Fadiga de Materiais Estruturais: Fundamentos e Aplicações

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AGENDA

1. *Motivação (Motivation)*
2. *Modos de Falha (Failures Modes)*
3. *Falhas Estruturais por Fadiga (Fatigue Failures)*
4. *Metodologias para Avaliação da Vida à Fadiga (Fatigue Methodologies)*
   - *Carregamento Constante (Constant Amplitude Loading)*
     - *S-N*
     - *ε-N*

     } Initiation
     - *da/dN-ΔK (Propagation)*

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4. *Metodologias para Avaliação da Vida à Fadiga* *(Fatigue Methodologies)*
   - *Carregamento Constante (Constant Amplitude)*
     - *S-N*
     - *ε-N*
     - *da/dN-ΔK*
   - *Efeitos de Entalhes (Notches)*
   - *Carregamento Variável (Variable Amplitude Loading)*
     - *Contagem de Ciclos (Cycle Counting)*
     - *Acúmulo de Dano (Damage Summing Methods)*
     - *Efeitos da Sequência (Sequence Effects)*
   - *Juntas Soldadas (Welded Joints)*
   - *Fadiga Multiaxial (Multiaxial Fatigue)*

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O Curso

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Motivação

- ***Fatores de Segurança Possuem Base Empírica***
- ***Cálculo de estruturas é feito com base na experiência previa***

Danos e Defeitos Comprometem a Integridade Estrutural!

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Motivação

- Integridade Estrutural

Considera-se que uma estrutura está integra quando pode suportar os carregamentos de operação com uma probabilidade mínima de falha durante o tempo de vida útil.

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Motivação

- Integridade Estrutural

Considera-se que uma estrutura está integra quando pode suportar os carregamentos de operação com uma probabilidade mínima de falha durante o tempo de vida útil.

- Uma falha impede que uma estrutura ou componente cumpra su função estrutural.
- As falhas podem ser catastróficas ou não

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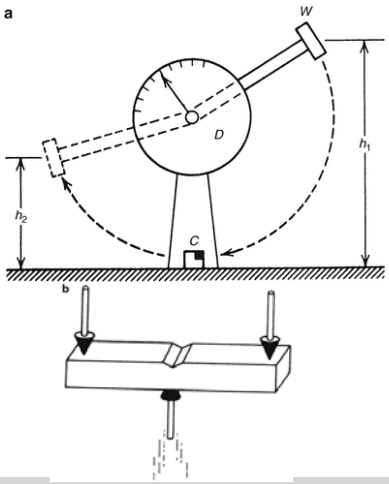
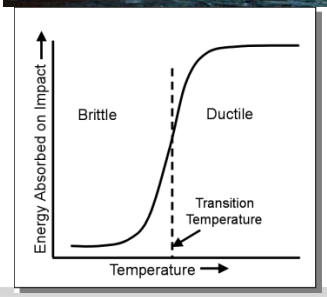
Navio *Titanic*

Temperatura de Transição Dúctil-Frágil





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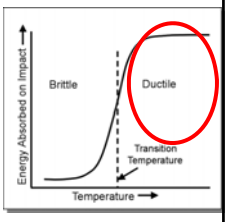
Navio *Titanic*

	C	*Mn*	*P*	*S*	*Si*	*Mn:S*
Aço Titanic	*0.21*	*0.47*	*0.045*	*0.069*	*0.017*	*6.8:1*
Aço ASTM A36	*0.20*	*0.55*	*0.012*	*0.037*	*0.007*	*14.9:1*

	σ_{ys} (MPa)	σ_t (MPa)	*Elong. (%)*
Aço Titanic	193	417	29
Aço ASTM A36	235	460	22

	T_{tr} (°C) @ 20 J
Aço Titanic (Longitudinal)	32
Aço Titanic (Transversal)	56
Aço ASTM A36	−27



Temperatura de Transição Elevada ⟷

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     } Initation
     - *da/dN-ΔK (Propagation)*

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Modos de Falha

- Deformação excessiva
- Escoamento / Colapso Plástico
- Fadiga
- Fratura
- Flambagem
- Corrosão
- Creep

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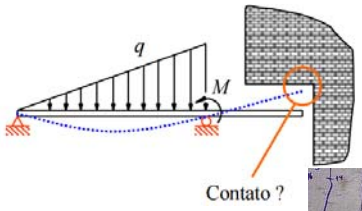
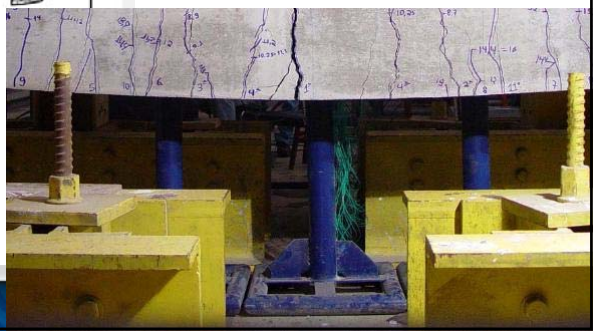
Deformação



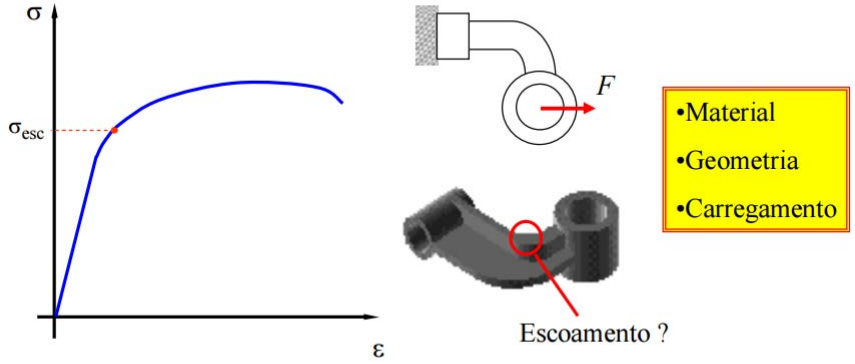
Normas: limitam deslocamentos máximos.



Deformação Excessiva

Escoamento

- Escoamento à temperatura ambiente



- Material
- Geometria
- Carregamento

Projeta-se para que as tensões nos pontos críticos não ultrapassem σ_{esc}.

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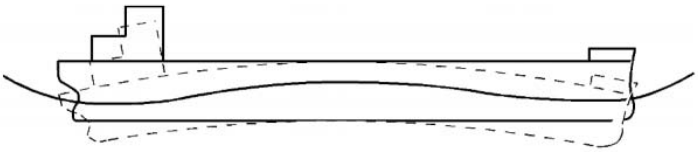
Fadiga

Hogging (Alquebramento)



Sagging (Tosamento)

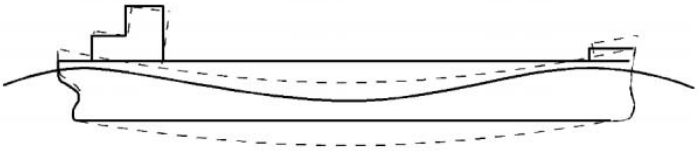


Fig. 2.2.1 Vertical bending due to waves

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Fadiga

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Fadiga

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Fratura Frágil

ano 2000

Figure 1. Forward section of the FLARE [1].

Falha acontece mesmo sob tensões menores que o limite de escoamento

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Flambagem "Viga-Navio"

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Fratura

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Oscilação auto-excitada(Ressonância)

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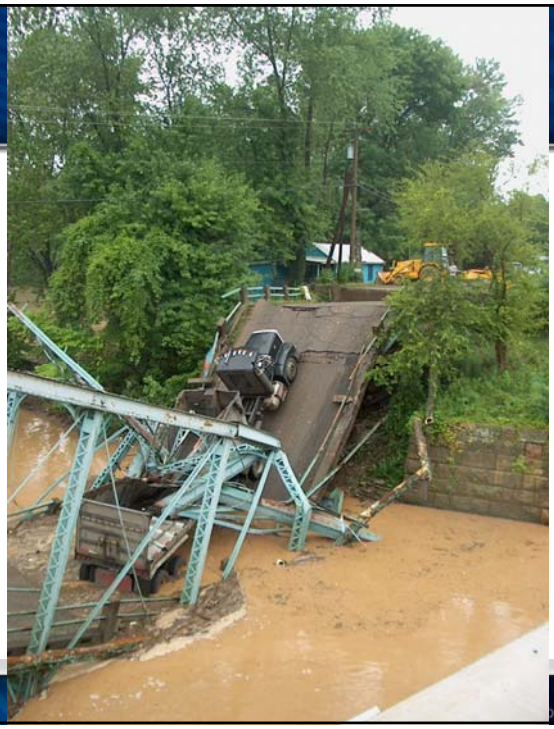
Modo de Falha Combinado

1+1= ?

1+1 <1
1+1>1



Incertezas nas Cargas

Somewhere out there

Cargas Ocasionais (Impacto)

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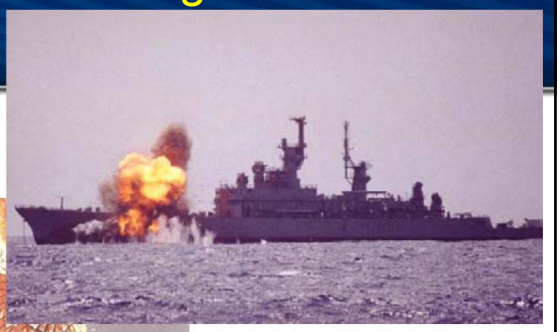
Incertezas nas Cargas



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Incertezas nas Cargas

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     - *ε-N* } Initation
     - *da/dN-ΔK (Propagation)*

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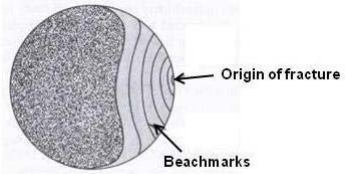
Falhas Fadiga

- A FADIGA representa mais de 50% de todas as falhas mecânicas reportadas na literatura.
- *Efeito cumulativo de Danos (Microestruturais) devido à ação cíclica de Esforços.*



Fatigue Fracture with Beachmarks

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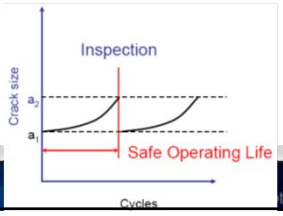
Falhas Catastróficas

- Custos devido à problemas da fadiga/fratura nos EUA $119 Bilhões 4% PIB (1980)

Estimativas da vida à fadiga muito conservadoras implica em altos custos de construção/manutenção/inspeção.



Plataforma semi-submersível Alexander Kielland

•1980 nas águas do Mar do Norte

- Fadiga da junta soldada circunferencial no contraventamento D-6

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Fadiga em Plataforma

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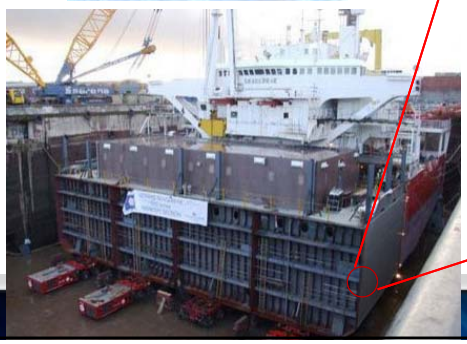
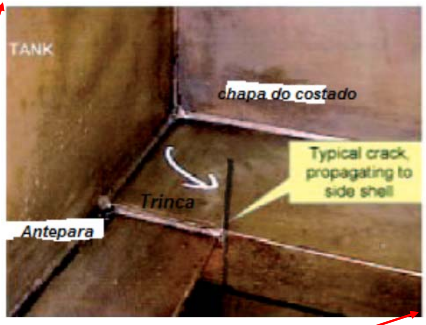
Fadiga em Navios





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Falhas Catastróficas por Fadiga

- CUSTOS?
- RESPONSABILIDADES ? Civil , Penal !
- IMPACTO NA NATUREZA?

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FADIGA

- O que é?
- Quando e porquê acontece?
- Como é avaliada a resistência à Fadiga dado um carregamento cíclico?
- Como é caracterizada a resistência à Fadiga de um material?

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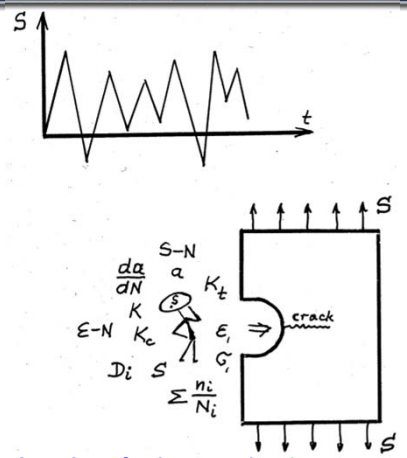
FADIGA – O que é?



N_i = ?

N_p = ?

N_T = ?

Fadiga mecânica é o fenômeno de dano progressivo de materiais sujeitos a esforços cíclicos (ΔP, ΔM, ΔT).

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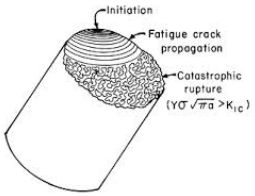
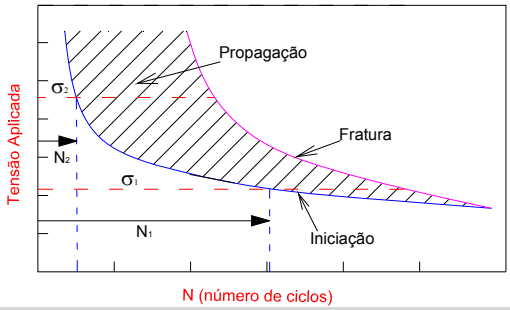
Objetivos do Estudo da Fadiga

- Estimativas acuradas do tempo de iniciação de uma trinca (N_I)
- As correspondentes taxas de propagação de trinca (da/dN)





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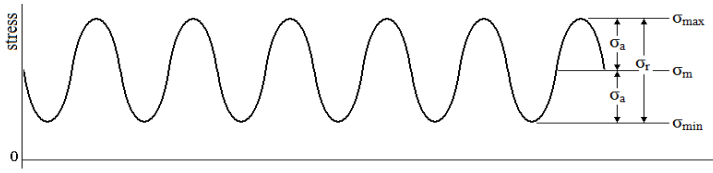
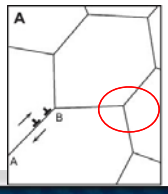
Quando Aconteça Fadiga

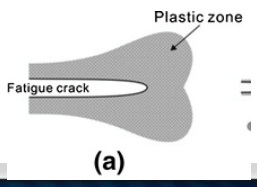
✓ Esforcos Alternados



$$\sigma_{max} < \sigma_{yielding}$$

✓ Deformação Plástica Localizada
(Processo Irreversível)





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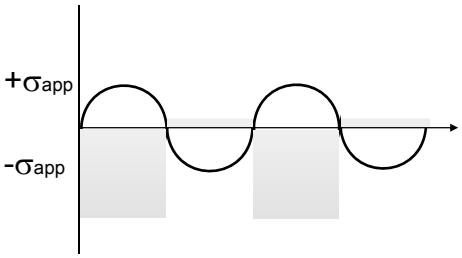
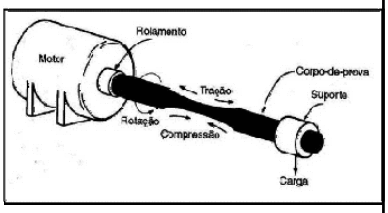
DEFINIÇÃO FADIGA

- **Fadiga mecânica** é o fenômeno de dano progressivo de materiais sujeitos a esforços cíclicos (ΔP, ΔM, ΔT).





Fadiga acontece mesmo que → $\sigma_{applied} < \sigma_{yielding}$

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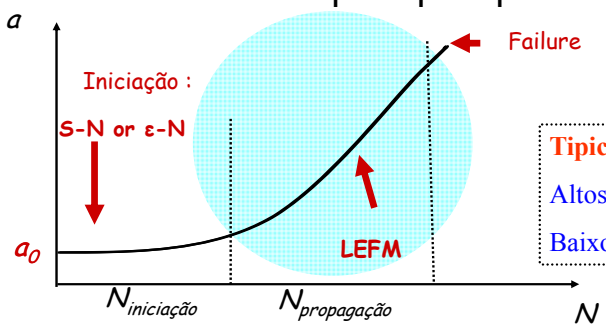
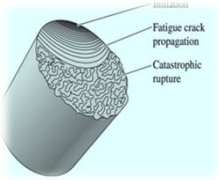
Avaliação da Vida à Fadiga

Vida à fadiga de um componente:

$$N_T = N_I + N_P$$





Tipicamente:

Altos esforços → $N_P \sim N_T$

Baixos esforços → $N_I \sim N_T$

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Iniciação de Trincas

- Duas metodologias
  - ❑ S x N (Alto ciclo)
  - ❑ ε x N (Baixo ciclo)

- Caracterizada por:
  - ❑ Deformação plástica altamente localizada
  - ❑ Fenômeno de superfície
  - ❑ Processo estocástico

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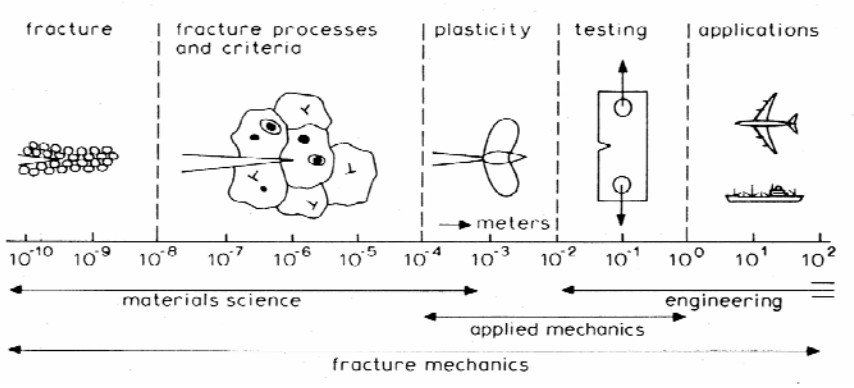
The Broad Field of Fracture Mechanics/Fatigue



(from Ewalds & Wanhil, ref.3)

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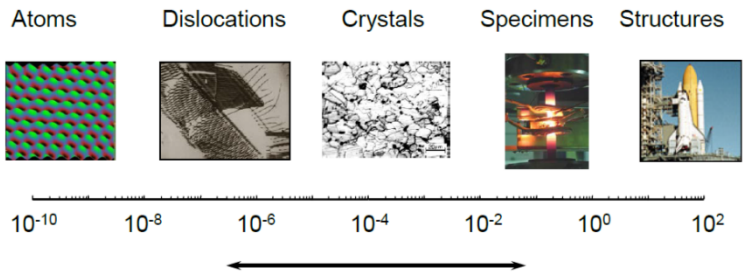

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}

Understand the physics on this scale

Model the physics on this scale

Use the models on this scale

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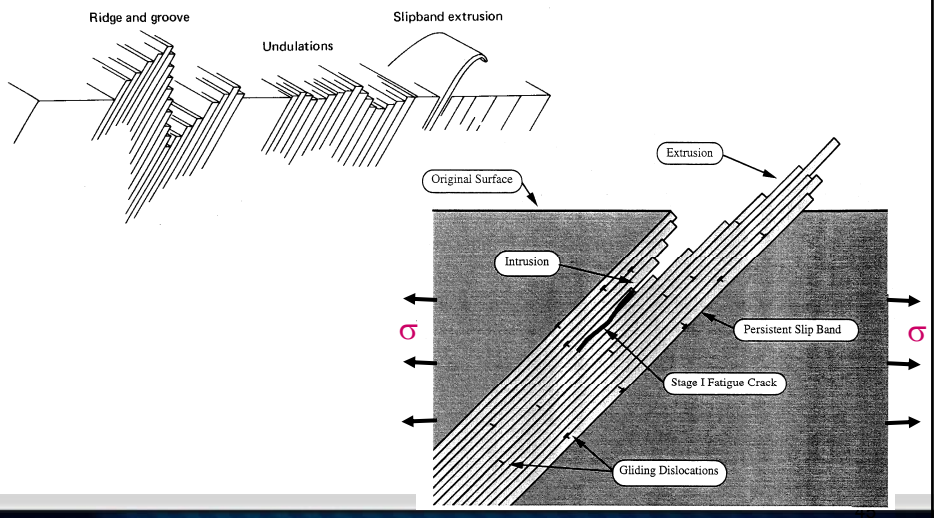
Intrusions and Extrusions:
The Early Stages of Fatigue Crack Formation



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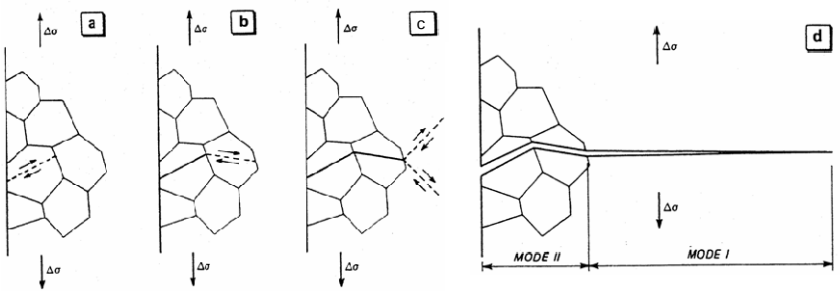
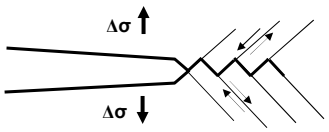
Schematic of Fatigue Crack Initiation Subsequent Growth Corresponding and Transition From Mode II to Mode I





Locally, the crack grows in shear;
macroscopically it grows in tension.

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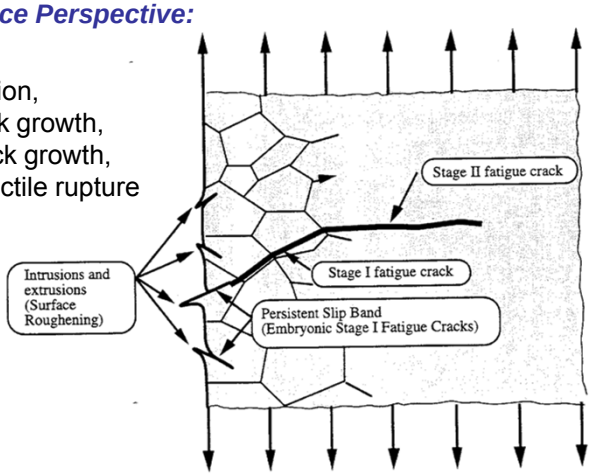
The Process of Fatigue

The Materials Science Perspective:

- Cyclic slip,
- Fatigue crack initiation,
- Stage I fatigue crack growth,
- Stage II fatigue crack growth,
- Brittle fracture or ductile rupture



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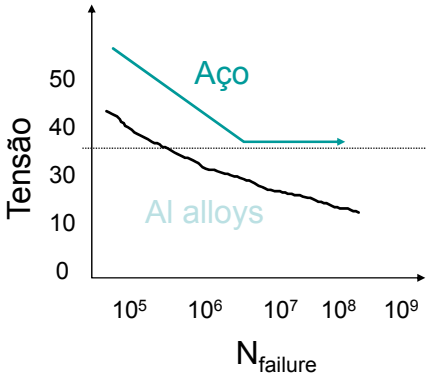
Curvas S-N

- Fadiga de alto ciclo
- Tensão aplicada $\Delta\sigma$
  $\sigma_{applied} < \sim {}^{2}/_{3}\ \sigma_{yield}$
- Tensões são nominalmente elásticas.
- Localmente o material deforma plasticamente



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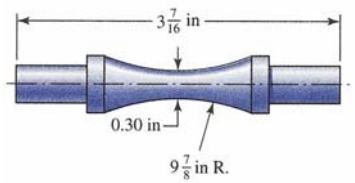
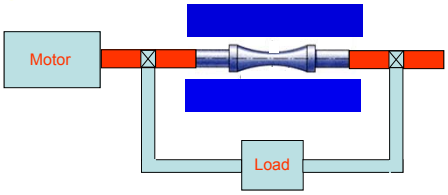
Avaliação Convencional das Propriedades S-N



Typical testing apparatus, pure bending

Superfície Polida

Momento Fletor Constante



Rotating beam machine – applies fully reverse bending stress

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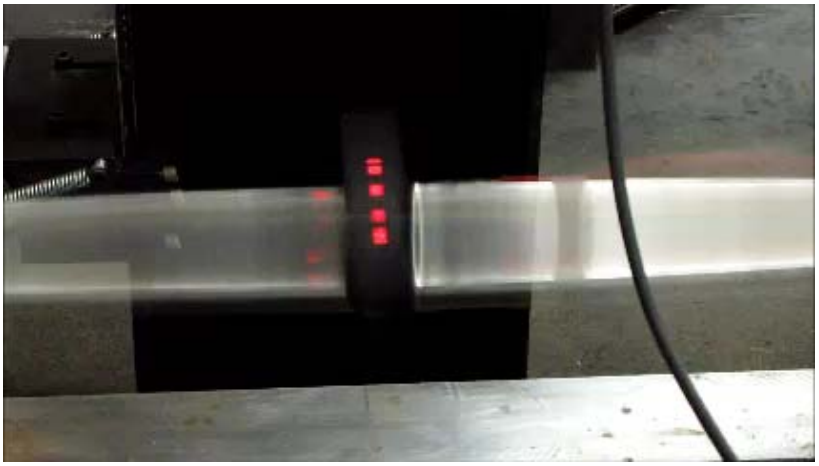
Avaliação Convencional das Propriedades S-N



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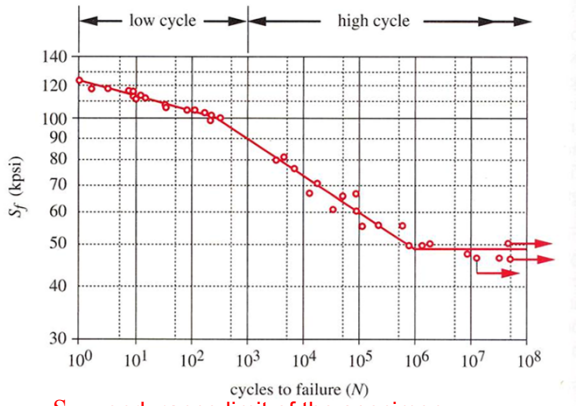
Typical S-N curve



S_e = endurance limit of the specimen

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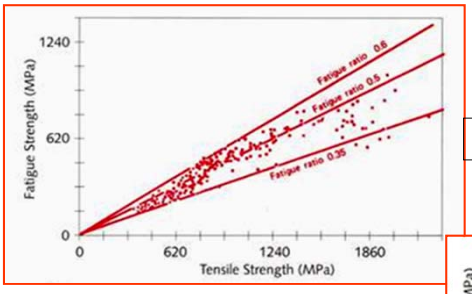
Relationship Between Endurance Limit and Ultimate Strength

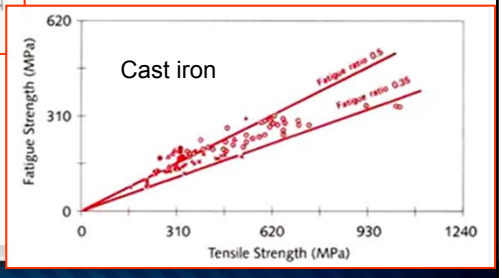


Steel

$S_e' = \begin{cases} 0.5S_{ut} & S_{ut} \le 200 \text{ ksi } (1400 \text{ MPa}) \\ 100 \text{ ksi} & S_{ut} > 200 \text{ ksi} \\ 700 \text{ MPa} & S_{ut} > 1400 \text{ MPa} \end{cases}$

Cast iron

$S_e' = \begin{cases} 0.4S_{ut} & S_{ut} < 60 \text{ ksi } (400 \text{ MPa}) \\ 24 \text{ ksi} & S_{ut} \ge 60 \text{ ksi} \\ 160 \text{ MPa} & S_{ut} < 400 \text{ MPa} \end{cases}$



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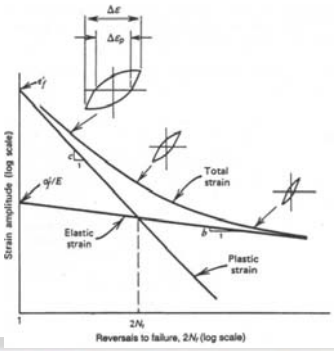
Curvas ε-N

Fadiga de baixo ciclo

- Carregamento aplicado produz deformações plásticas => $\Delta\varepsilon_{total} > \varepsilon_{escoamento}$
  - $\Delta\varepsilon_{total} = \Delta\varepsilon_{elásticas} + \Delta\varepsilon_{plasticas}$

- Entalhes
- Descontinuidades



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Curvas ε-N

- Fadiga de baixo ciclo

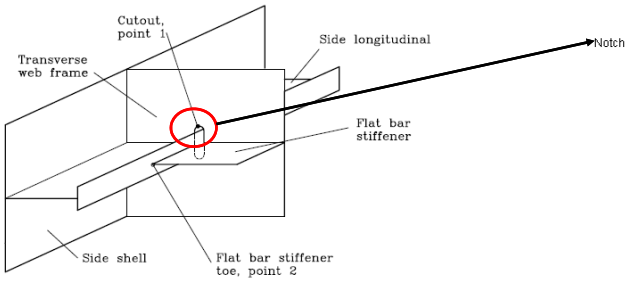
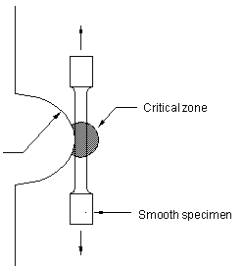


Figure 3.11: *Potential crack locations for the conventional design.*



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Low Cycle Fatigue

- Overloads
- Plastic Deformation
- Strain Life Analysis

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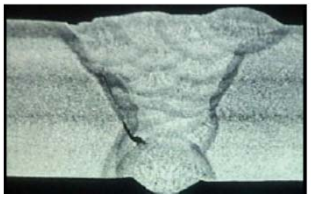
Propagação de Trinca

Contudo...para estruturas soldadas: $N_T \sim N_P$



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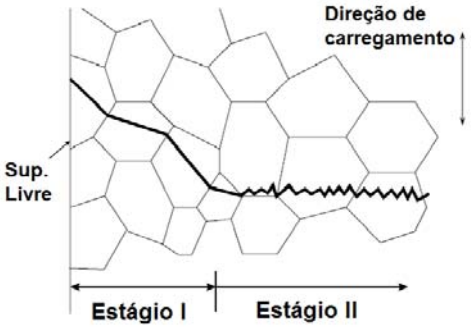
Propagação de Trinca



Estágio I de Propagação

Estágio II de Propagação

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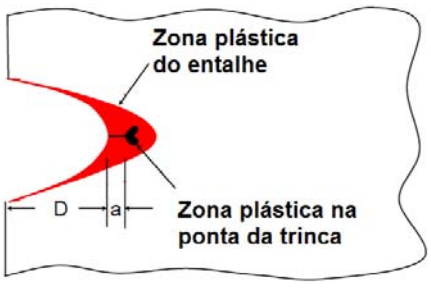
Propagação de Trinca

- Estágio I



•Tamanho (a) ~ 2-4 grãos (D)

•Fortemente Influenciada pela microestrutura

•Planos de escorregamento

•Nível de tensão

•Plasticidade na ponta da trinca

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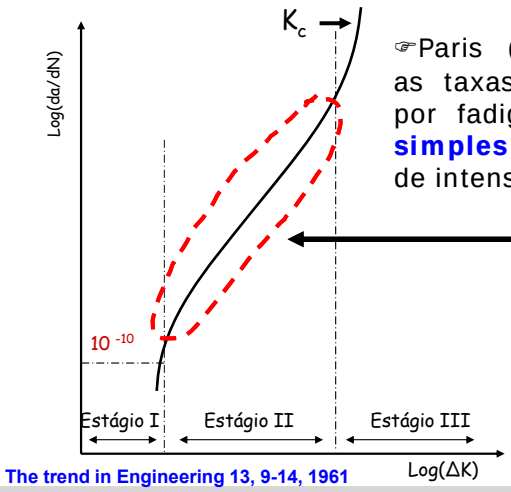
Propagação de Trincas (Estágio II)



The trend in Engineering 13, 9-14, 1961

☞Paris (1961) propus caracterizar as taxas de crescimento de trinca por fadiga - em forma **elegante** e **simples** - por meio do fator elástico de intensidade de tensões *K*:

$$\frac{da}{dN} = C(\Delta K)^m$$

$$\Delta K = \xi \Delta \varepsilon_{ij}$$

$$\xi = \left(\frac{E\sqrt{2\pi r}}{f_{ij}(\theta)} \right)$$

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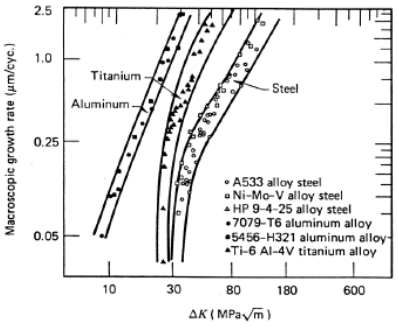
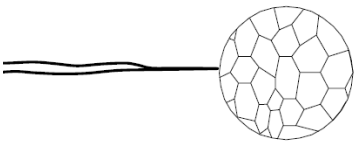
Propagação de Trincas (Estágio II)

- Pouca influencia da resistência do material



- Zona plástica >> microestrutura do material (pouca influência da microestrutura)



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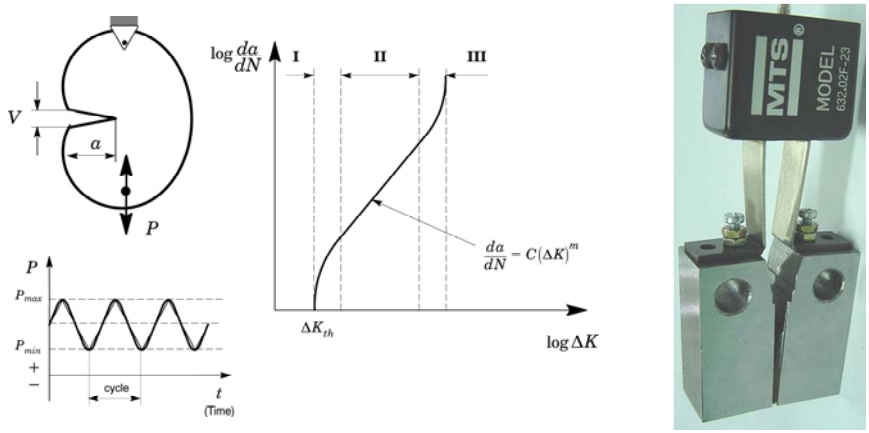
Avaliação Convencional das Propriedades da/dN



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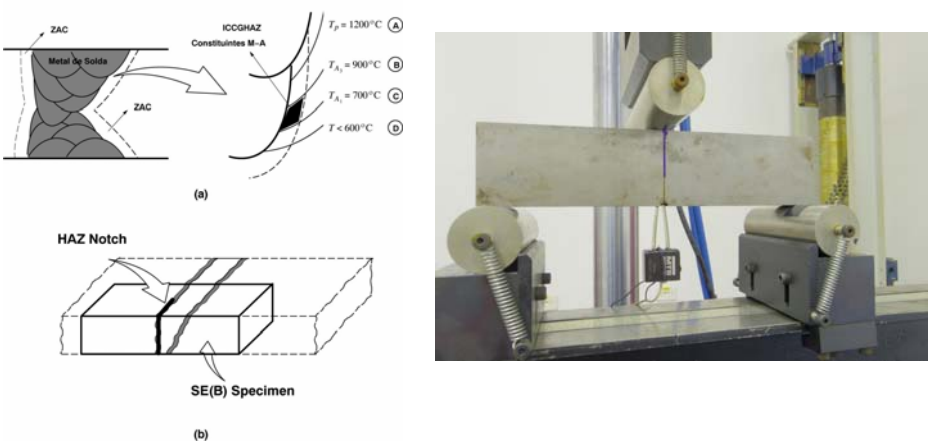
Avaliação Experimental de Fadiga



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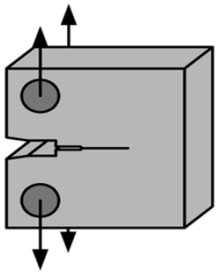
Correlação Laboratório *vs.* Estrutura



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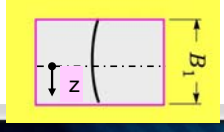
Análise Numérica de Fadiga

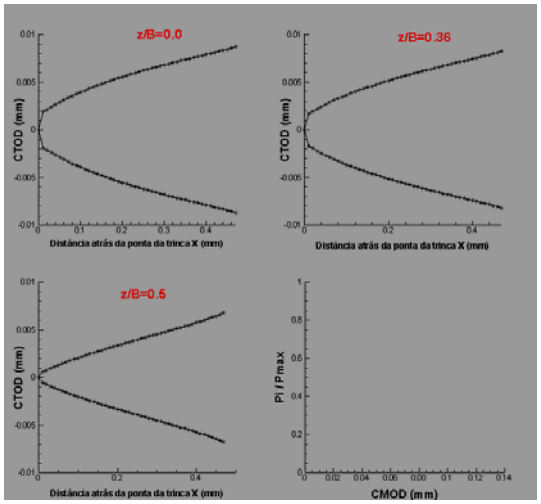
Força Motriz Efetiva

$$\Delta K_{eff} = f(P_{max}, P_o, a_j, t, W)$$

$$\frac{da}{dN} = C\left(\Delta K_{eff}\right)^m$$

Fechamento Parcial da trinca





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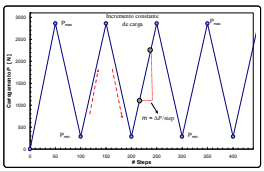
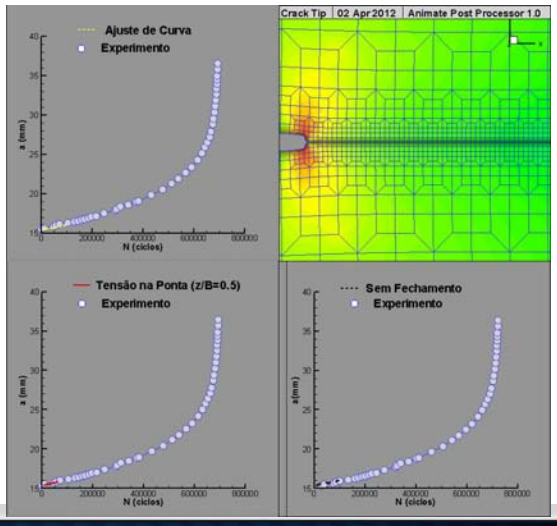
Análise Numérica de Fadiga

Propagação de defeitos

$$N = \int_{a_i}^{a_f} \frac{da}{C\left(\Delta K_{eff}\right)^m}$$

$$\Delta K_{eff} = f(P_{max}, P_o, a_j, t, W)$$





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AGENDA

4. *Metodologias para Avaliação da Vida à Fadiga* (*Fatigue Methodologies*)
   - *Carregamento Constante (Constant Amplitude)*
     - *S-N*
     - *ε-N*
     - *da/dN-ΔK*
   - *Efeitos de Entalhes (Notches)*
   - *Carregamento Variável (Variable Amplitude Loading)*
     - *Contagem de Ciclos (Cycle Counting)*
     - *Acúmulo de Dano (Damage Summing Methods)*
     - *Efeitos da Sequência (Sequence Effects)*
   - *Juntas Soldadas (Welded Joints)*
   - *Fadiga Multiaxial (Multiaxial Fatigue)*

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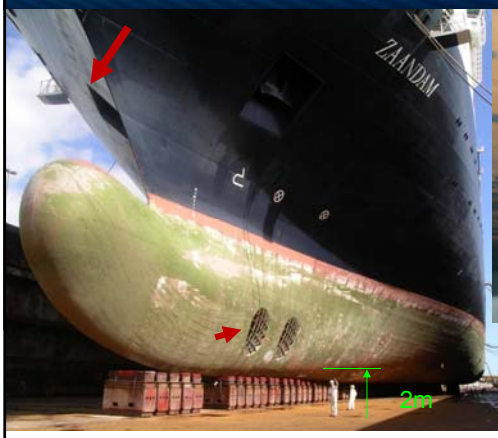
Opening (Notch)



- Notches can not be avoided!

Notches = stress raisers

Entalhes (Notches)

- Notches can not be avoided!

Notches = stress raisers

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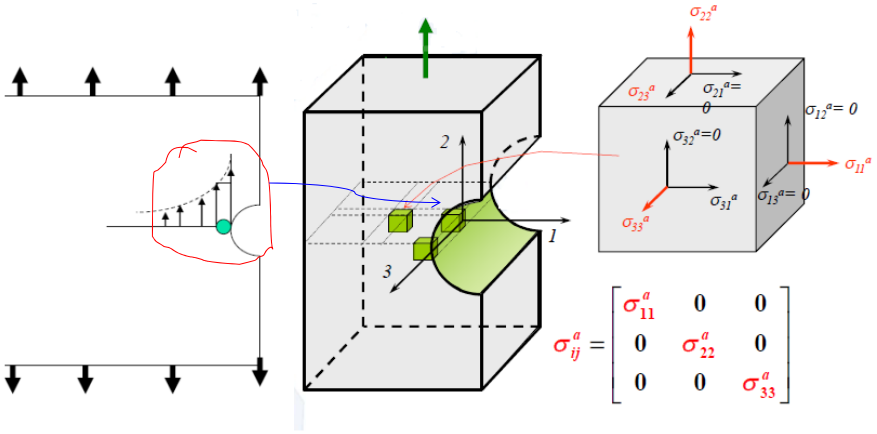
NOTCH EFFECTS



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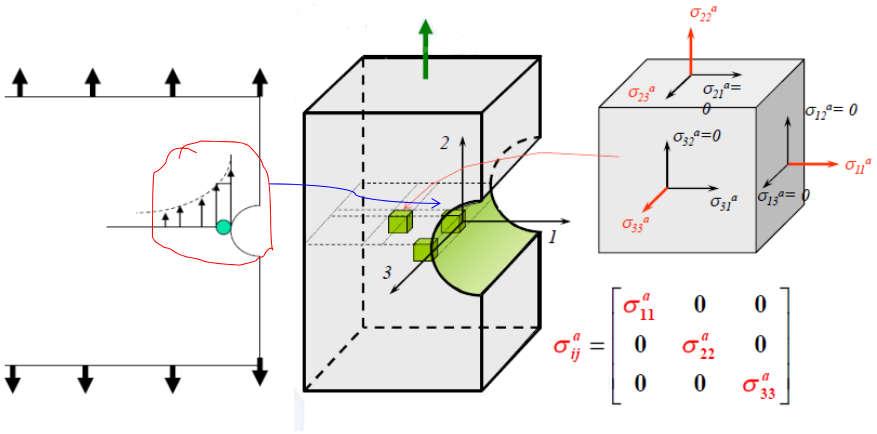
NOTCH EFFECTS



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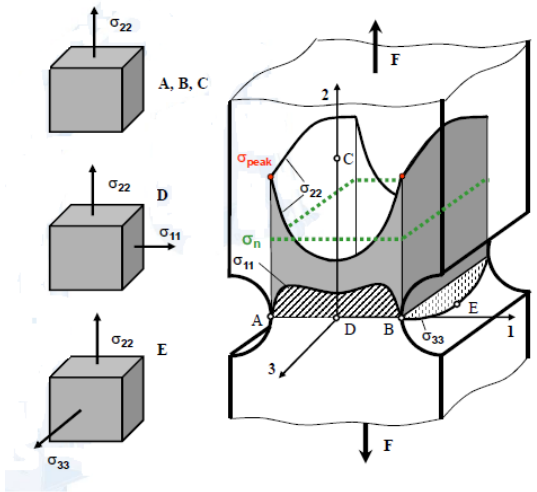
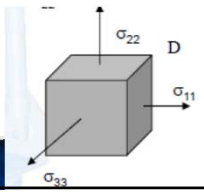
NOTCH EFFECTS



$$\sigma_n = \frac{F}{A_{net}}$$

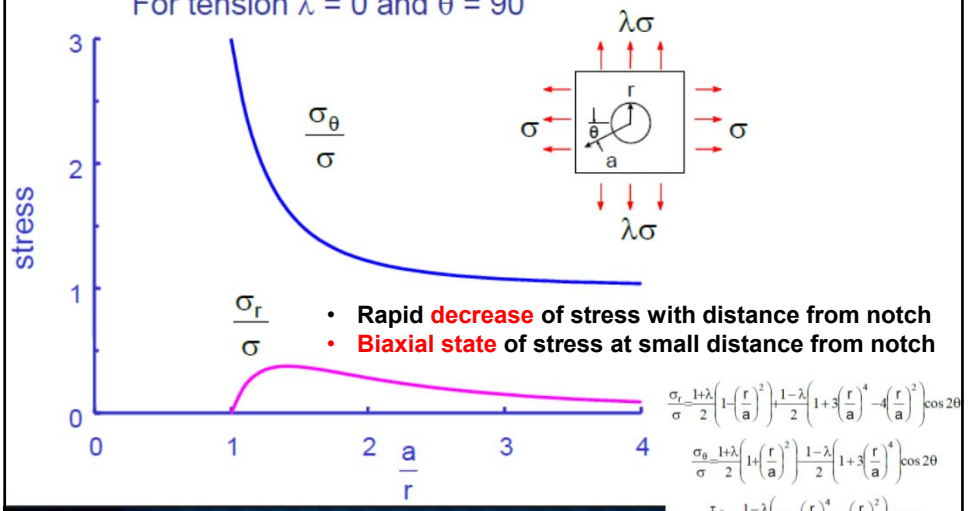
and

$$\sigma_{peak} = K_t \sigma_n$$



NOTCH EFFECTS

For tension λ = 0 and θ = 90



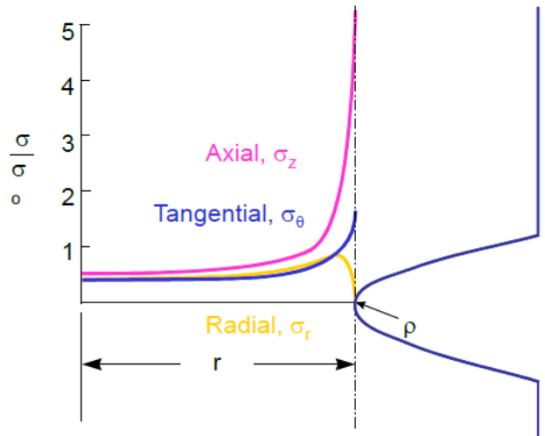
- Rapid **decrease** of stress with distance from notch
- **Biaxial state** of stress at small distance from notch

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

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

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

NOTCH EFFECTS



- Rapid decrease of stress with distance from notch
- Triaxial state of stress at small distance from notch

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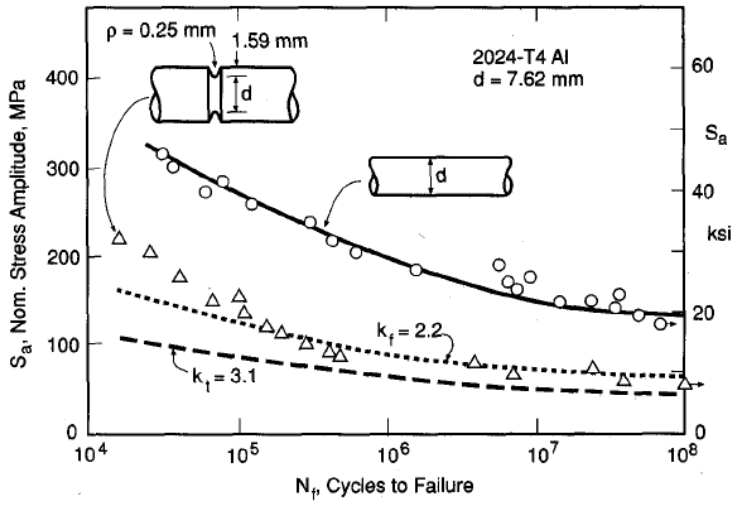
NOTCH EFFECTS



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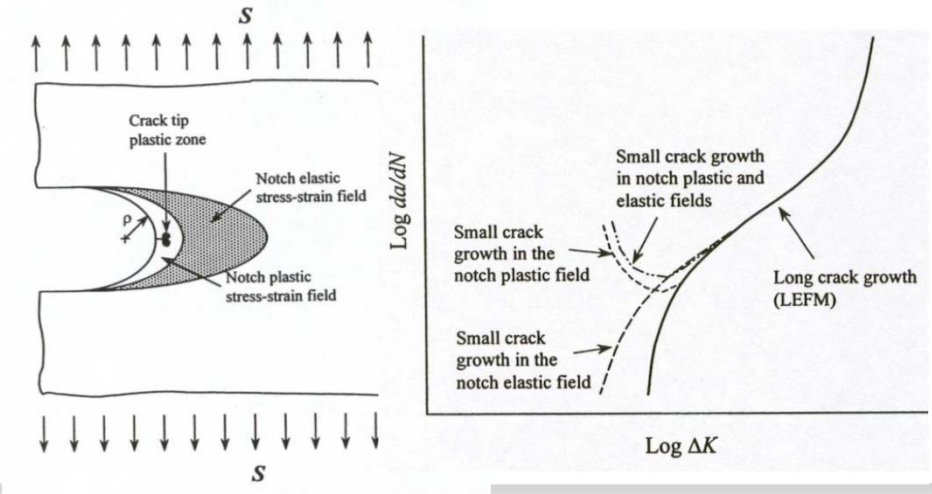
CRACK GROWTH AT NOTCHES



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AGENDA

4. *Metodologias para Avaliação da Vida à Fadiga (Fatigue Methodologies)*
   - *Carregamento Constante (Constant Amplitude)*
     - *S-N*
     - *e-N*
     - *da/dN-DK*
   - *Efeitos de Entalhes (Notches)*
   - *Carregamento Variável (Variable Amplitude Loading)*
     - *Contagem de Ciclos (Cycle Counting)*
     - *Acúmulo de Dano (Damage Summing Methods)*
     - *Efeitos da Sequência (Sequence Effects)*
   - *Juntas Soldadas (Welded Joints)*
   - *Fadiga Multiaxial (Multiaxial Fatigue)*

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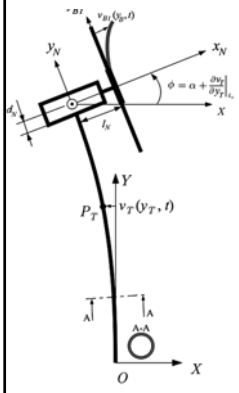
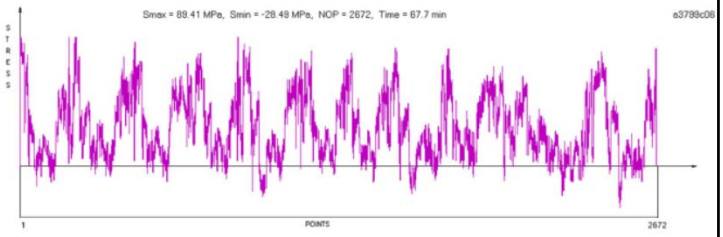
Variable Loading

Wind Turbine Blade





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Stress Fluctuations

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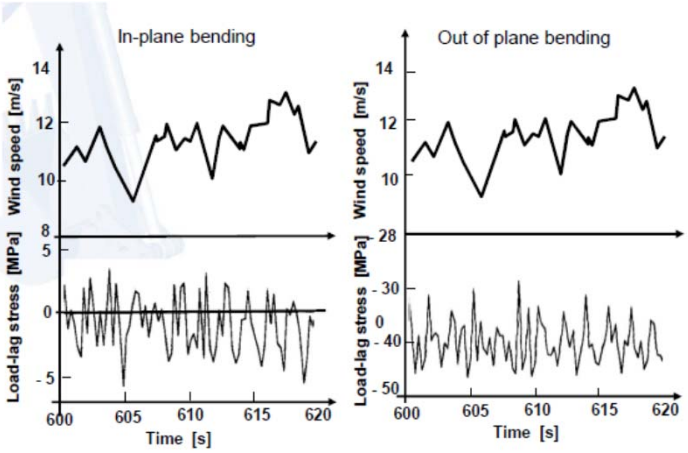
Variable Loading

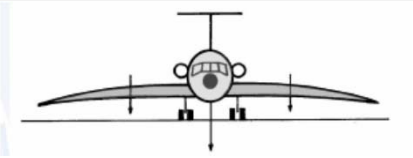
Wind Turbine Blade

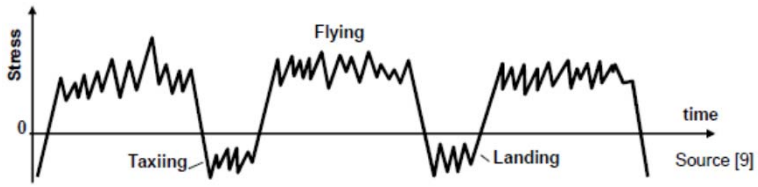


Note! One reversal of the wind speed results in several stress reversals

Variable Loading

Aircraft wing skin





Stress Fluctuations

79

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Variable Loading

Ship

Stress Fluctuations

80

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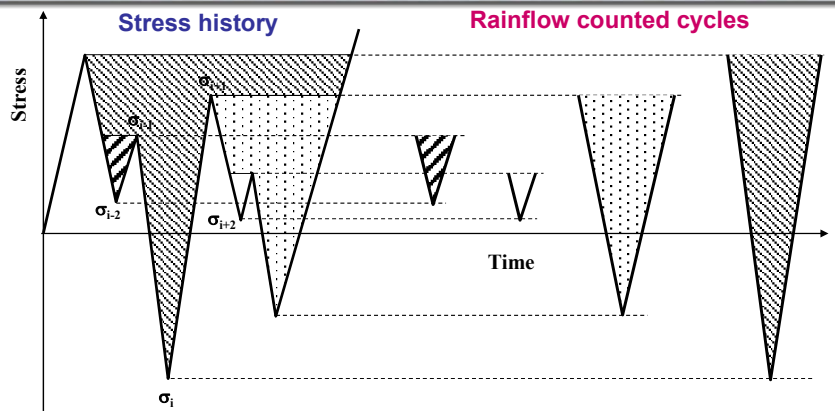
Rainflow Counted Cycles



A *rainflow counted cycle* is identified when any two adjacent reversals in thee stress history satisfy the following relation:

$$ABS\left|\sigma_{i-1}-\sigma_i\right| < ABS\left|\sigma_i-\sigma_{i+1}\right|$$

81

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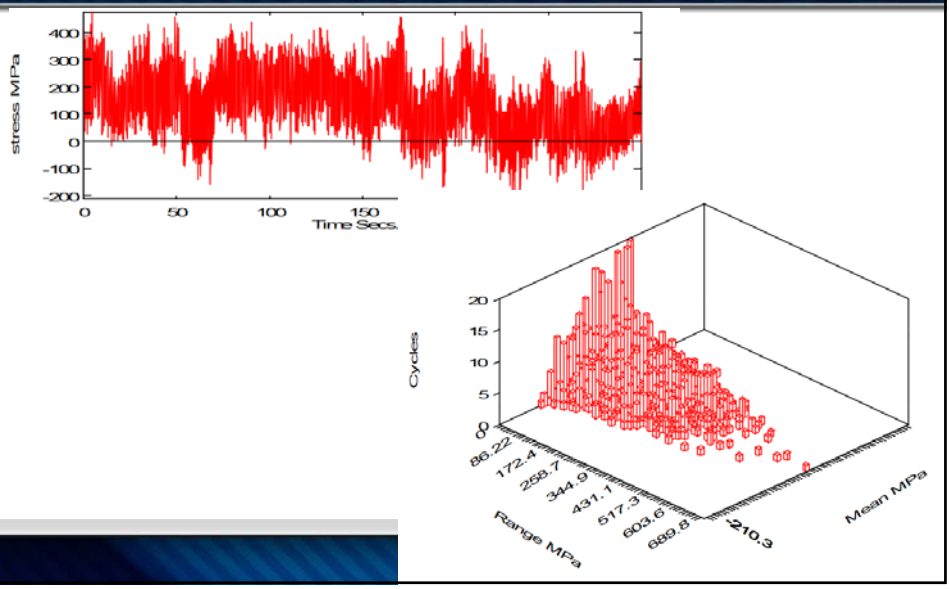
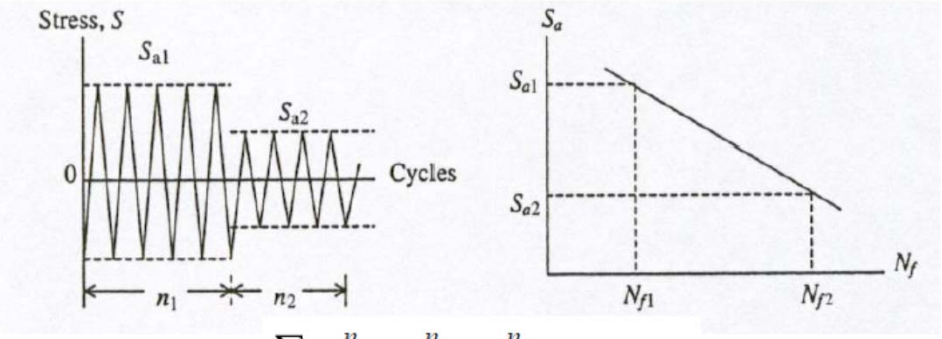
Range-mean histogram by rainflow



DAMAGE EVOLUTION

Palmgren-Miner Linear Damage Rule



$$\sum \frac{n_i}{N_{fi}} = \frac{n_1}{N_{fi}} + \frac{n_2}{N_{f2}} + \ldots\ldots = 1$$

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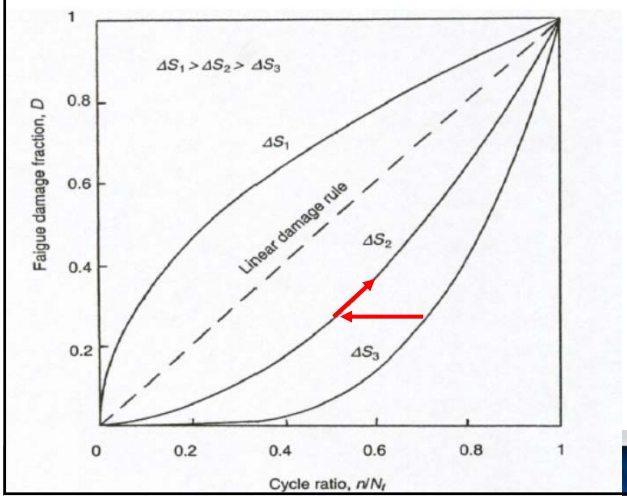
DAMAGE EVOLUTION

Nonlinear Damage Rule



$$D = \sum_i \left(\frac{n}{N} \right)^{\alpha}$$

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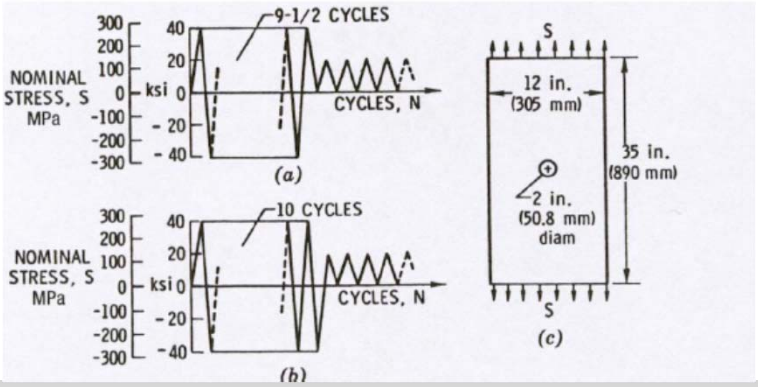
DAMAGE EVOLUTION

Nonlinear Damage Rule (Initiation)

$$D = \sum_i \left(\frac{n}{N} \right)^{\alpha}$$



Cycles

460×10^3

63×10^3

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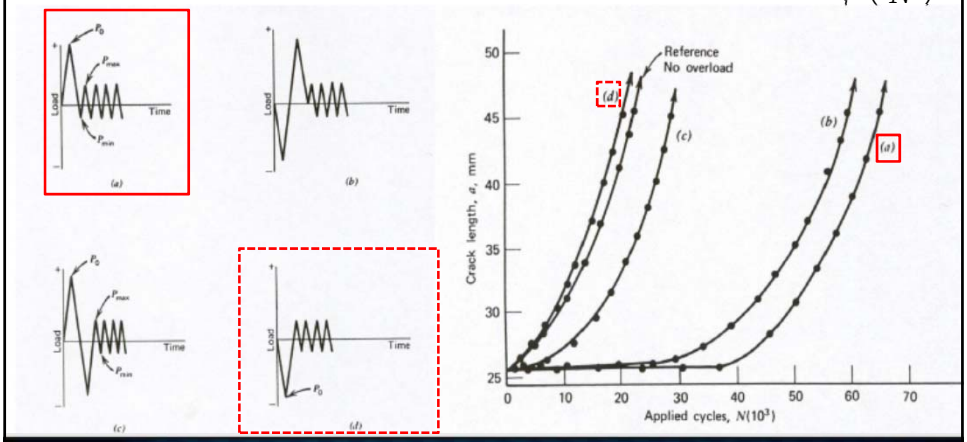
DAMAGE EVOLUTION

Nonlinear Damage Rule (Propagation)

$$D = \sum_i \left(\frac{n}{N} \right)^{\alpha}$$



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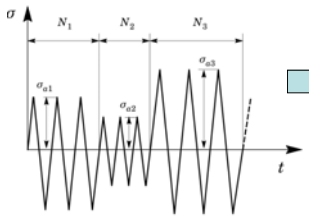
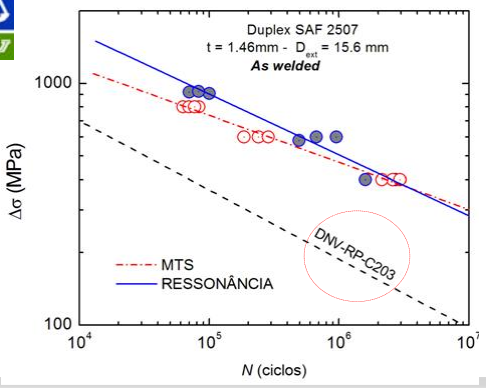
Rainflow + Damage

– Análise dos procedimentos correntes de avaliação usando normas de construção naval e de estruturas oceânicas.

$$D_{mp} = \sum_{i}^{m} \frac{n_i}{N_{fi}}$$





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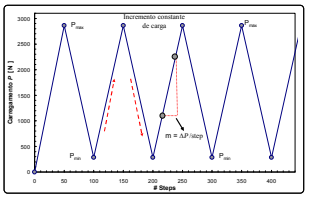
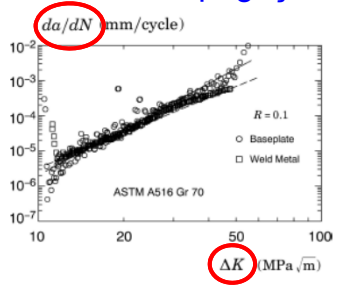
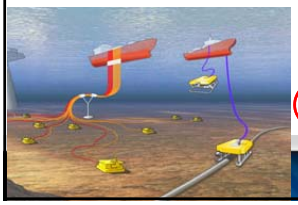
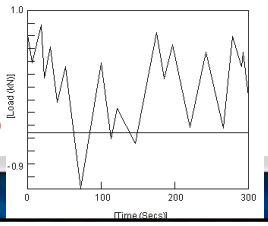
Rainflow + Damage

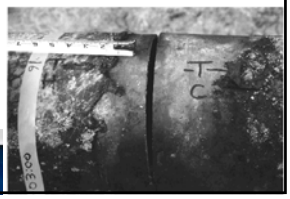
- **Forças Motrizes Cíclicas** (efetivas) e Taxas de Propagação











AGENDA

4. *Metodologias para Avaliação da Vida à Fadiga (Fatigue Methodologies)*
   - *Carregamento Constante (Constant Amplitude)*
     - *S-N*
     - *ε-N*
     - *da/dN-ΔK*
   - *Efeitos de Entalhes (Notches)*
   - *Carregamento Variável (Variable Amplitude Loading)*
     - *Contagem de Ciclos (Cycle Counting)*
     - *Acúmulo de Dano (Damage Summing Methods)*
     - *Efeitos da Sequência (Sequence Effects)*
   - *Juntas Soldadas (Welded Joints)*
   - *Fadiga Multiaxial (Multiaxial Fatigue)*

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Fatigue of Welds

Weld Problems

NYSDOT

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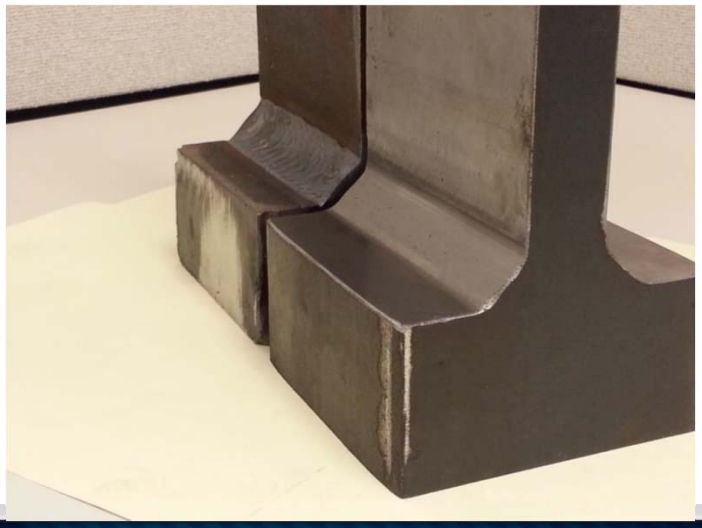
Fatigue of Welds



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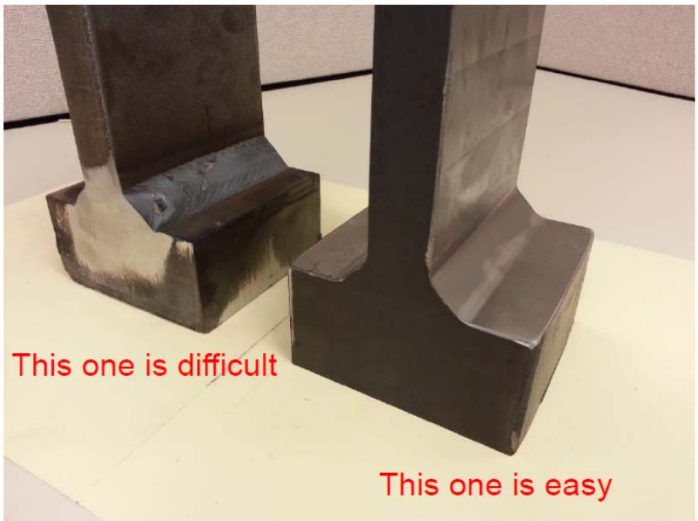
Fatigue of Welds



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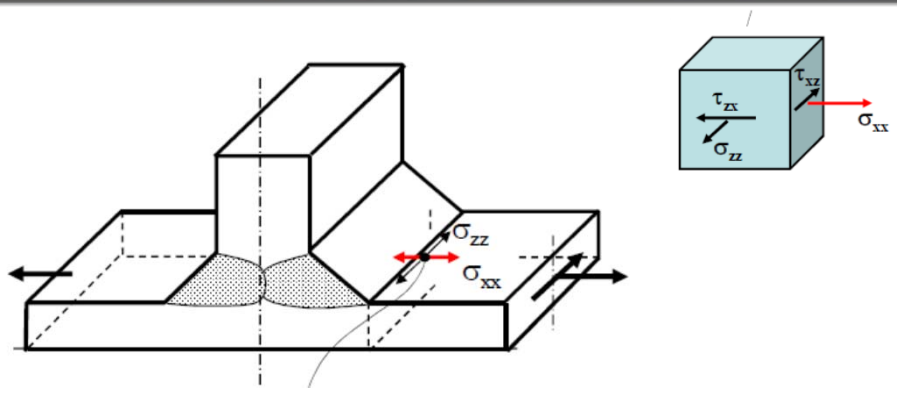
Stress State

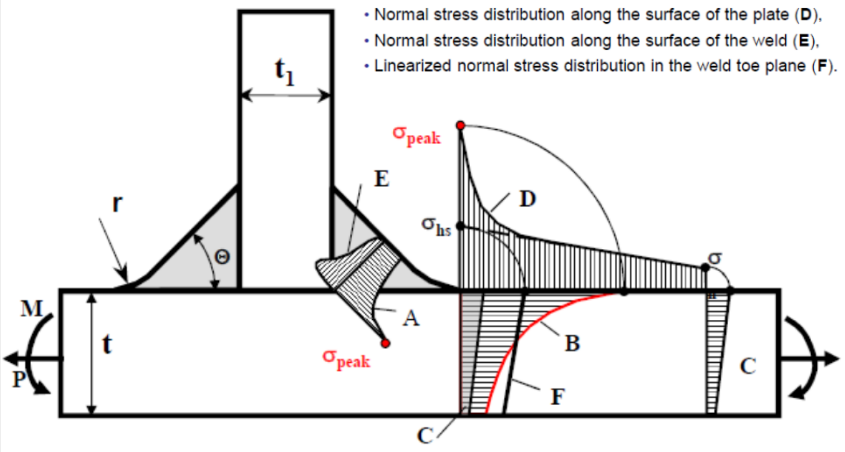


- Multiaxial State of Stress at the weld toe
- Due to notch σ_{xx} is the largest componente and responsible for fatigue damage

2008 Grzegorz Glinka

Stress Distribution in Welds

- Normal stress distribution in the weld throat plane (**A**),
- Through the thickness normal stress distribution in the weld toe plane (**B**),
- Through the thickness normal stress distribution away from the weld (**C**),
- Normal stress distribution along the surface of the plate (**D**),
- Normal stress distribution along the surface of the weld (**E**),
- Linearized normal stress distribution in the weld toe plane (**F**).



Various stress distributions in a T-butt weldment with transverse fillet welds;

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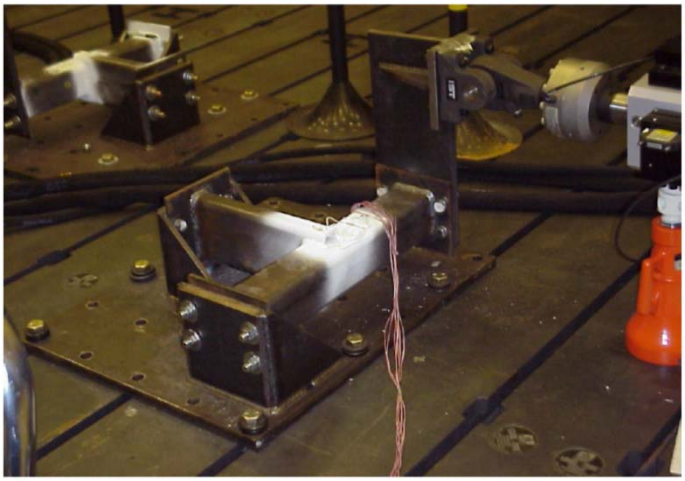
Design Fatigue Curves

Tubular Welded Joint under Torsion and Bending



Courtesy of John Deere Co.

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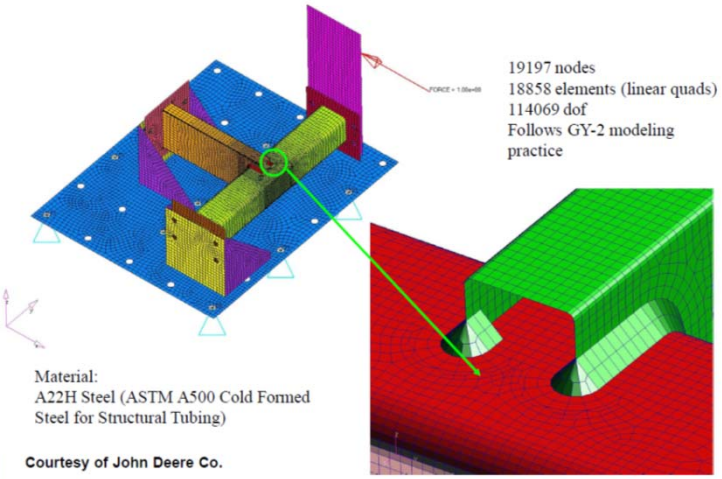
Design Fatigue Curves

Shell Element Model Details



19197 nodes
18858 elements (linear quads)
114069 dof
Follows GY-2 modeling practice

Material:
A22H Steel (ASTM A500 Cold Formed Steel for Structural Tubing)

Courtesy of John Deere Co.

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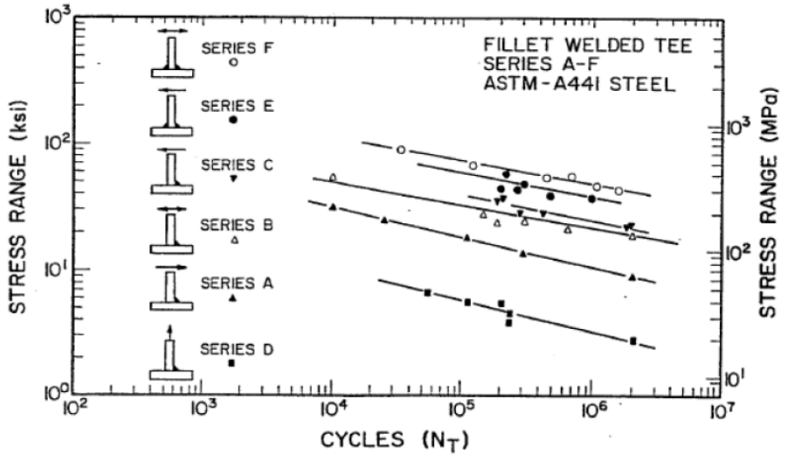
Design Curves



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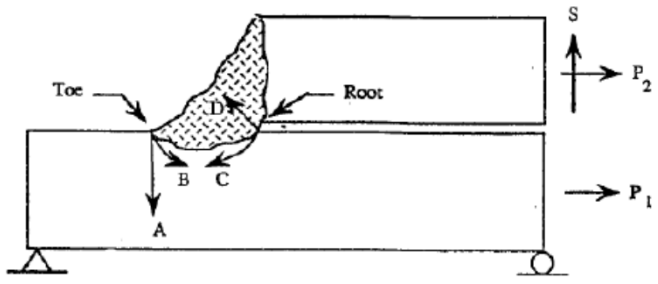
Failure Locations



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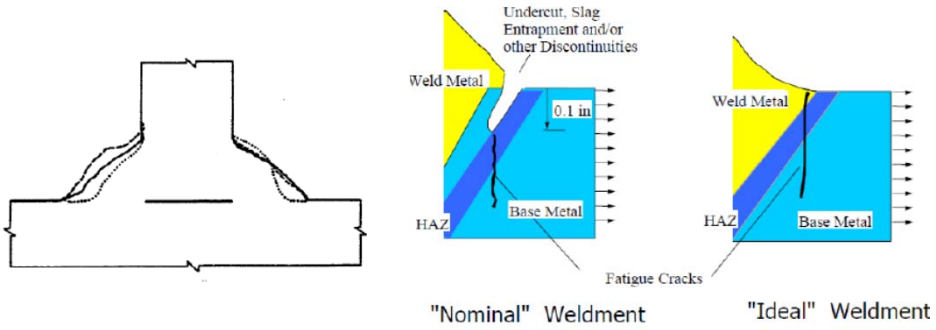
Fatigue of Welds

Weld Shape?

Weld Quality?



"Nominal" Weldment

"Ideal" Weldment

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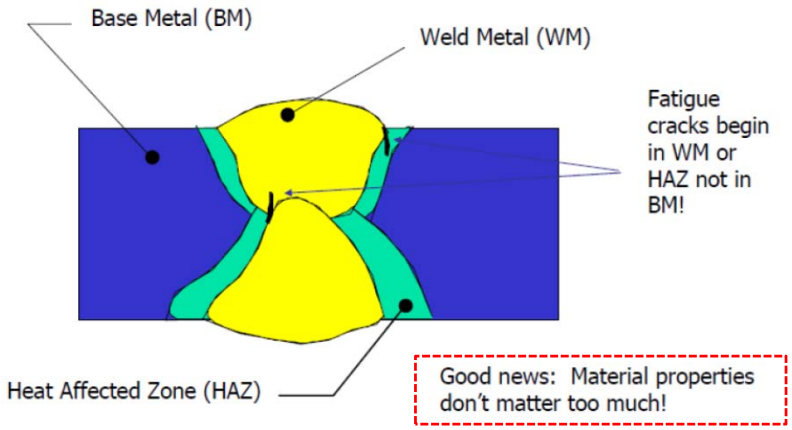
Material Properties



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Fatigue of Welds

The variables influencing weldment fatigue life can be thought of as being only two:

- the magnitude of the notch root stresses.
- the properties of the notch root material.

In this sense, the applied stresses, the degree of bending, the welding residual stresses, the fabrication residual stresses, the applied mean stresses, the weldment geometry, the notch root weld defects, and the weldment size all influence the magnitude of the notch root stresses.

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Fatigue of Welds

The fatigue behavior of a weldment is controlled by the local (notch root, hot-spot) stress-strain history.

For structural steel weldments: material properties are of minor importance except (as we shall see) to the degree that they determine and limit the value of the residual stresses.

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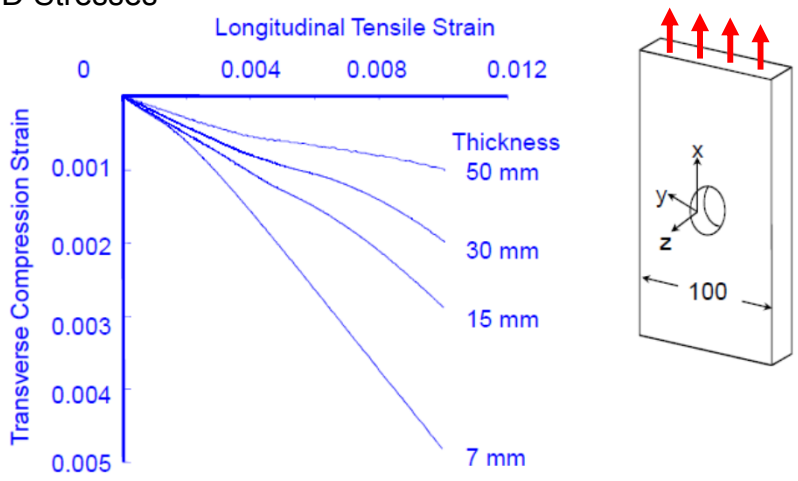
Multiaxial Fatigue

3D Stresses



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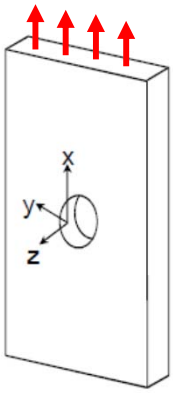
Multiaxial Fatigue

3D Stresses



t	ε_x	ε_z	σ_x	σ_z
7	0.01	-0.005	63.5	0
15	0.01	-0.003	70.6	14.1
30	0.01	-0.002	73.0	21.8
50	0.01	-0.001	75.1	29.3

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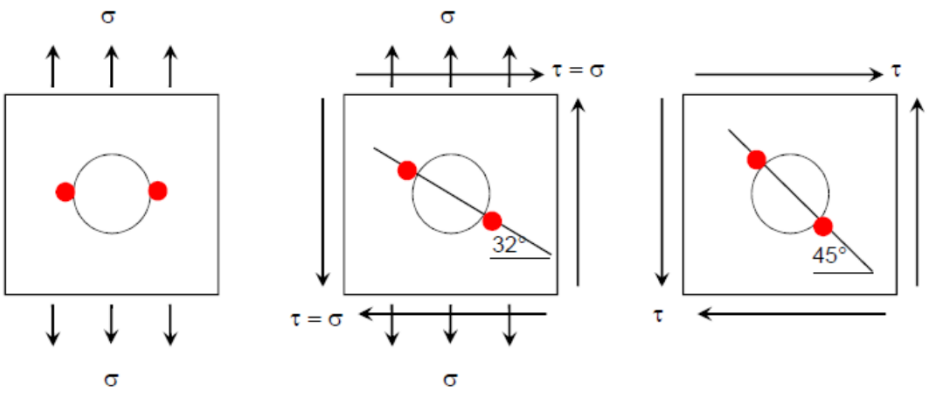
Multiaxial Fatigue

Maximum Stress (Plane)

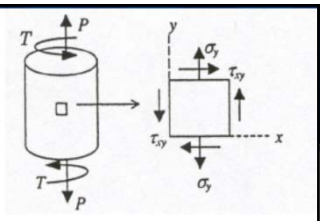


$K_t = 3$
$\sigma_1 = \sigma$

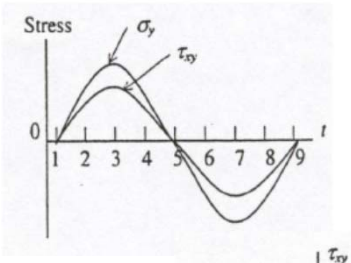
$K_t = 3.41$
$\sigma_1 = 1.72\sigma$

$K_t = 4$
$\sigma_1 = \tau$

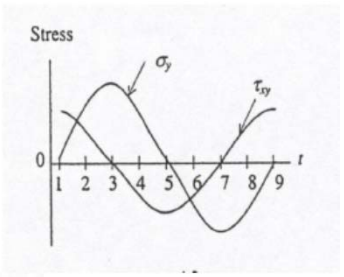
Multiaxial Fatigue

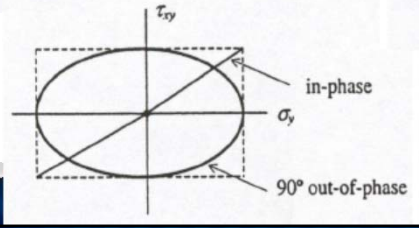


Proportional Loading



Nonproportional Loading





Out-of-phase

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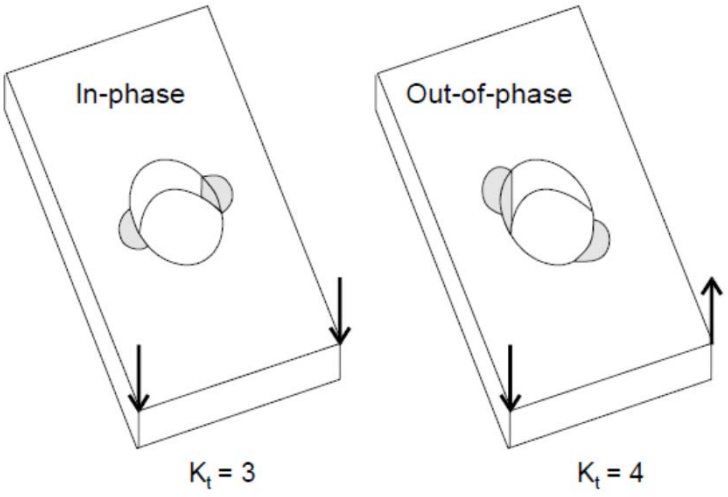
Multiaxial Fatigue



Damage location changes with load phasing

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Obrigado!

Diego F. B. Sarzosa
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