Fadiga de Materiais Estruturais: Fundamentos e Aplicações Efeitos dos Entalhes (Notch Effects)

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AGENDA

1. *Introdução (Introduction)*
2. *Concentração e Gradiente de Tensões (Stress Concentration)*
3. *S-N para corpos com entalhes (S-N approach for notched members)*
4. *E-N para corpos com entalhes(ε-N approach for notched members)*
5. *da/dN para corpos com entalhes(Fracture mechanics approach for notched members)*
6. *Exemplo de aplicação (Example)*

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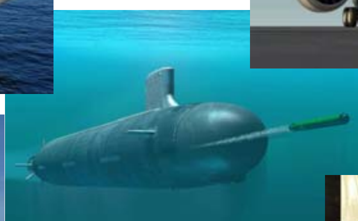
Introduction

- ***Notched Structures***





Introduction

Notched Structures

- Notches:
  - can not be avoided
  - are key problem in fatigue behavior
  - very dangerous
  - can be minimized by suitable treatment
- To understand notch effects we must consider:
  - Stress/strain concentration
  - Stress gradient
  - Mean stress and residual stress
  - Local yielding

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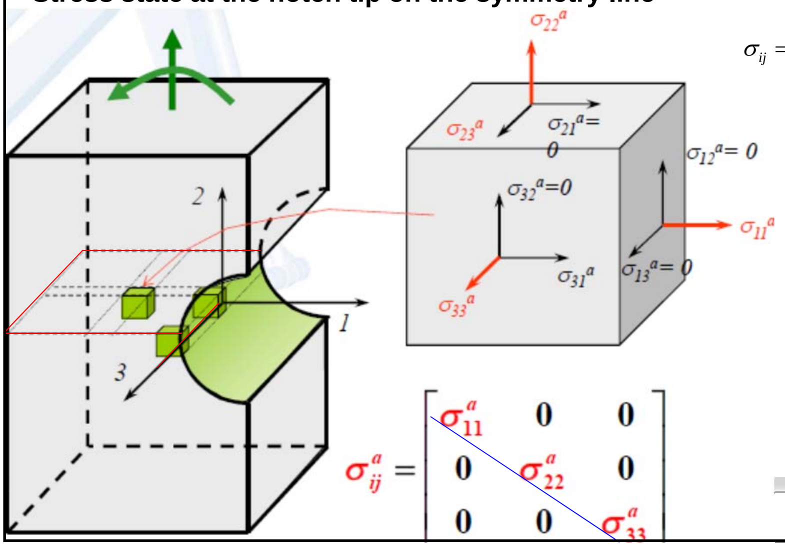
Stress State

Stress state at the notch tip on the symmetry line

$$\sigma_{ij} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}$$

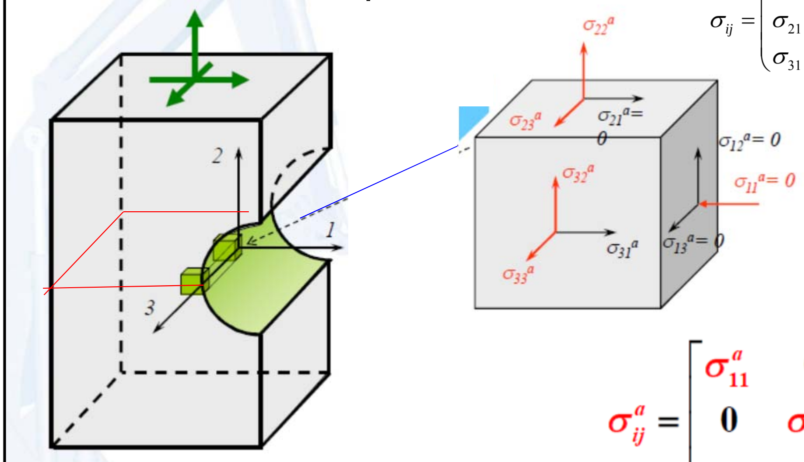


$$\sigma_{ij}^{a} = \begin{bmatrix} \sigma_{11}^{a} & 0 & 0 \\ 0 & \sigma_{22}^{a} & 0 \\ 0 & 0 & \sigma_{33}^{a} \end{bmatrix}$$

Stress State

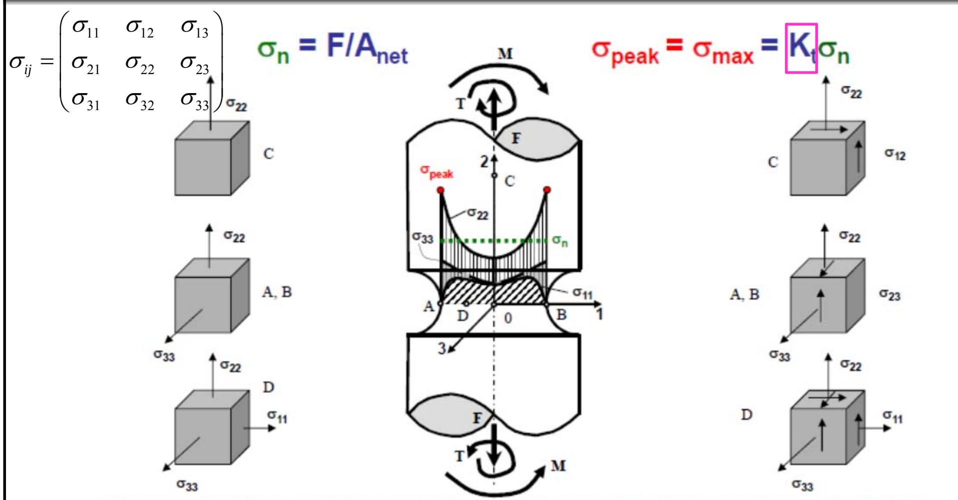
Stress state at the notch tip on FREE surface

$$\sigma_{ij} = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}$$



$$\sigma_{ij}^{a} = \begin{bmatrix} \sigma_{11}^{a} & 0 & 0 \\ 0 & \sigma_{22}^{a} & \sigma_{23}^{a} \\ 0 & \sigma_{32}^{a} & \sigma_{33}^{a} \end{bmatrix}$$

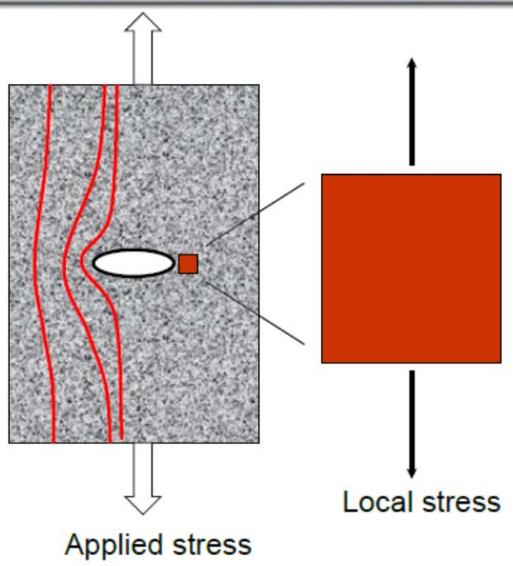
Stress Concentration Factor Kt



Stresses in axisymmetric notched body under axial loading

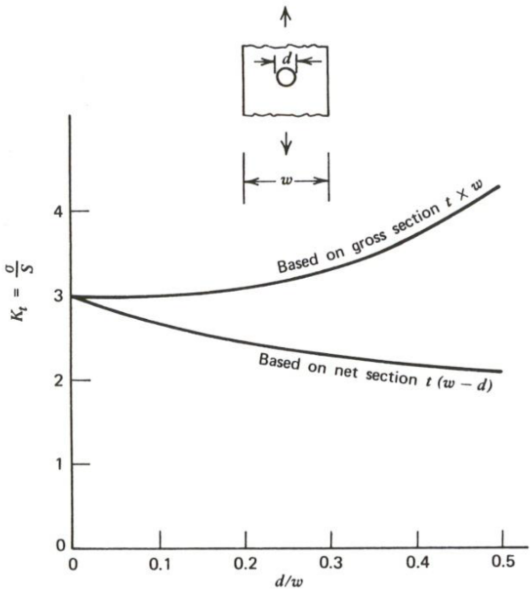
Stresses in axisymmetric notched body under axial, bending and torsion loading

Stress Concentration Factor Kt



Intensification of stress amplitude measured by the elastic stress concentration fator Kt

Stress Concentration Factor Kt



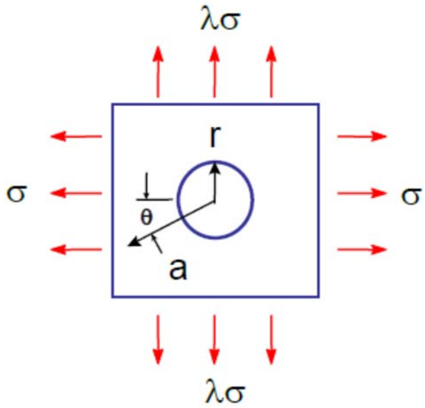
Circular Notch

	Kt
Tension....................	3
Biaxial tension...........	2
Shear........................	2 (based on max. Shar)

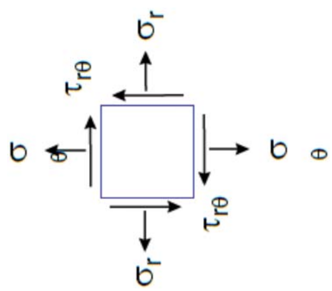
Kt depende do modo de carregamento/definição usada

Stress Concentration Factor Kt

Circular notch

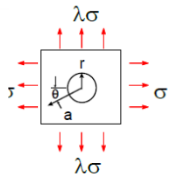


$$\sigma_\theta\left(0^\circ\right) = \sigma$$



Stress Concentration Factor Kt

Circular notch



$$\frac{\sigma_r}{\sigma}=\frac{1+\lambda}{2}\left(1-\left(\frac{r}{a}\right)^2\right)+\frac{1-\lambda}{2}\left(1+3\left(\frac{r}{a}\right)^4-4\left(\frac{r}{a}\right)^2\right)\cos 2\theta$$

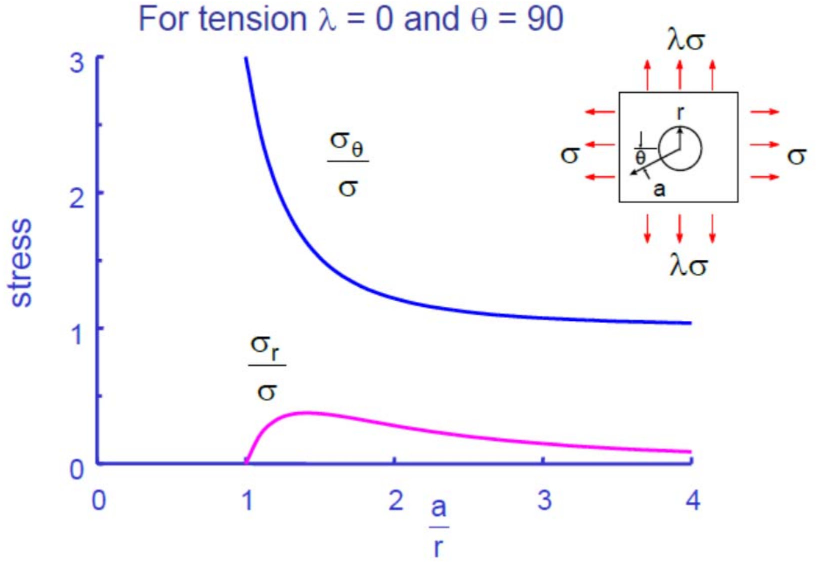
$$\frac{\sigma_\theta}{\sigma}=\frac{1+\lambda}{2}\left(1+\left(\frac{r}{a}\right)^2\right)-\frac{1-\lambda}{2}\left(1+3\left(\frac{r}{a}\right)^4\right)\cos 2\theta$$

$$\frac{\tau_{r\theta}}{\sigma}=-\frac{1-\lambda}{2}\left(1-3\left(\frac{r}{a}\right)^4+2\left(\frac{r}{a}\right)^2\right)\sin 2\theta$$

Independent of size, dependant only on r/a

Stress Concentration Factor Kt

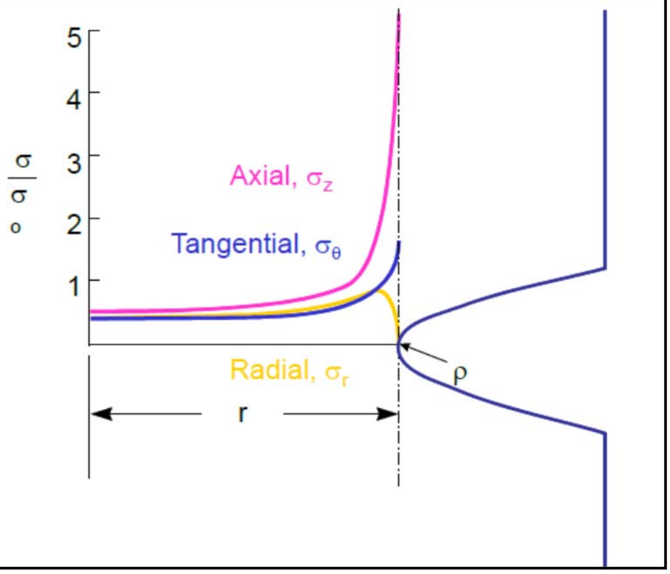
For tension $\lambda = 0$ and $\theta = 90$



Stress Concentration Factor Kt

Notched bar

1. Elevado gradiente de tensões
2. Estado triaxial (biaxial) de tensões ao redor do entahe



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Fatigue Notch Factor Kf

K_f → **Describe the elastic deformation around a notch**

The reduction in fatigue life due to the notch is taken into account by the fatigue notch fator, Kf:

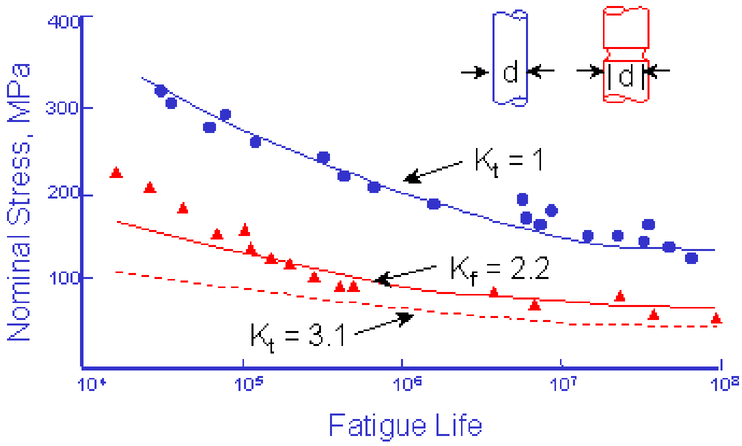
$$K_f = \frac{\sigma_{ar}}{S_{ar}}$$

σ_{ar} → Fatigue life strength for the smooth specimen (R=-1)

S_{ar} → Fatigue life strength for the notched specimen (R=-1)

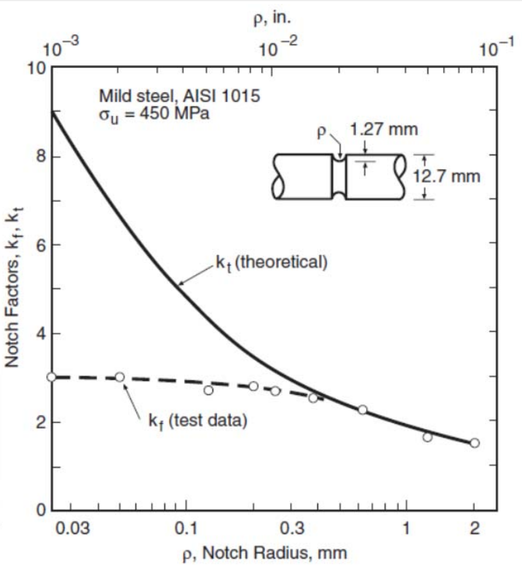
Fatigue Notch Factor Kf

K_t, K_f → **Describe the elastic deformation around a notch**



From MacGregor and Grossman, "Effects of Cyclic Loading on Mechanical Behavior of 24S-T4 and 75S-T6 Aluminum Alloys and SAE 4130 Steel", NACA TN 2812, 1952)

Fatigue Notch Factor Kf

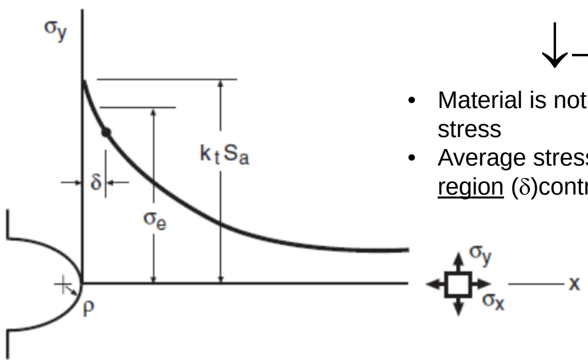


$$\uparrow \rho \rightarrow K_f \approx K_t$$

$$\downarrow \rho \rightarrow K_f < K_t$$

Fatigue Notch Factor Kf

Process Zone Size



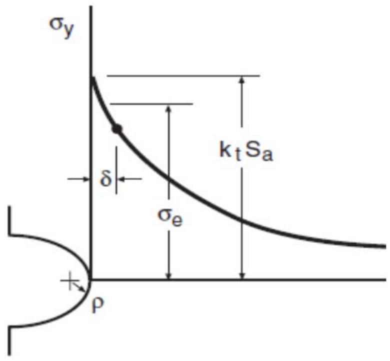
- Stress gradient magnitude is large near sharp notches

$$\downarrow \rightarrow K_f < K_t$$

- Material is not sensitive to the peak stress
- Average stress that acts over small region (δ)controls the fatigue damage.

Fatigue Notch Factor Kf

Weakest-Link Effects



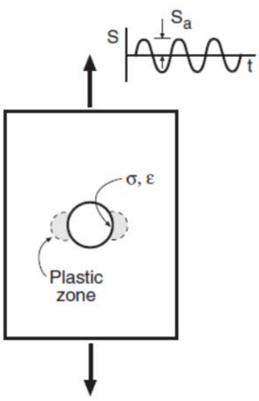
- Stress gradient magnitude is large near sharp notches

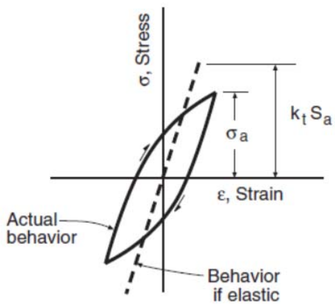
$$\downarrow \rightarrow K_f < K_t$$

- For a sharp notch there is a possibility that no damage initiation site ocurrs in the region where the stress is near the peak value.
- Hence, on average the notched member will be more resistant to fatigue than expected if the comparison is made on the basis of the local notch stress σa=KtSa.

Fatigue Notch Factor Kf

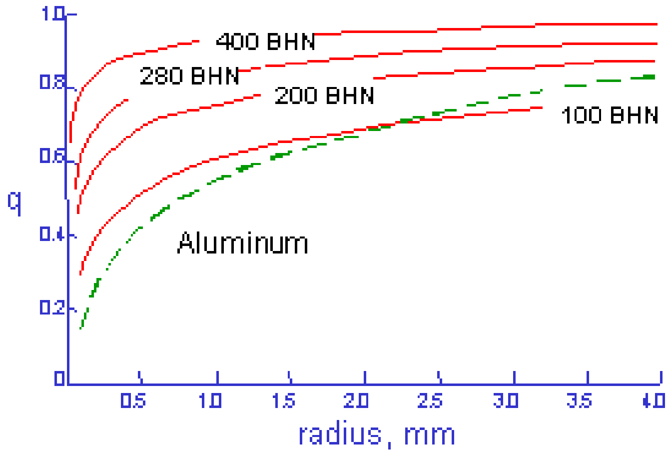
Reversed Yielding $\rightarrow K_f < K_t$





- Valid for short and intermediate fatigue lifes.
- This explanation is insuficiente for long lives.

Notch Sensitivity Factor



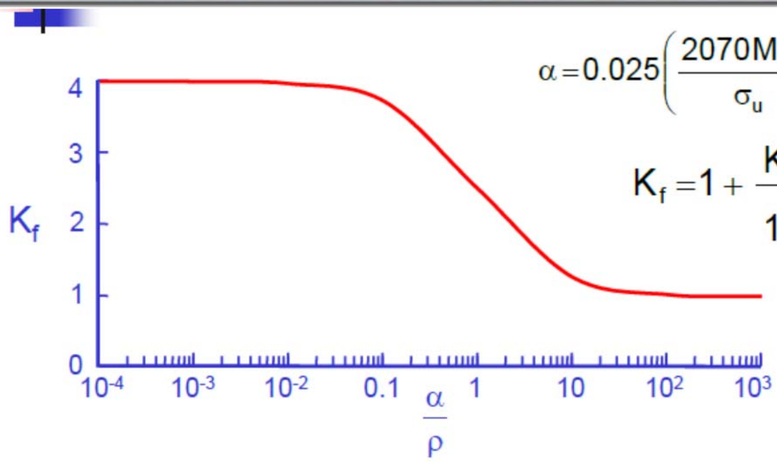
$$q = \frac{K_f - 1}{K_t - 1}$$

$$K_f = q\left(K_t - 1\right) + K_t$$

Material very sensitive to notches q~1

From Peterson "Notch Sensitivity", *Metal Fatigue*, Sines and Waisman, McGraw Hill, 1959)

Notch Sensitivity Factor (Peterson)



$$\alpha = 0.025\left(\frac{2070\text{MPa}}{\sigma_u}\right)^{1.8} \text{mm}$$

$$K_f = 1 + \frac{K_t - 1}{1 + \frac{\alpha}{\rho}}$$

No effect when $\rho \ll \alpha$

Full effect when $\rho \gg \alpha$

Mean Stress+Notch Effects

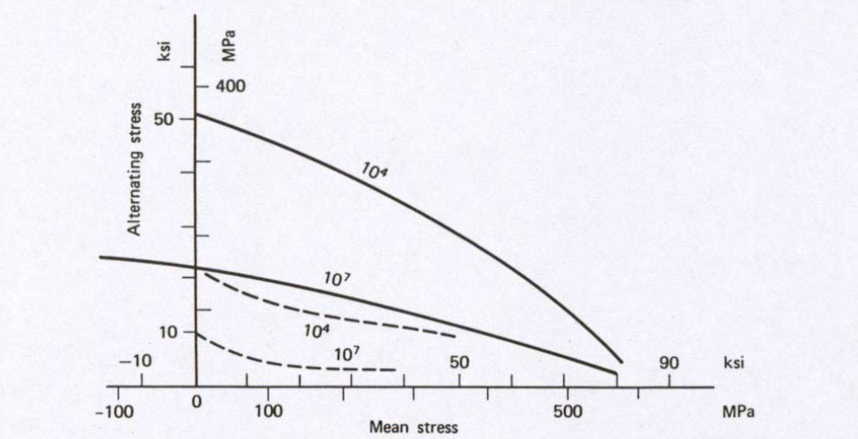
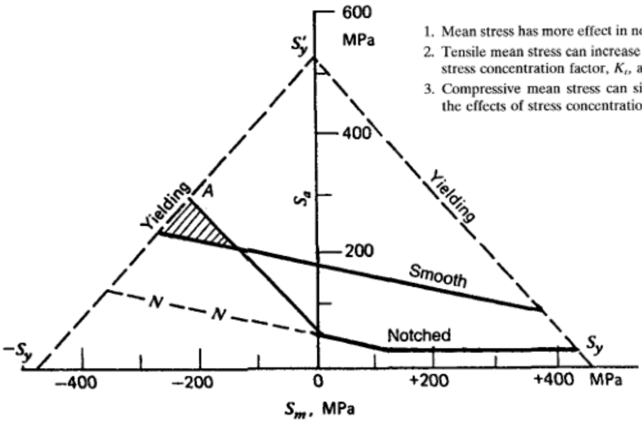


Figure 7.9 Constant life diagram for 7075-T6 wrought aluminum alloy with S_u = 570 MPa (82 ksi) [2]. (——) Unnotched, (---) notched, K_t = 3.4.

Mean Stress+Notch Effects



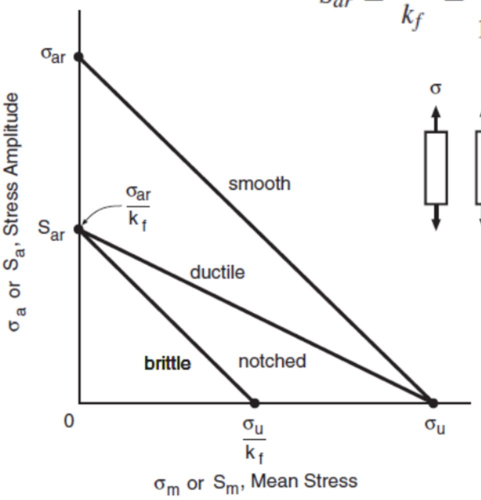
1. Mean stress has more effect in notched parts than in smooth specimens.
2. Tensile mean stress can increase the fatigue notch factor, K_f, above the stress concentration factor, K_t, and can be fatal in fatigue loading.
3. Compressive mean stress can significantly reduce and even eliminate the effects of stress concentrations and save parts.

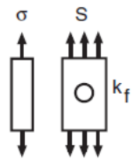
Figure 7.10 Haigh diagram for 7075-T6 aluminum alloy at 1 million cycles, with and without a notch.

Mean Stress+Notch Effects

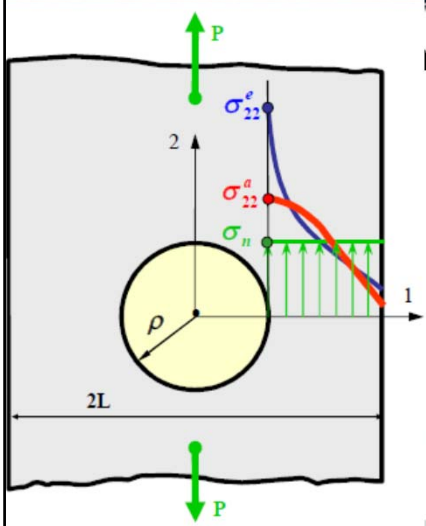
Goodman Equation

$$S_{ar} = \frac{\sigma_{ar}}{k_f} = \frac{S_a}{1 - \frac{S_m}{\sigma_u}}$$ (ductile materials)





Neuber's Rule



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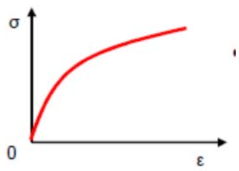
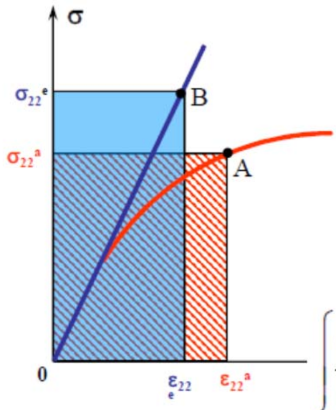
$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}$$



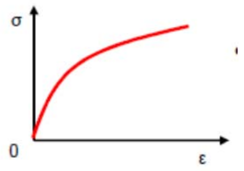
$$\frac{(K_t \sigma_n)^2}{E} = \sigma_{22}^a \varepsilon_{22}^a \quad or \quad \sigma_{22}^e \varepsilon_{22}^e = \sigma_{22}^a \varepsilon_{22}^a$$

$$\varepsilon_{22}^a = \frac{\sigma_{22}^a}{E} + f\left(\sigma_{22}^a\right)$$

Neuber's Rule



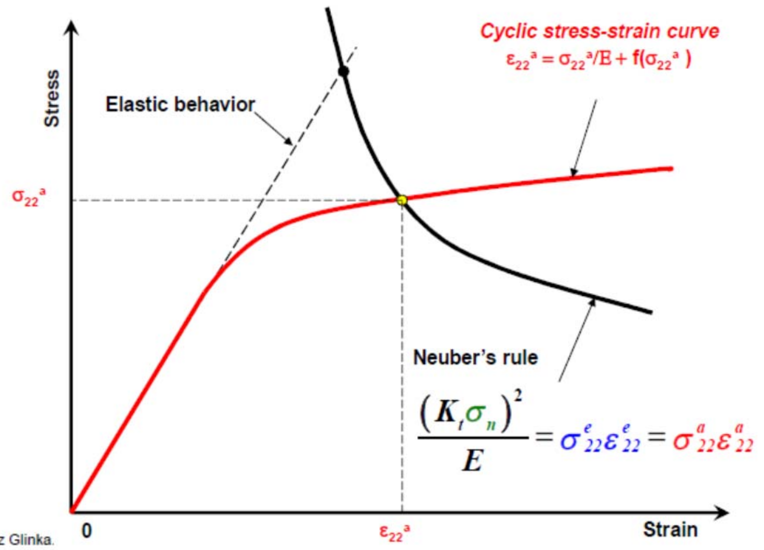
$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}}$$



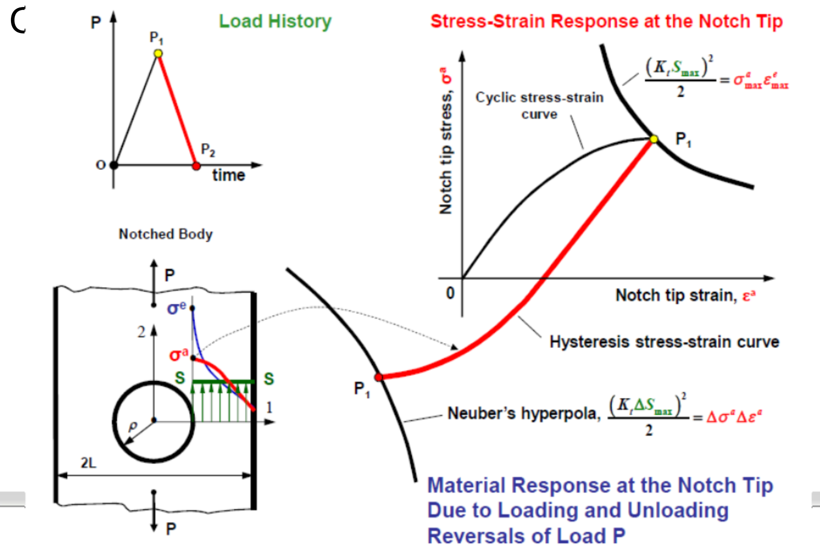
$$\frac{(K_t \sigma_n)^2}{E} = \sigma_{22}^a \varepsilon_{22}^a \quad or \quad \sigma_{22}^e \varepsilon_{22}^e = \sigma_{22}^a \varepsilon_{22}^a$$

$$\varepsilon_{22}^a = \frac{\sigma_{22}^a}{E} + f\left(\sigma_{22}^a\right)$$

Neuber's rule Solution



Stress-strain response at notch tip



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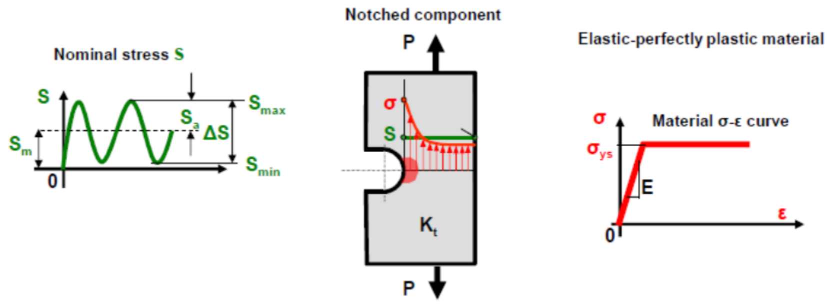

Stress-strain response at the notch tip

Local mean stress at notch tip