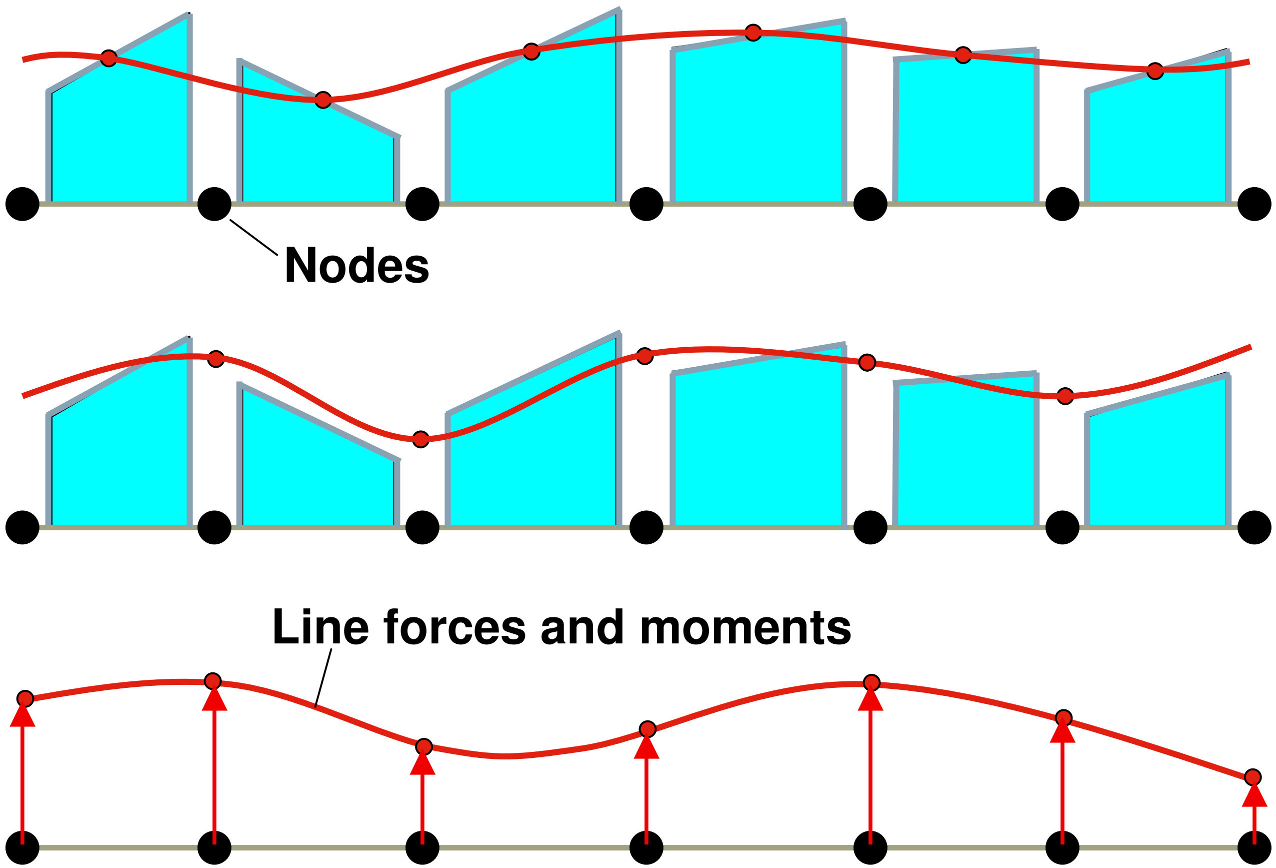
Determination of Line Forces Based on Grid-Point Forces (Nodal Forces)

Averaged over Elements

Averaged on Nodes

Method of Dong, Battelle



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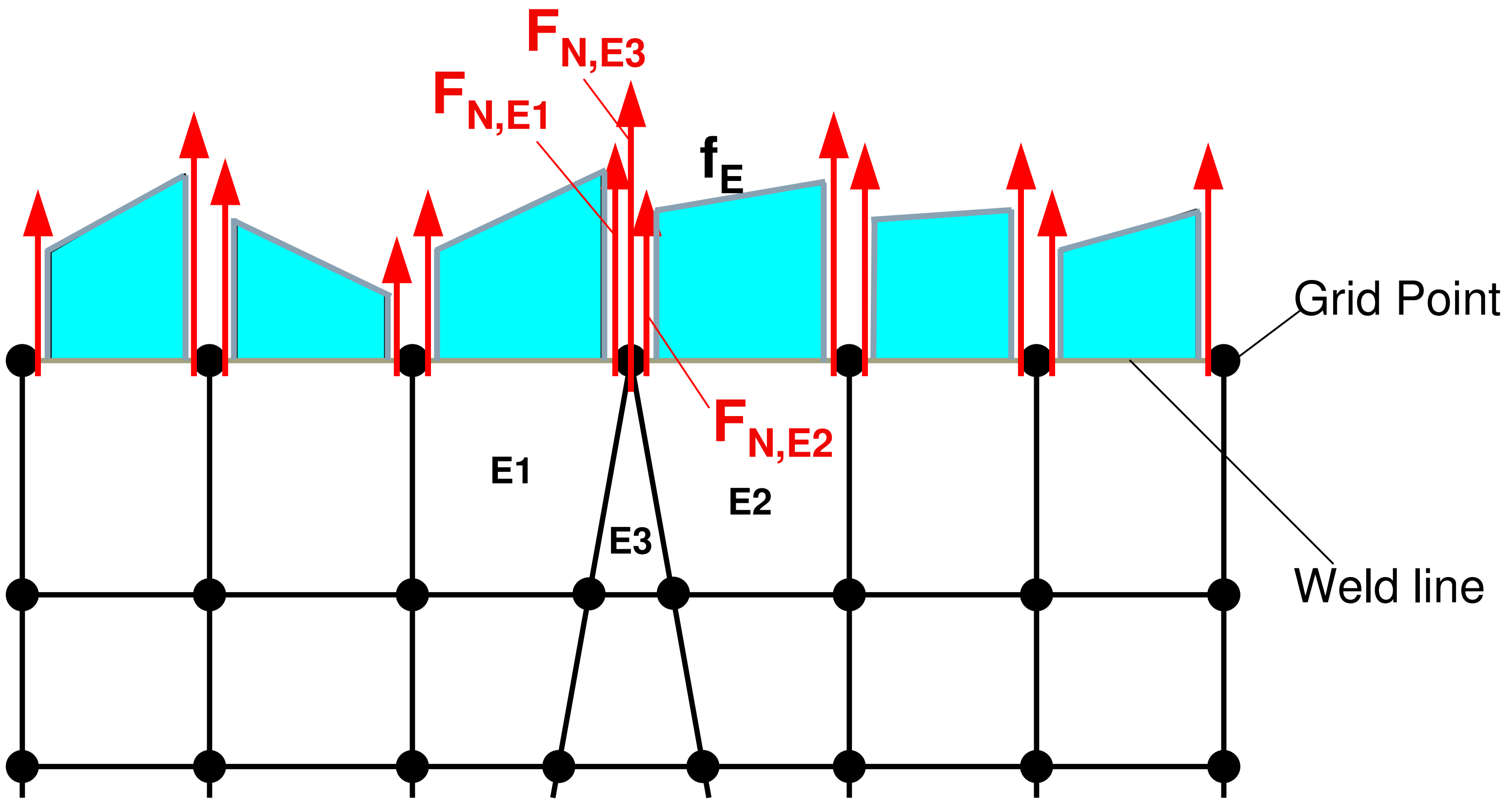
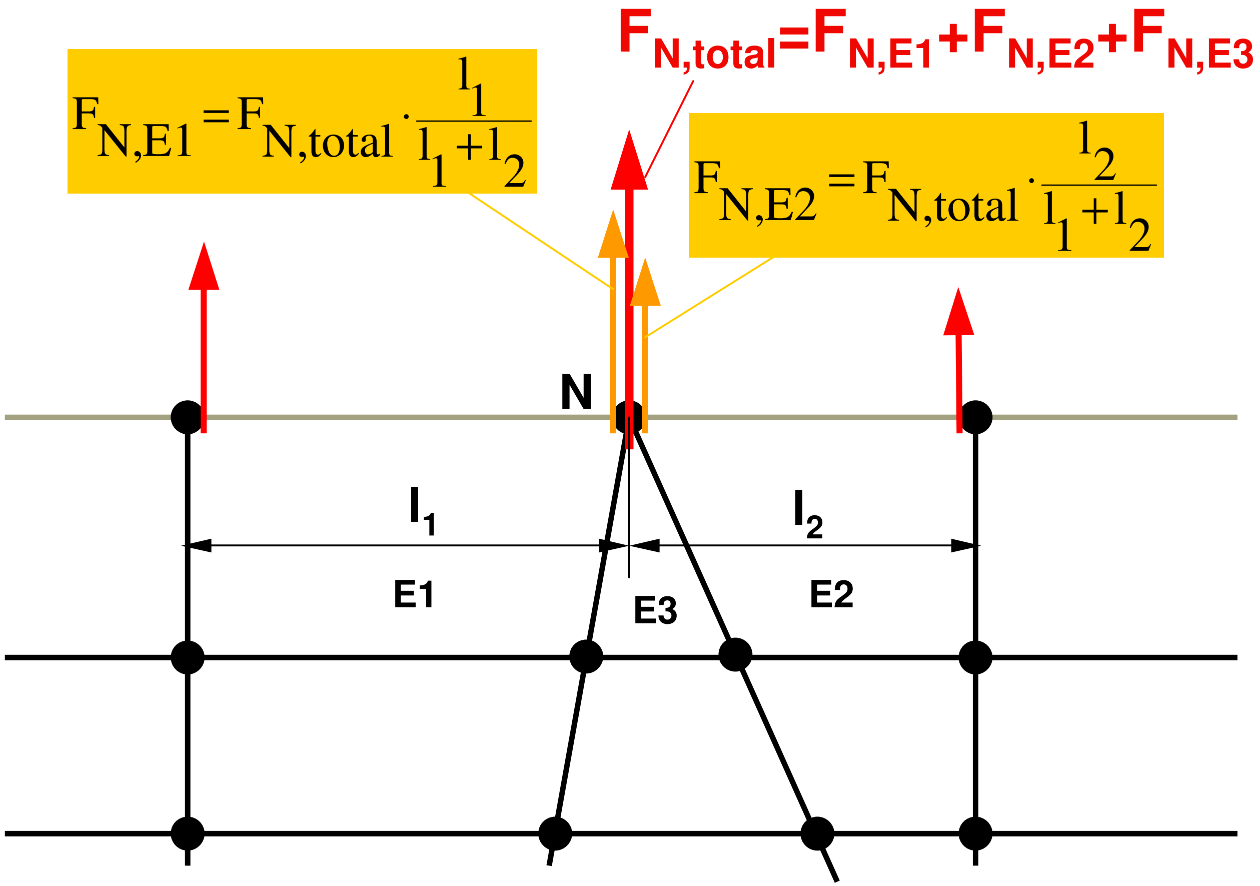
Line Forces Averaged over Elements

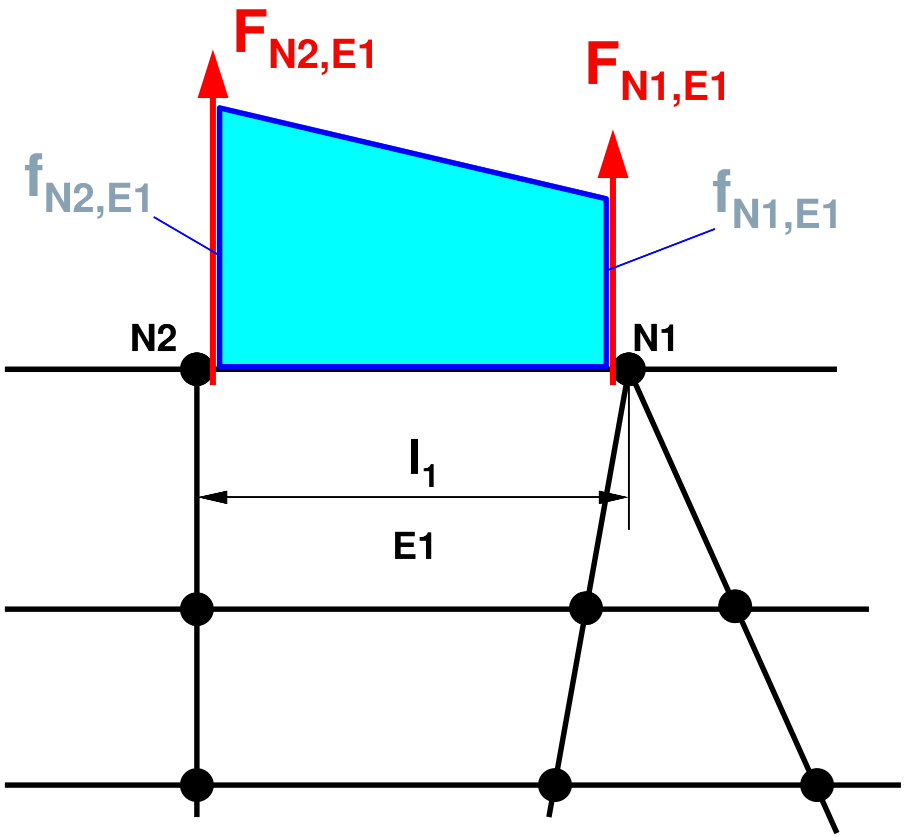
Linearly distributed line force f_E to be determined by grid-point forces F_N:



Total GP-Forces Weighted by Element Length



Converting of Forces into Line Forces



$$f_{N1,E1} = \frac{2}{l_1}\left(2F_{N1,E1} - F_{N2,E1}\right)$$

$$f_{N2,E1} = \frac{2}{l_1}\left(2F_{N2,E1} - F_{N1,E1}\right)$$

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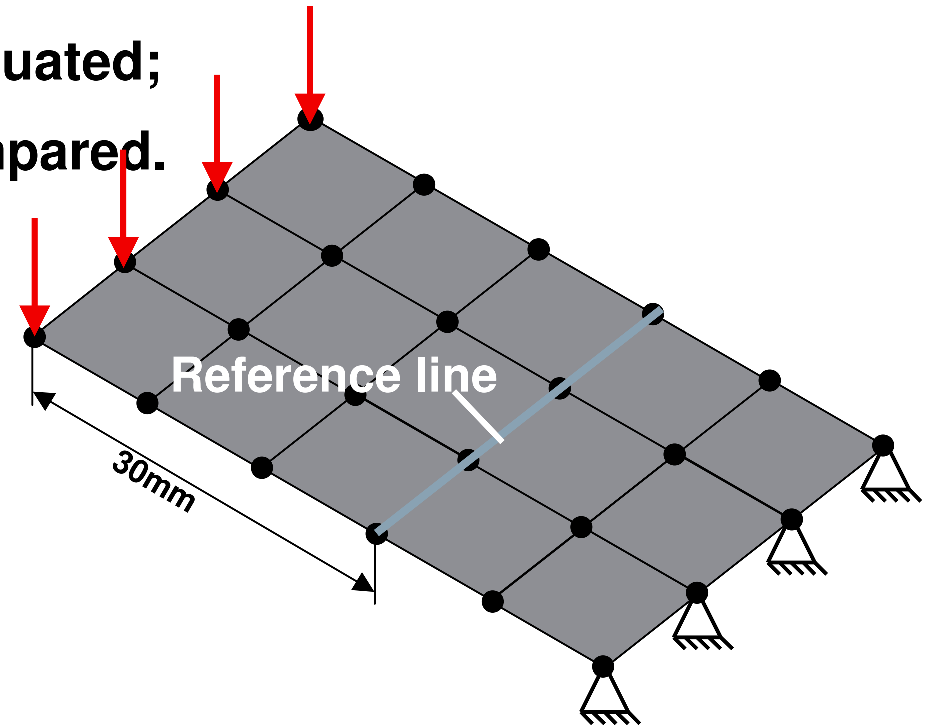
Validation of Line Force Calculation

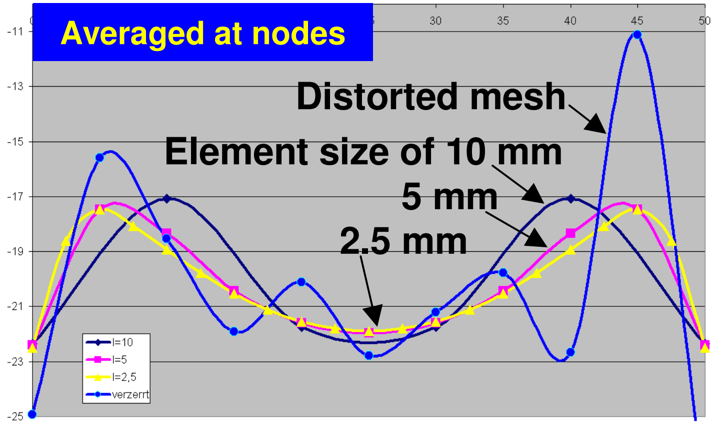
A panel of size 30mm x 50mm with different meshes under a transverse load is analyzed by NASTRAN;

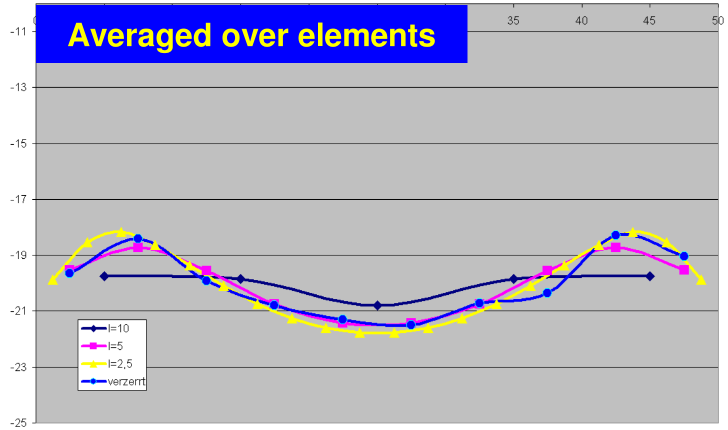
Grid-Point-Forces (Nodal Forces) along the reference line are evaluated;

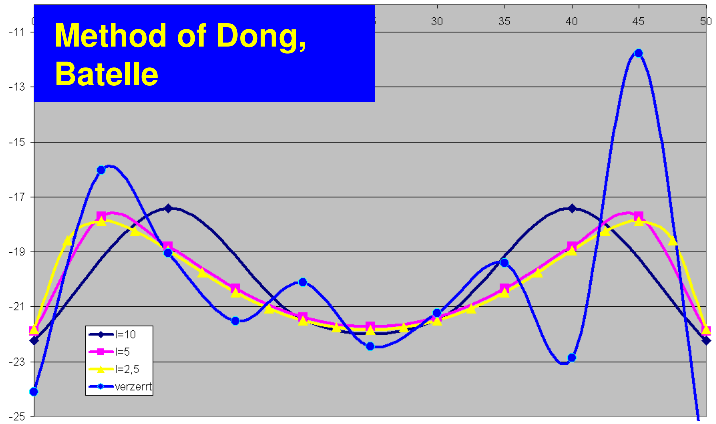
Line forces are calculated and compared.



Validation of Line Force Calculation



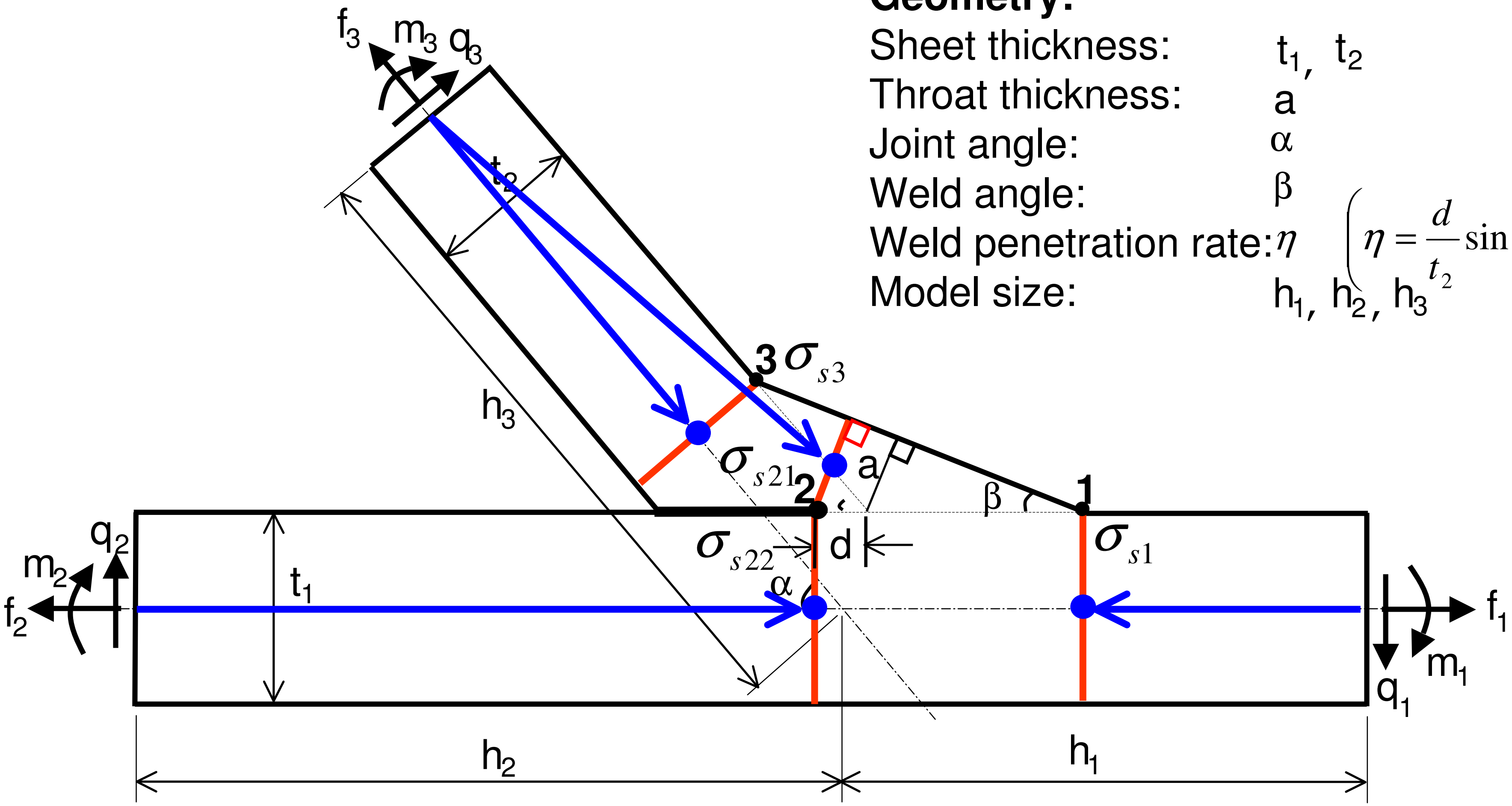




Result:

Line forces averaged over elements are less sensitive to mesh quality.

Derivation of Structural Stresses according to Zhang (SSZ)



Geometry:

Sheet thickness: t_1, t_2

Throat thickness: a

Joint angle: α

Weld angle: β

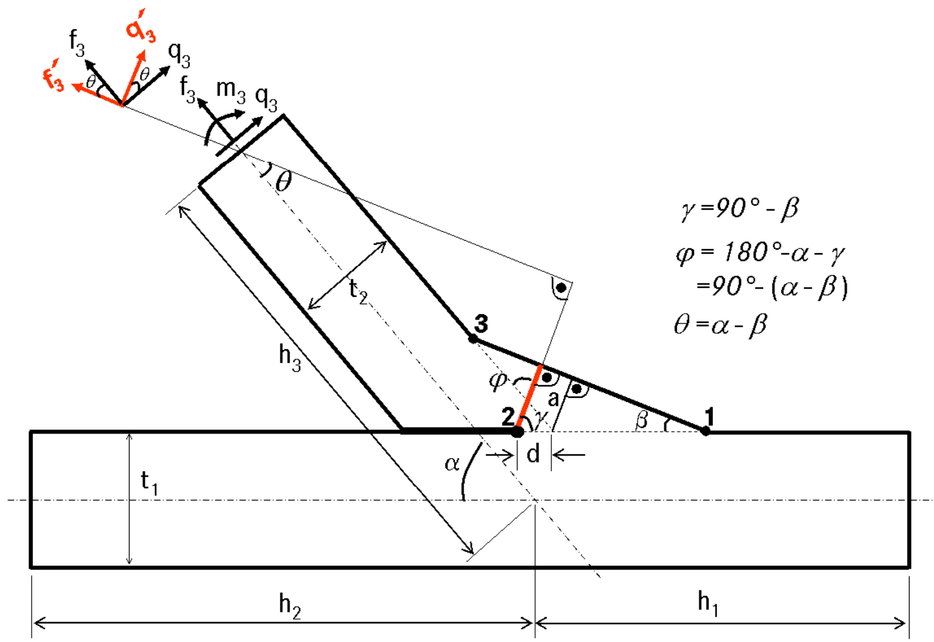
Weld penetration rate: η $\left(\eta = \frac{d}{t_2}\sin\alpha\right)$

Model size: h_1, h_2, h_3

Derivation of SSZ (Example: σ_{S21})

Simple beam theory:

$$\sigma_s = \sigma_m + \sigma_b = \frac{f}{t} + \frac{6m}{t^2}$$



Effective height:

$$t = t_{21} = a + \frac{\eta t_2 \sin\beta}{\sin\alpha}$$

Line force and moment:

$$f = f_3 \cos(\alpha - \beta) - q_3 \sin(\alpha - \beta)$$

$$m = m_3 + c_1\left[f_3 \sin(\alpha - \beta) + q_3 \cos(\alpha - \beta)\right] - c_2\left[f_3 \cos(\alpha - \beta) - q_3 \sin(\alpha - \beta)\right]$$

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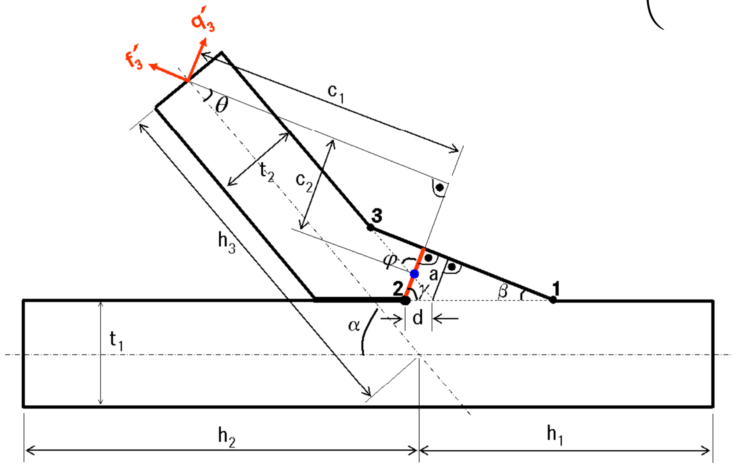
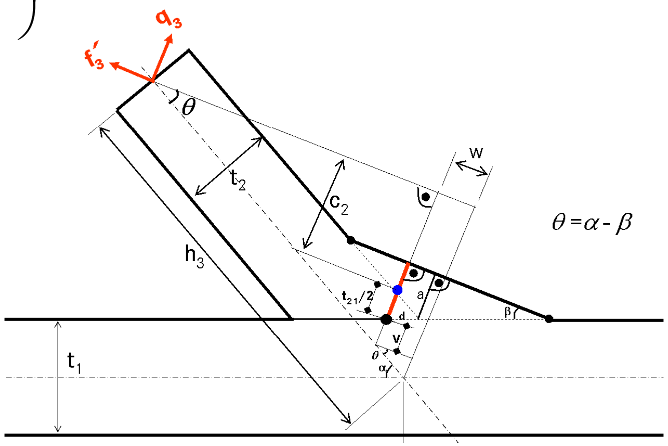
Derivation of SSZ (Example: σ_{S21})

$$\sigma_{s21} = \frac{f}{t} + \frac{6m}{t^2}$$

$$= \frac{f_3 \cos(\alpha - \beta) - q_3 \sin(\alpha - \beta)}{a + \frac{\eta t_2 \sin\beta}{\sin\alpha}}$$

$$+ \frac{6\{m_3 + c_1[f_3 \sin(\alpha - \beta) + q_3 \cos(\alpha - \beta)] - c_2[f_3 \cos(\alpha - \beta) - q_3 \sin(\alpha - \beta)]\}}{\left(a + \frac{\eta t_2 \sin\beta}{\sin\alpha}\right)^2}$$





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Derivation of SSZ (σ_{S1}, σ_{S22} and σ_{S3})

Similarly:

$$\sigma_{s1} = \frac{f_1}{t_1} + \frac{6\left[m_1 + q_1\left(h_1 + \frac{t_1}{2\tan\alpha} - \frac{t_2}{2\sin\alpha} - \frac{a}{\sin\beta}\right)\right]}{t_1^2}$$

$$\sigma_{s22} = \frac{f_2}{t_1} - \frac{6\left[m_2 + q_2\left(h_2 + \frac{t_2(1-2\eta)}{2\sin\alpha} - \frac{t_1}{2\tan\alpha}\right)\right]}{t_1^2}$$

$$\sigma_{s3} = \frac{f_3}{t_2} - \frac{6\left[m_3 + q_3\left(h_3 + \frac{t_2}{2\tan\alpha} - \frac{t_1}{2\sin\alpha} - \frac{a}{\sin(\alpha-\beta)}\right)\right]}{t_2^2}$$

MSZ Notch Stresses

Analytic Approximation of Notch Effects in Seam Welds by

$$\sigma_{kj} = \sigma_{sj} \cdot \left(1 + s \cdot \sqrt{\frac{t_j}{\rho_j}} \right)$$

σ_{sj}: SSZ stresses
σ_{kj}: MSZ notch stresses (approximate)

ρ_j : Notch radius
t_j : Effective thickness
s : Factor

Basis: Creager solution in Fracture Mechanics and its application to welded joints, see:

[1] Tada, H., Paris, P. and Irwin, G. 1985. The stress analysis of cracks Handbook, Paris Productions Incorporated and Del Research Corporation.
[2] Zhang, S. 1997. Stress intensities at spot welds. *International Journal of Fracture* 88, pp. 167-185.
[3] Zhang, S. 2001. Fracture mechanics solutions to spot welds. *International Journal of Fracture* 112, pp. 247-274.

Determination of t_j

$$\sigma_{kj} = \sigma_{sj} \cdot \left(1 + s \cdot \sqrt{\frac{t_j}{\rho_j}}\right)$$

	t_j			
	Y-joint single fillet	Overlap joint	Butt joint	Y-joint double fillets
σ_{s1}	t_1	t_1	t_1	t_1
σ_{s2}			t_1	
σ_{s21}	$a + \frac{\eta t_2 \sin\beta}{\sin\alpha}$	$a + \eta t_2 \sin\beta$		
σ_{s22}	t_1	t_1		
σ_{s3}	t_2	$\sqrt{\eta^2 t_2^2 + \left(\frac{a}{\cos\beta}\right)^2}$	t_2	t_2
σ_{s4}			t_2	
σ_{s5}				t_1
σ_{s6}				
σ_{s7}				t_2

Determination of *s*-Factor

$$\sigma_{k\,j} = \sigma_{s\,j} \cdot \left(1 + s \cdot \sqrt{\frac{t_j}{\rho_j}} \right)$$

	Y-joint single fillet	Overlap joint	Butt joint	Y-joint double fillets
s	1.0	0.58	0.85	1.0

Concept of $\rho_j = 0.05t$

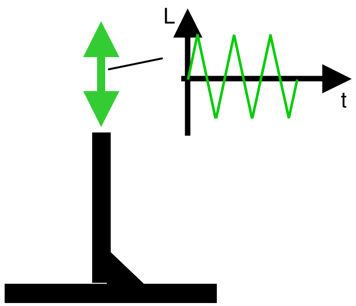
$$\sigma_{kj} = \sigma_{sj} \cdot \left(1 + s \cdot \sqrt{\frac{t_j}{\rho_j}}\right)$$

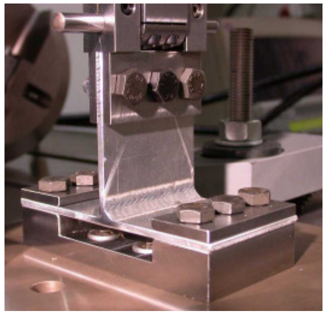
	$\rho_j=0.05t$, t takes the following values:			
	Y-joint single fillet	Overlap joint	Butt joint	Y-joint double fillets
σ_{s1}	t_1	t_1	t_1	t_1
σ_{s2}			t_1	
σ_{s21}	$(t_1 + t_2)/2$	$(t_1 + t_2)/2$		
σ_{s22}	t_1	t_1		
σ_{s3}	t_2	t_2	t_2	t_2
σ_{s4}			t_2	
σ_{s5}				t_1
σ_{s6}				
σ_{s7}				t_2

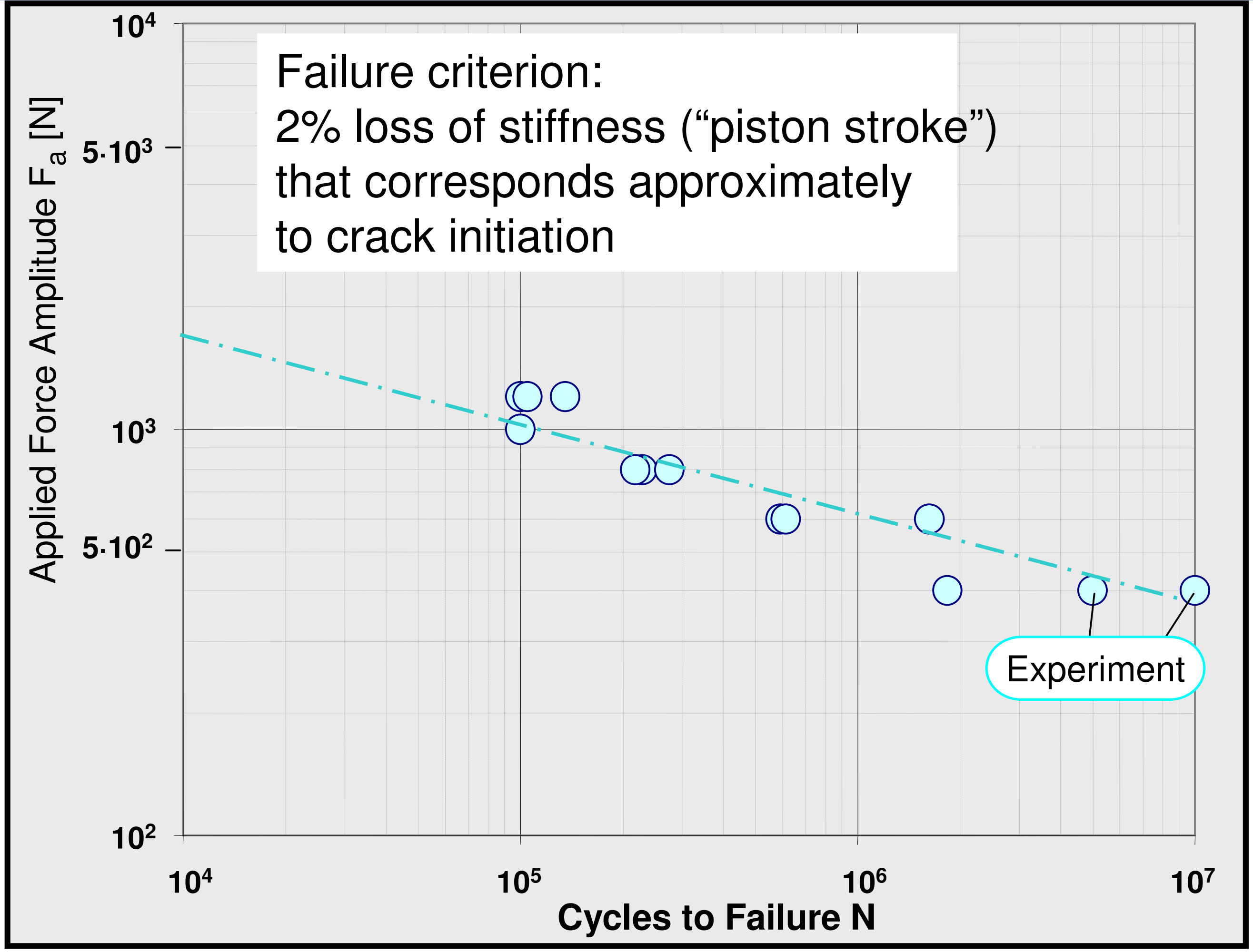
Fictitious notch radius is 5% of sheet thickness (relative value) instead of 0.05mm (absolute value).

Example of Fatigue Test

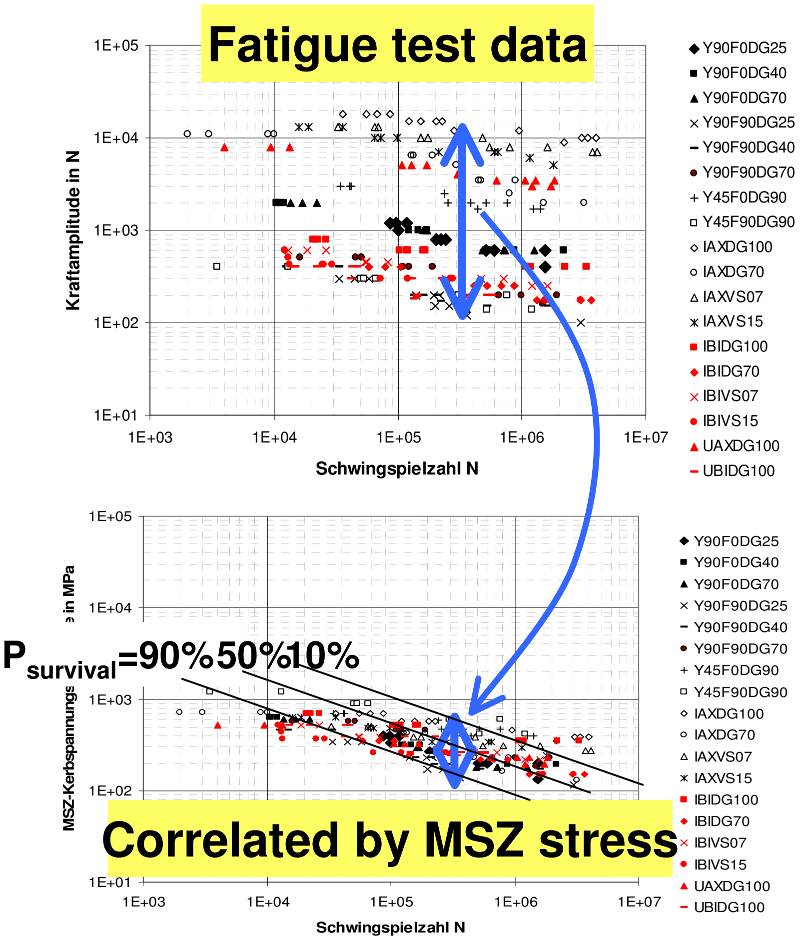
T-Joint (Alu)
Load case:
Load angle: 0°





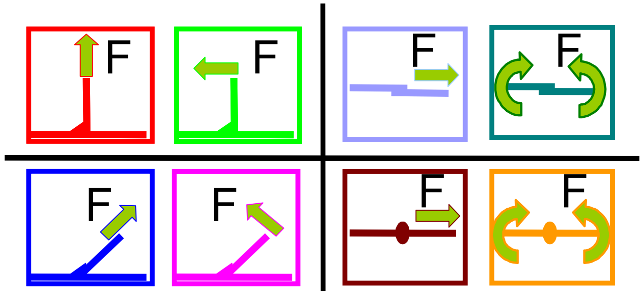


Correlation of Fatigue Test Data

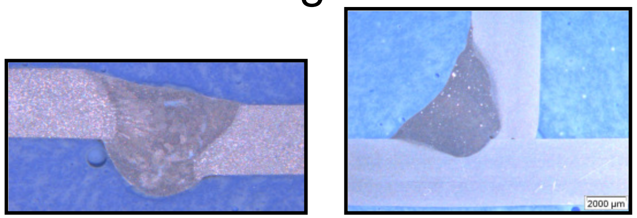


Fatigue Test: 18 series
Material: AlMg3Mn

Different joint types and loads:

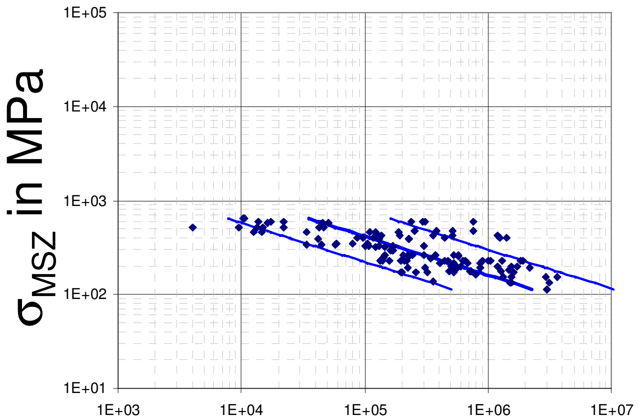


Different weld geometries:



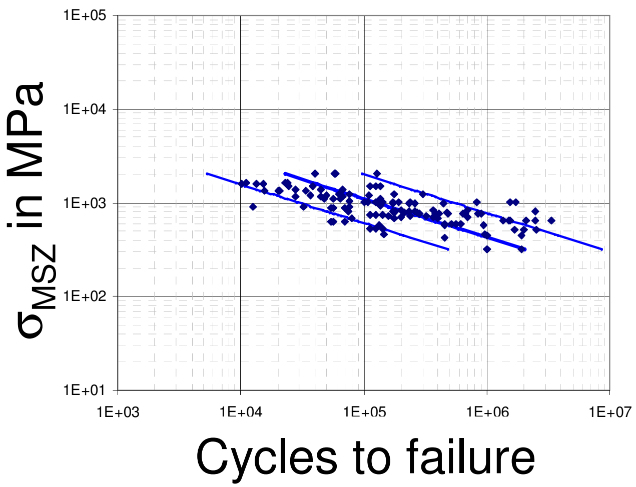
Master S-N Curves

Master S-N Curve for Aluminium Alloys:



$$\sigma_{\mathrm{MSZ}} = 0{,}55\left(\frac{10^{12}}{N}\right)^{\frac{1}{2{,}43}}$$

Master S-N Curve for Steels:



$$\sigma_{\mathrm{MSZ}} = 1{,}73\left(\frac{10^{12}}{N}\right)^{\frac{1}{2{,}50}}$$

Two New Modules in Principle

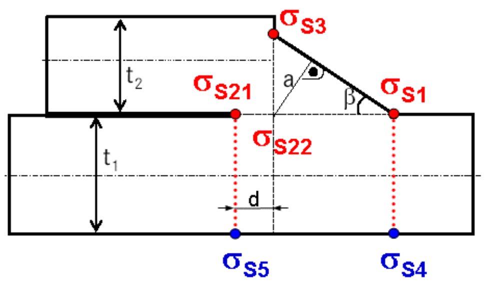
SSZ-Method:

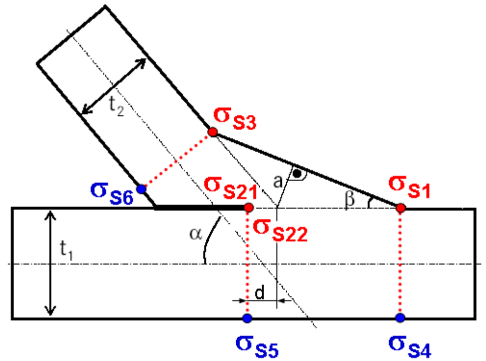
SSZ Stresses + Notch Factors from FEMFAT Standard ≤ S-N Curves from FEMFAT Standard

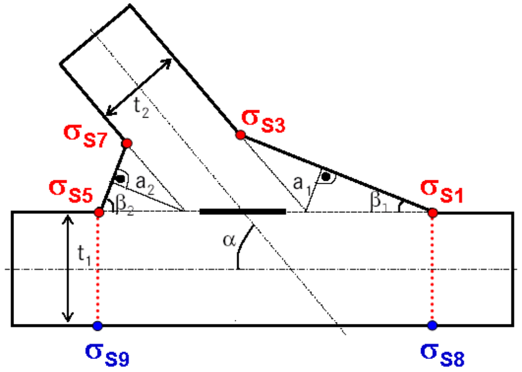
MSZ-Method:

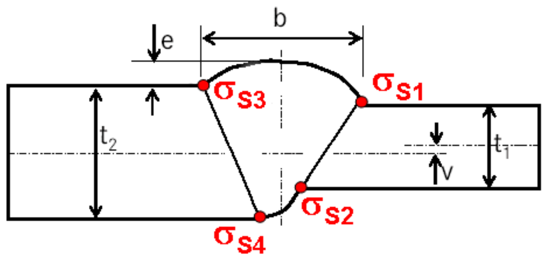
SSZ Stresses + Notch Factors from MSZ-Approximation ≤ Master S-N Curves (User Defined)

Convention of SSZ in Seam Welds









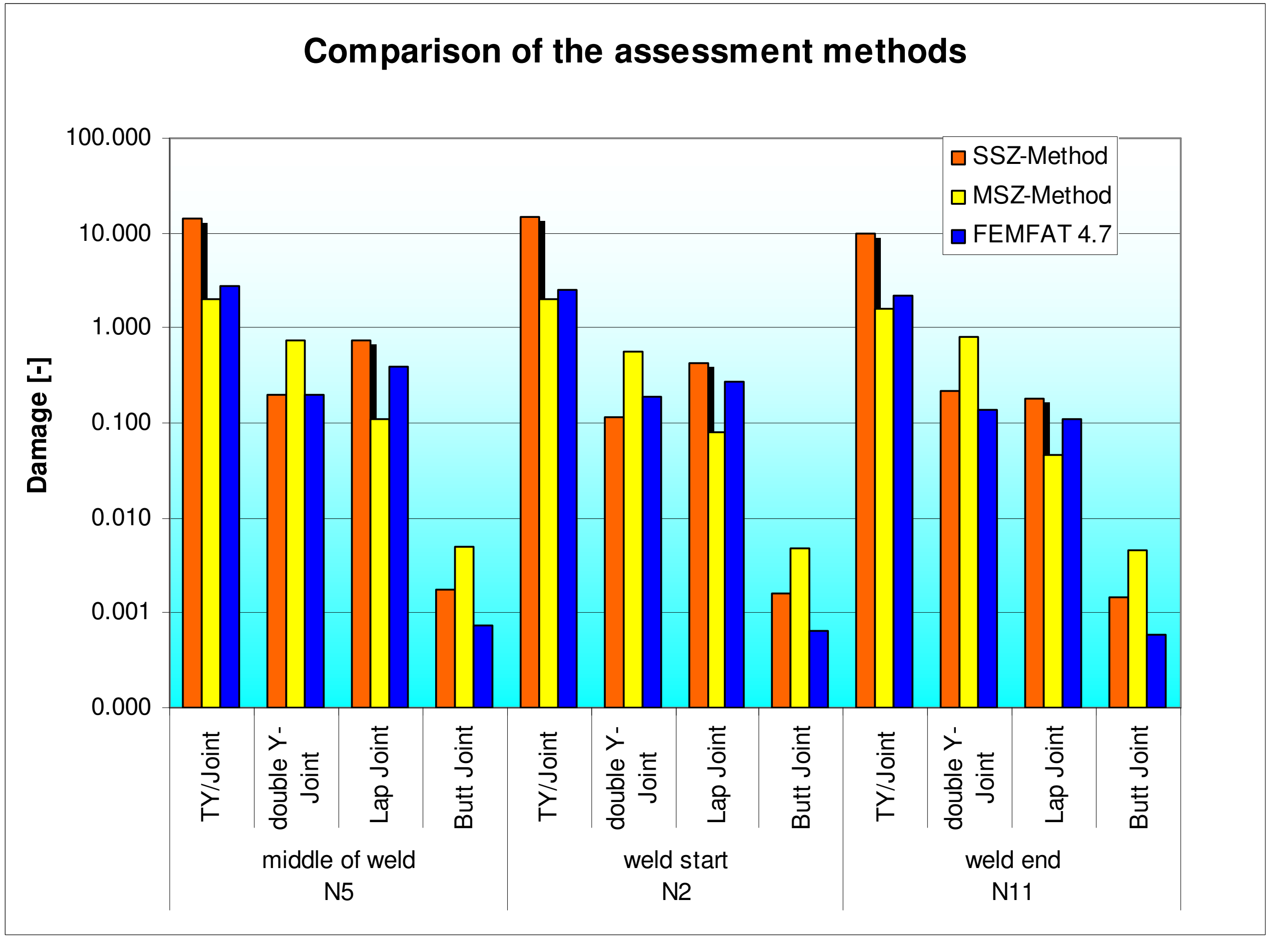
	Stress Ratio for Determination of Notch Stress*	Stresses for Damage Calculations
T/Y-Joint, Single Fillet	$\sigma_{S1}/\sigma_{S4}; \sigma_{S3}/\sigma_{S6}; \sigma_{S22}/\sigma_{S5}$	$\sigma_{S1}; \sigma_{S3}; \sigma_{S21}$ $(\sigma_{S6}{}^{*}); \sigma_{S22}$
T/Y-Joint, Double Fillets	$\sigma_{S1}/\sigma_{S8}; \sigma_{S3}/\sigma_{S7}; \sigma_{S5}/\sigma_{S9}$	$\sigma_{S1}; \sigma_{S3}; \sigma_{S5}; \sigma_{S7}$
Overlap Joint	$\sigma_{S1}/\sigma_{S4}; \sigma_{S3}/\sigma_{S21}; \sigma_{S22}/\sigma_{S5}$	$\sigma_{S1}; \sigma_{S3}; \sigma_{S21}; \sigma_{S22}$
Butt Joint	$\sigma_{S1}/\sigma_{S2}; \sigma_{S3}/\sigma_{S4}$	$\sigma_{S1}; \sigma_{S2}; \sigma_{S3}; \sigma_{S4}$

* **Only for SSZ Method**

Comparison of Methods in FEMFAT

	FEMFAT 4.7	SSZ-Method	MSZ-Method
Type of Stresses	Element stresses	Structural stresses derived from grid-point forces	
Applicable Stress Components	$\sigma_\perp$, $\sigma_{\|\|}$, τ	$\sigma_\perp$	
Determination of Notch Factors	Notch factors from weld database; Membrane and bending stress will be determined using the stress ratio of the top and bottom side of shell elements		Analytically estimated notch factors
Damage Calculation	Compare notch stresses with joint-type-dependent S-N curves from weld database		Compare notch stresses with a Master S-N curve

Application Example on Coupon Level



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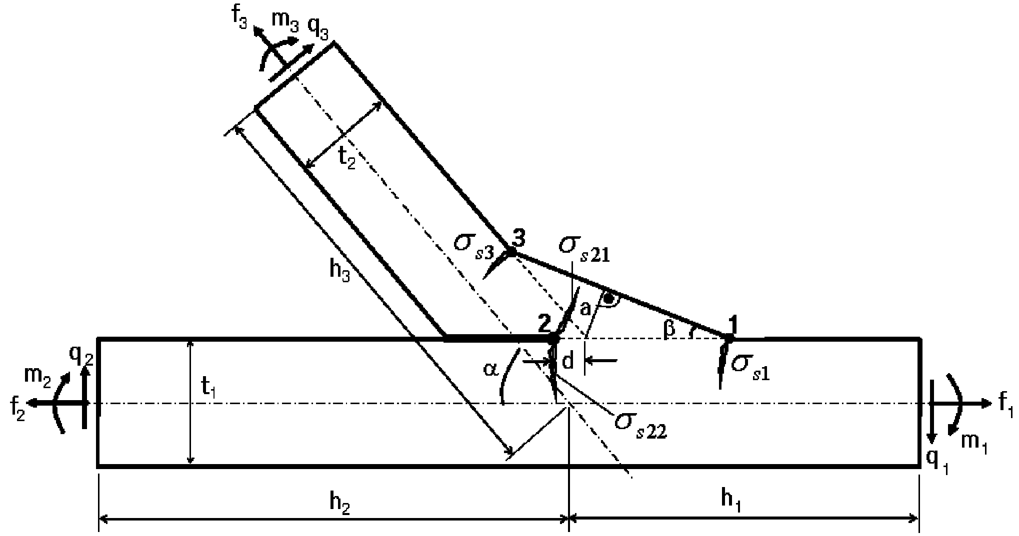
Scenario Analysis (Y-Joint, Single Fillet)
Good, Normal, Bad Weld Quality

Parameter:	Default Value:	Extreme Values:
a-Value: $a = \lambda(t_1 + t_2)/2$	$\lambda = 0,6$	$0,5 \le \lambda \le 0,707$
Weld angle: $\beta = \kappa\alpha$	$\kappa = 0,5$	$0,4 \le \kappa \le 0,6$
Weld penetration: η $\left(\eta = \frac{d}{t_2}\sin\alpha\right)$	$\eta = 0,3$	$0,1 \le \eta \le 0,5$

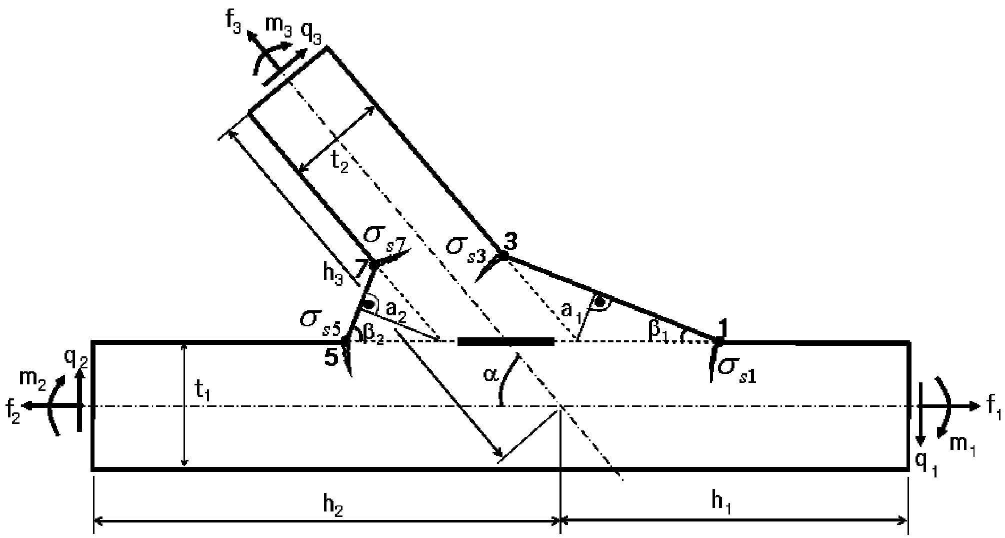
Default value → Normal Weld Quality; lower extreme values → Bad Weld Quality; upper extreme values → Good Weld Quality



Scenario Analysis (Y-Joint, Double Fillets)
Good, Normal, Bad Weld Quality

Parameter:		Default Value:	Extreme Values:
a-Value 1:	$a_1 = \lambda_1(t_1 + t_2)/2$	$\lambda_1 = 0{,}6$	$0{,}5 \le \lambda_1 \le 0{,}707$
a-Value 2:	$a_2 = \lambda_2(t_1 + t_2)/2$	$\lambda_2 = 0{,}6$	$0{,}5 \le \lambda_2 \le 0{,}707$
Weld angle 1:	$\beta_1 = \kappa_1 \alpha$	$\kappa_1 = 0{,}5$	$0{,}4 \le \kappa_1 \le 0{,}6$
Weld angle 2:	$\beta_2 = \kappa_2 \alpha$	$\kappa_2 = 0{,}5$	$0{,}4 \le \kappa_2 \le 0{,}6$

Normal Weld Quality (default values) — Bad Weld Quality (lower extreme values) — Good Weld Quality (upper extreme values)



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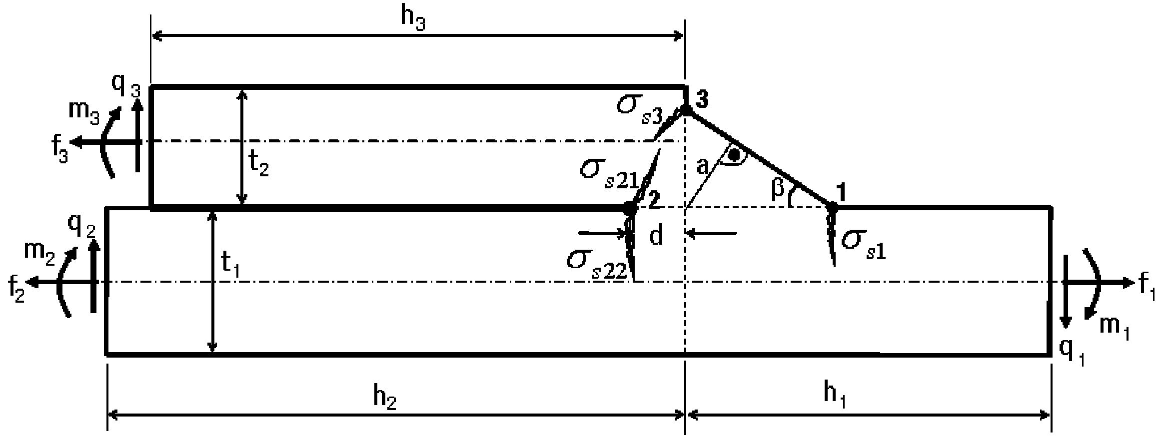
Scenario Analysis (Overlap Joint)
Good, Normal, Bad Weld Quality

Parameter:		Default Value:	Extreme Values:
a-Value:	$a = \lambda t_2$	$\lambda = 0{,}6$	$0{,}5 \le \lambda \le 0{,}707$
Weld angle:	β	$\beta = 45°$	$30° \le \beta \le 45°$
Weld penetration:	η	$\eta = 0$	$-0{,}25 \le \eta \le 0{,}25$

$(a \le t_2 \cos\beta)$

$$\left(\eta = \frac{d}{t_2}\right)$$

Normal Weld Quality (default values) · Bad Weld Quality (lower extreme values) · Good Weld Quality (upper extreme values)

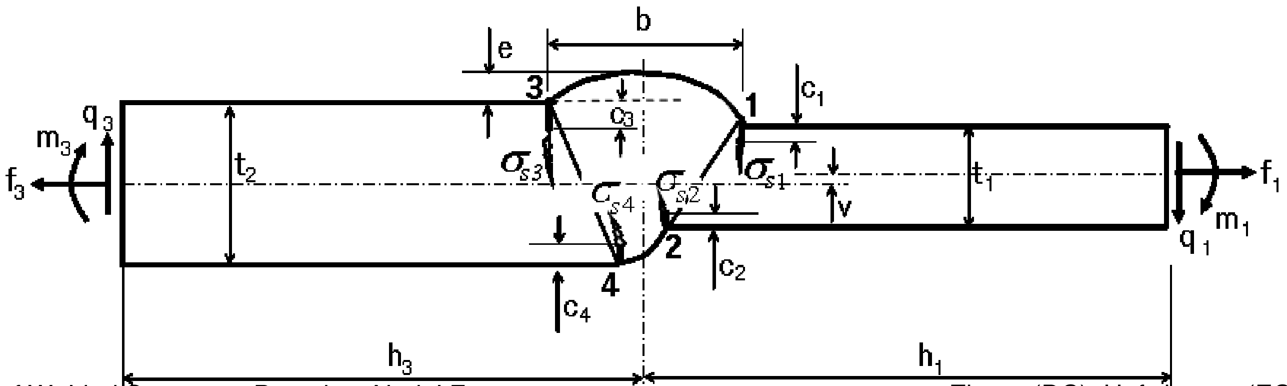


Scenario Analysis (Butt Joint)
Good, Normal, Bad Weld Quality

Parameter:		Default Value:		Extreme Values:
Weld width:	$b = \kappa t_1$	$\kappa = 1{,}0$		$0{,}8 \le \kappa \le 2{,}0$
Weld reinforcement:	$e = \lambda_1 t_1$	$\lambda_1 = 0$		$-0{,}2 \le \lambda_1 \le 0{,}2$
Sheet offset:	$v = \lambda_2 (t_2 - t_1)/2$	$\lambda_2 = 1{,}0$	$(-1{,}0 \le \lambda_2 \le 1{,}0)*$	
Toe cut depth:	$c_1 = k_1 t_1$	$k_1 = 0{,}1$		$0{,}2 \ge k_1 \ge 0$
Root cut depth:	$c_2 = k_2 t_1$	$k_2 = 0{,}1$		$0{,}2 \ge k_2 \ge -0{,}1$
Toe cur depth:	$c_3 = k_3 t_2$	$k_3 = 0{,}1$		$0{,}2 \ge k_3 \ge 0$
Root cut depth:	$c_4 = k_4 t_2$	$k_4 = 0{,}1$		$0{,}2 \ge k_4 \ge -0{,}1$

* not a weld quality parameter

Default values (yellow): Normal Weld Quality; left extreme values (orange): Bad Weld Quality; right extreme values (green): Good Weld Quality



Potentials and Limitations of the Method

Potentials:

- The SSZ/MSZ method allows weld geometry to be considered explicitly in fatigue assessment.
- Failure locations, notably, at weld root and toe, are clearly indicated by the SSZ/MSZ stresses.
- Weld quality can be evaluated by scenario analysis in three classes of good, normal and bad weld quality.

Limitations:

- MSZ notch stresses are only approximations.
- SSZ/MSZ method is still not sufficiently validated in FEMFAT.
- The relation between weld quality and weld geometry should be further verified by experiment or experience.