Fadiga de Materiais Estruturais: Fundamentos e Aplicações

Carregamento Variável
(Variable Amplitude Loading)

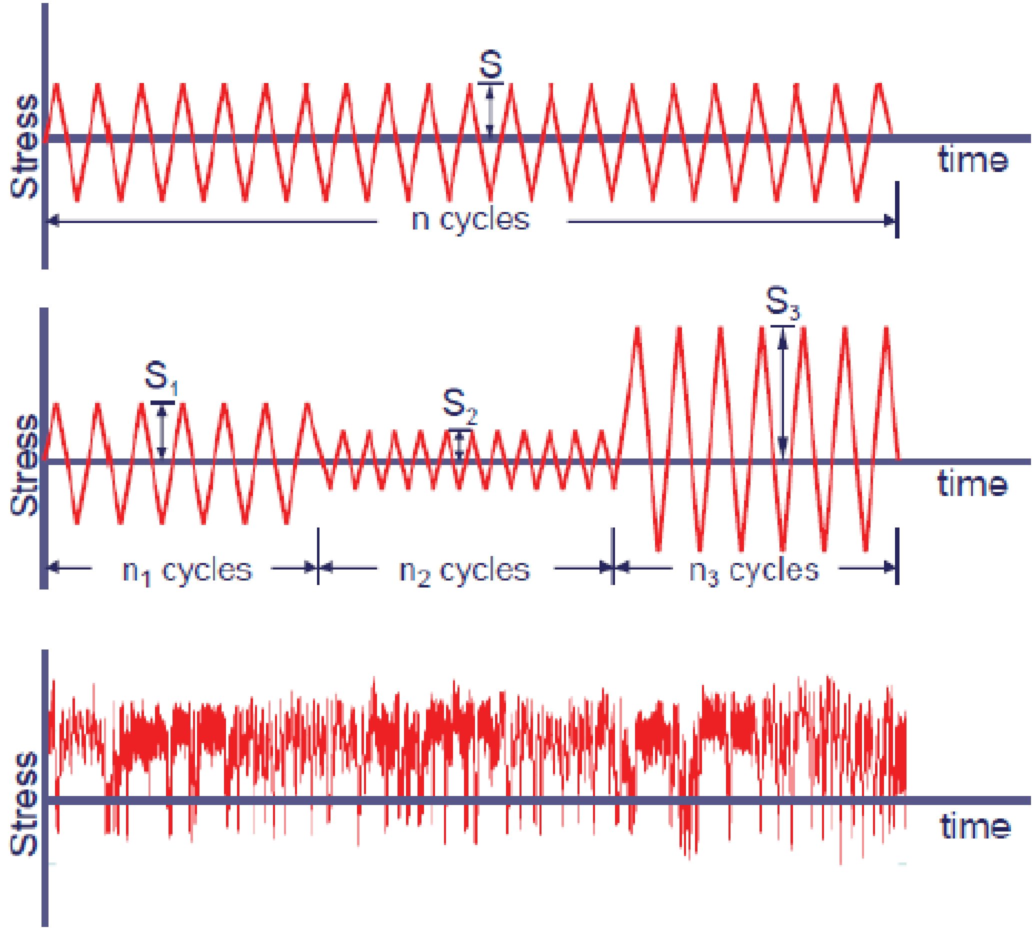
Diego Felipe Sarzosa Burgos
dsarzosa@usp.br

AGENDA

- *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)*

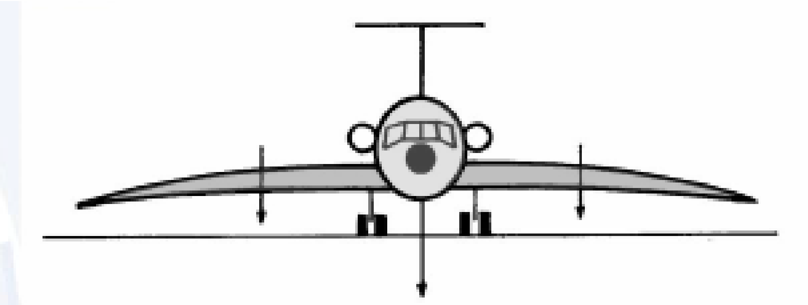
Variable Loading

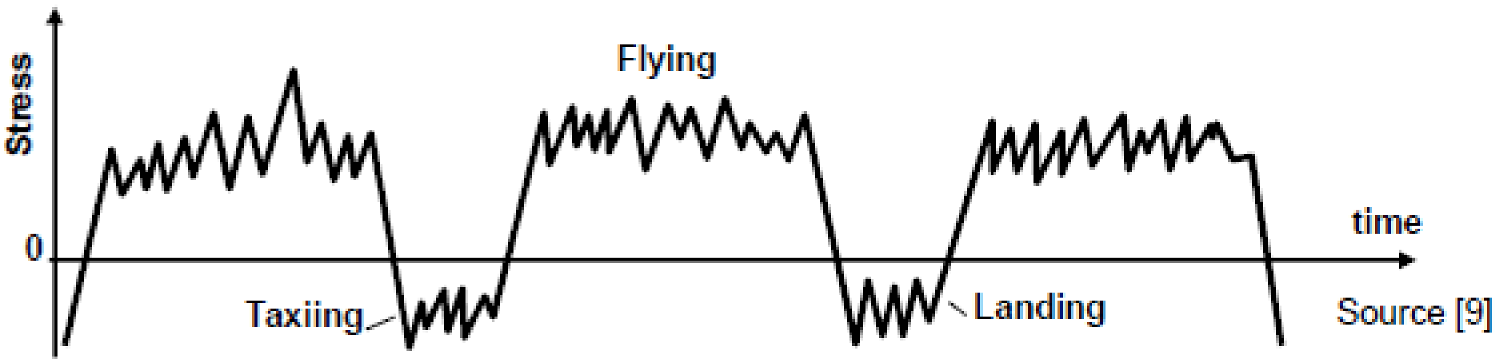
- Constant Amplitude
- Block Loading
- Variable Amplitude



Variable Loading

Aircraft wing skin

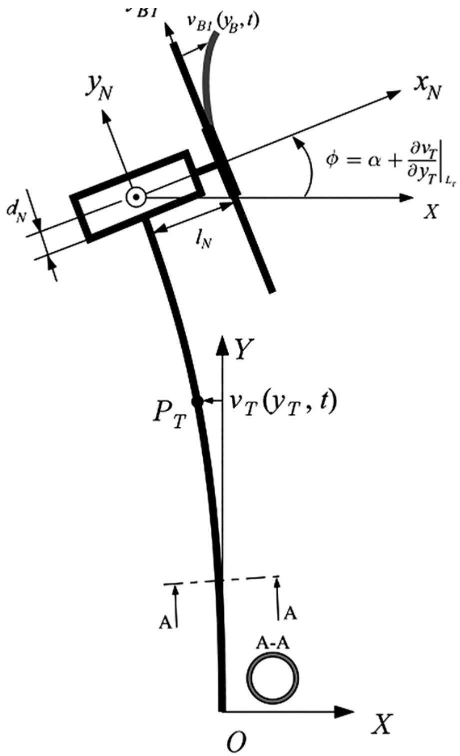


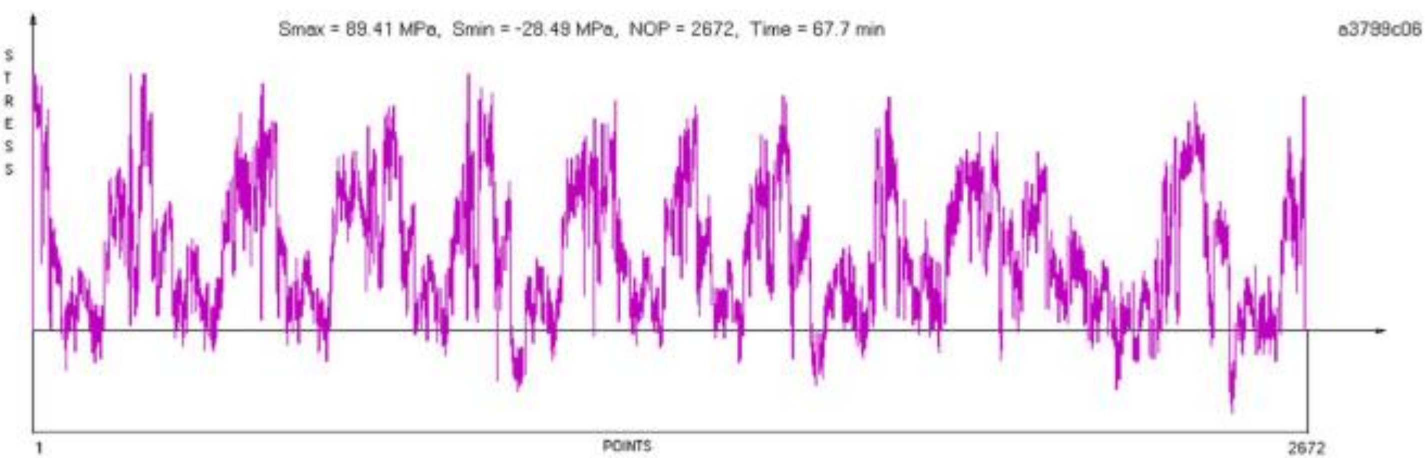


Stress Fluctuations

Variable Loading

Wind Turbine Blade

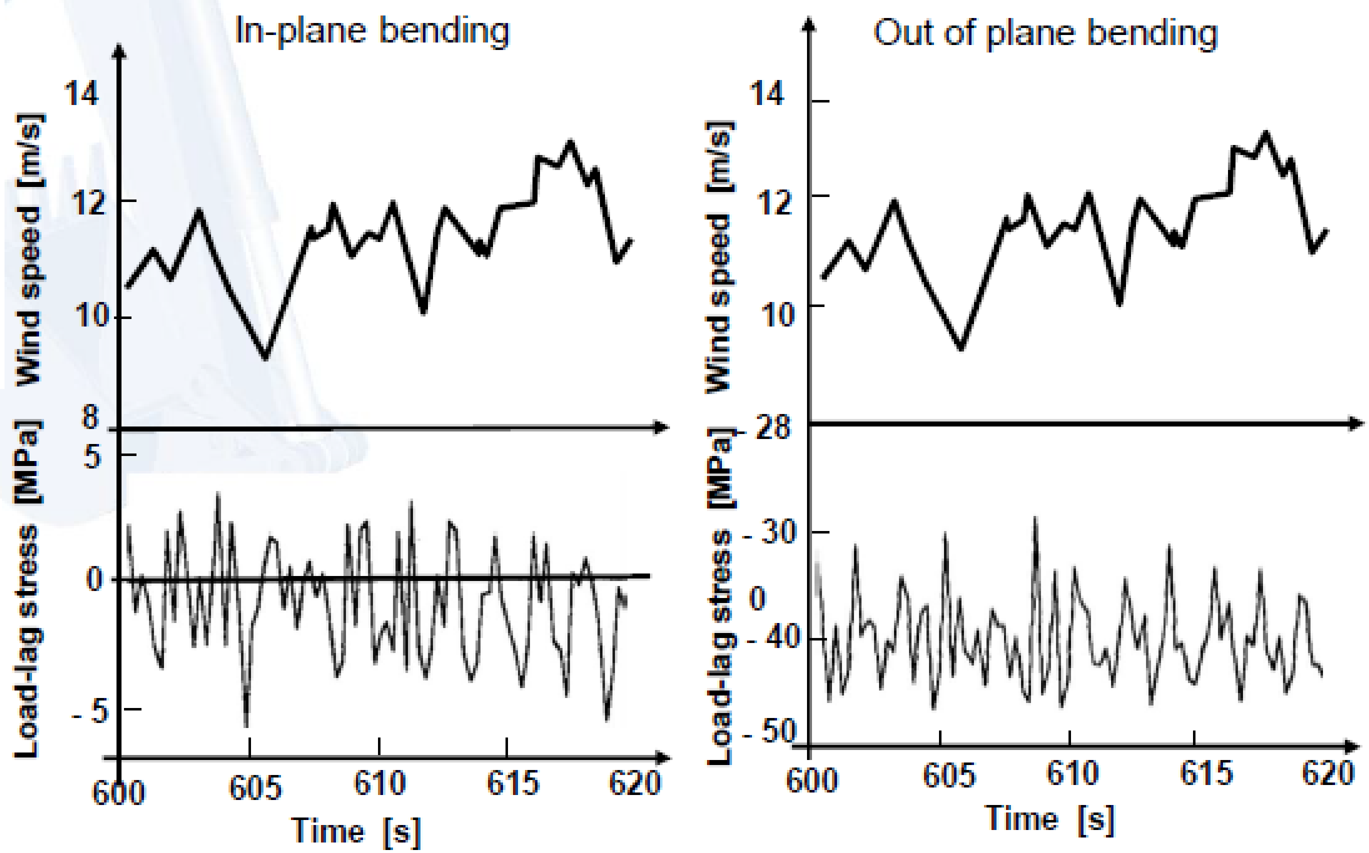




Stress Fluctuations

Variable Loading

Wind Turbine Blade



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

Variable Loading

Ship

Rainflow Counted Cycles

Rainflow Counting Method by Matsuishi and Endo (1968)

- The first accepted method used to extract closed loading reversals or cycles
- The “rainflow” was named from a comparison of this method to the flow of rain falling on a pagoda and running down the edges of the roof.

Rainflow Counted Cycles

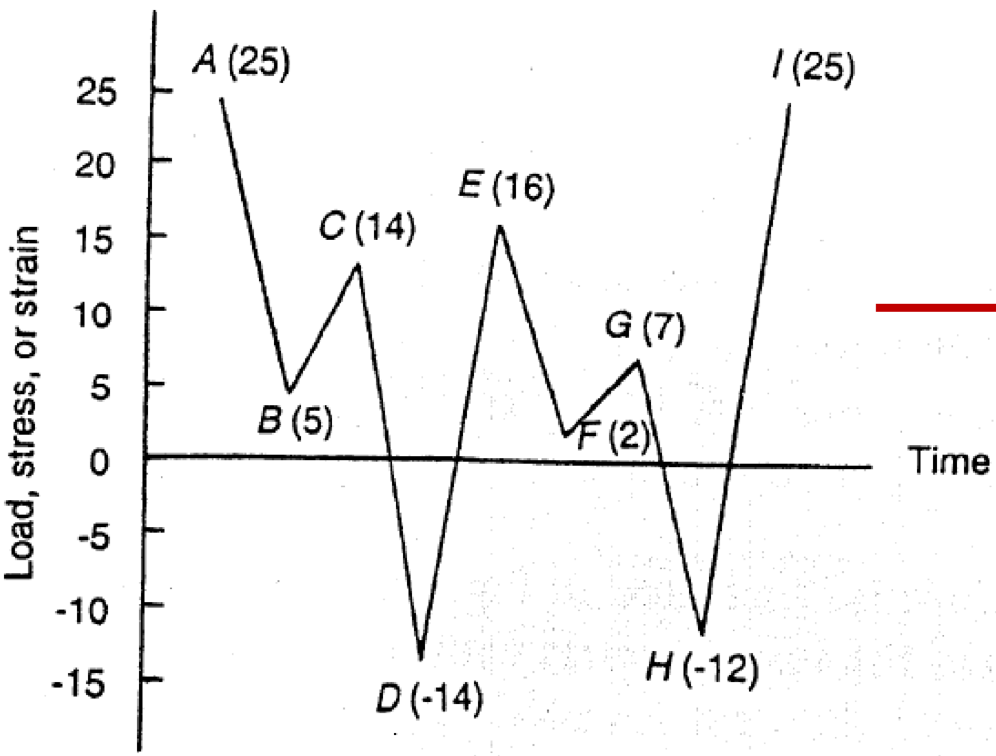
Rainflow Counting Method by Matsuishi and Endo (1968)

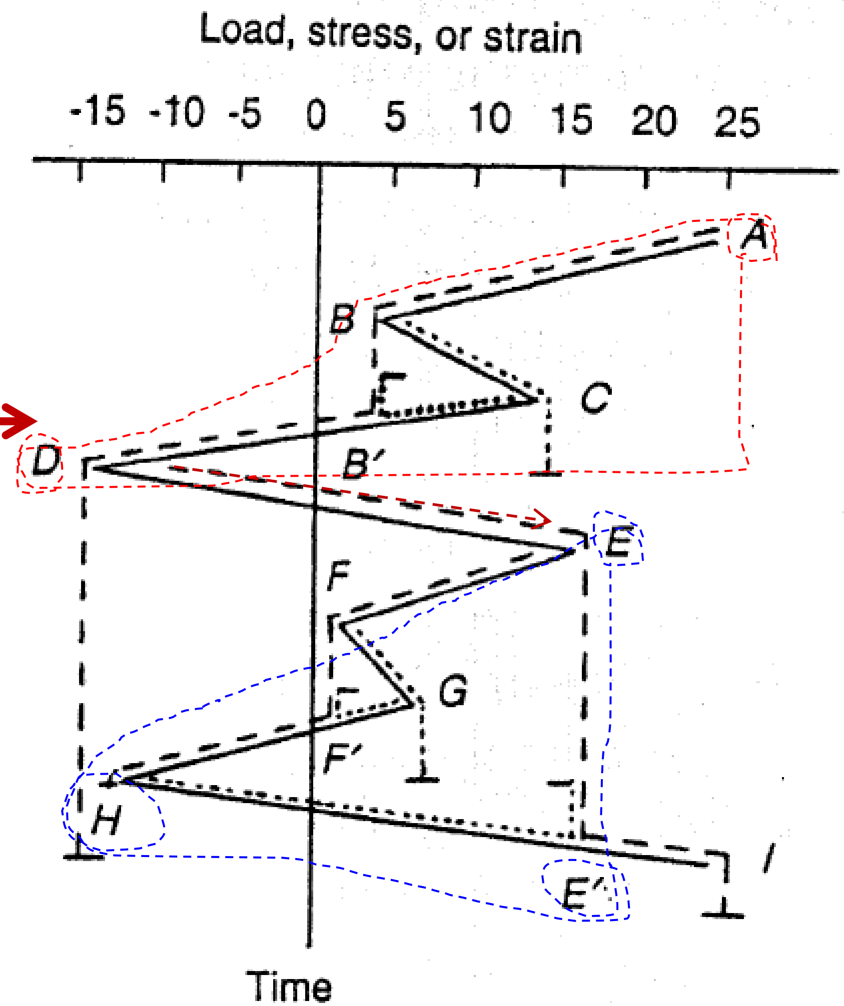
The rainflow cycle counting algorithm is summarized as follows:

1. Rotate the loading history 90° such that the time axis is vertically downward and the load time history resembles a pagoda roof.
2. Imagine a flow of rain starting at each successive extremum point.
3. Define a loading reversal (half-cycle) by allowing each rainflow to continue to drip down these roofs until:
   a. It falls opposite a larger maximum (or smaller minimum) point.
   b. It meets a previous flow falling from above.
   c. It falls below the roof.
4. Identify each hysteresis loop (cycle) by pairing up the same counted reversals.

Rainflow Counted Cycles

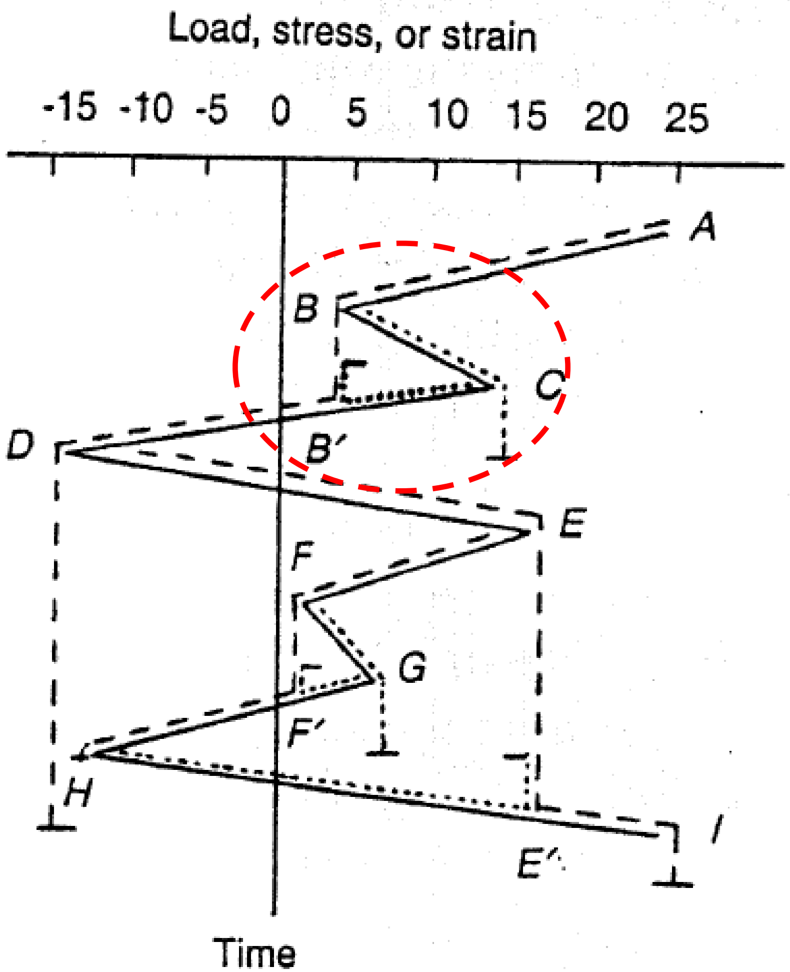
Illustration

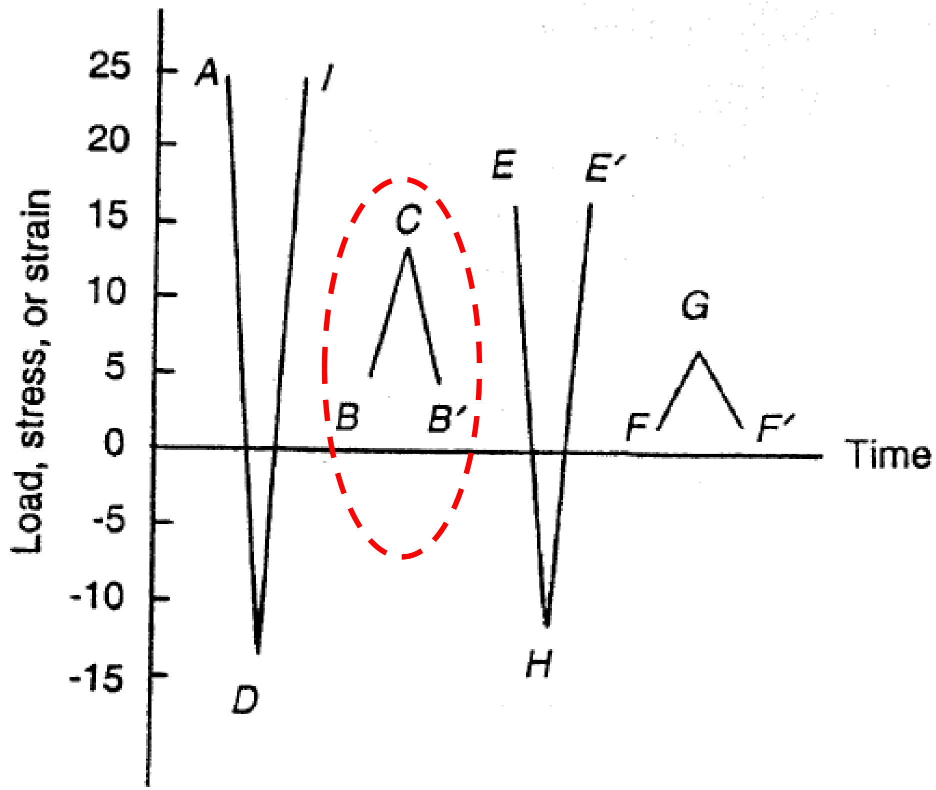




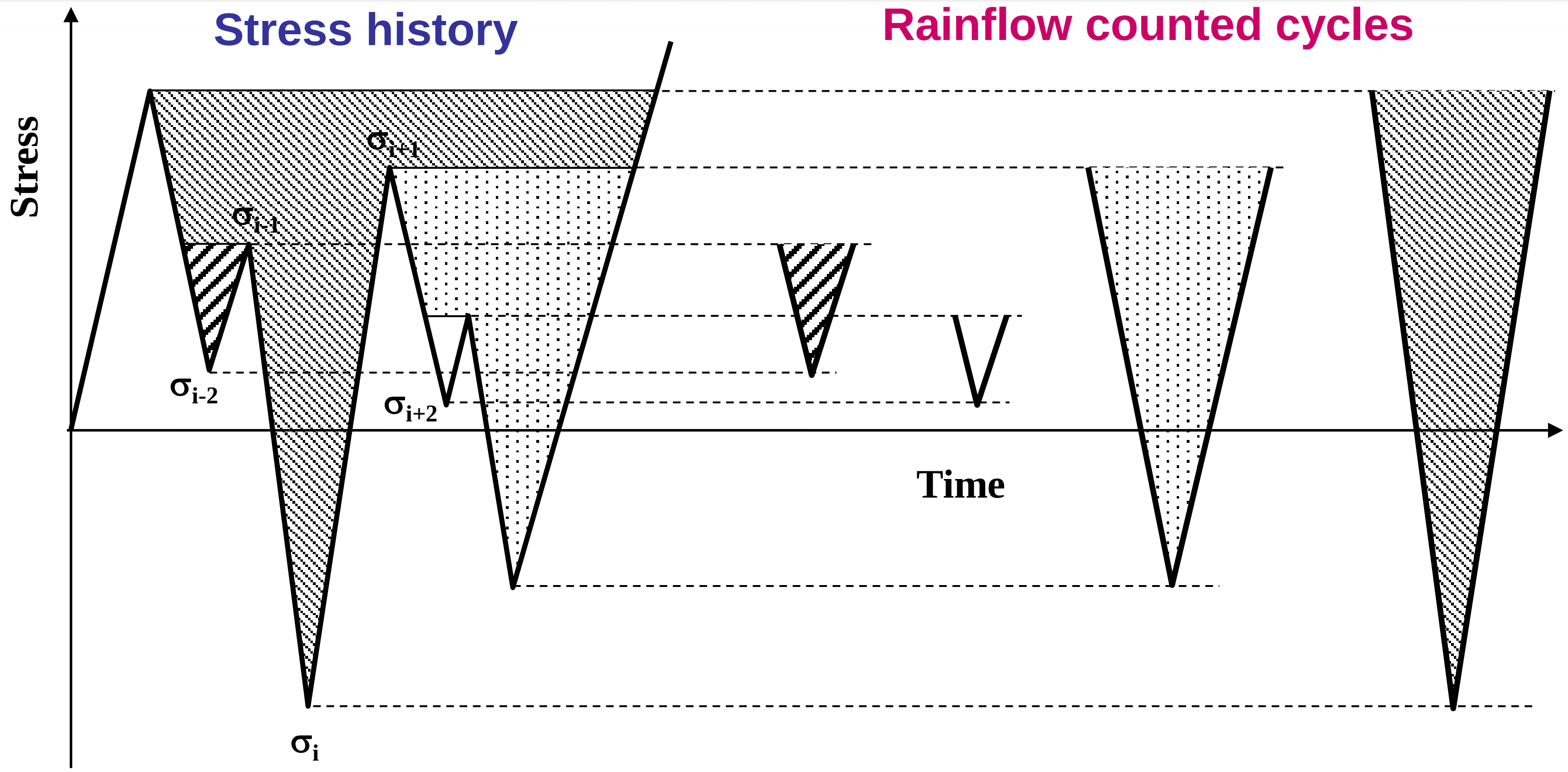
Rainflow Counted Cycles

Illustration





Rainflow Counted Cycles

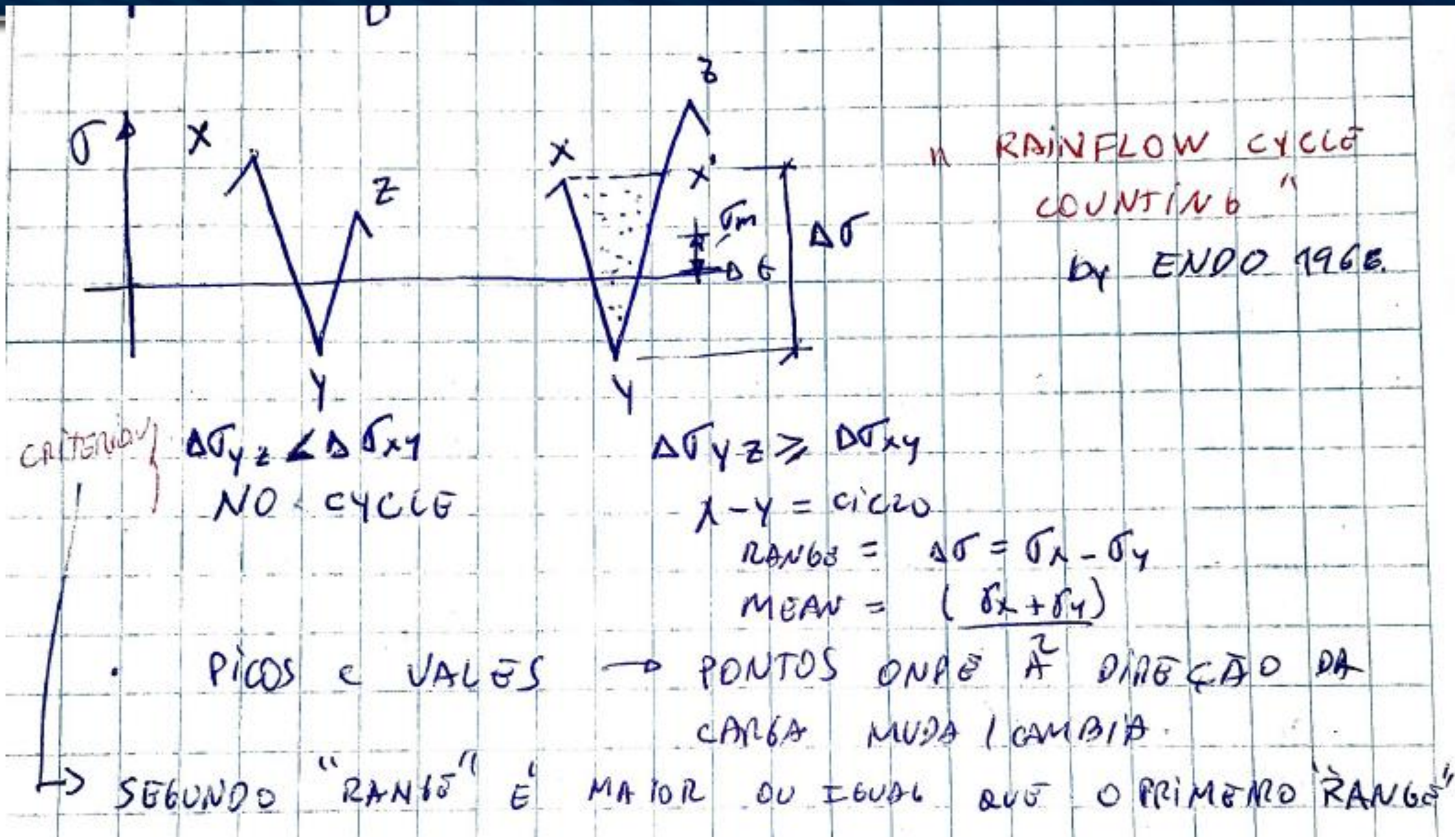


A *rainflow counted cycle* is identified when any two adjacent reversals in thee stress history satisfy the following relation:

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

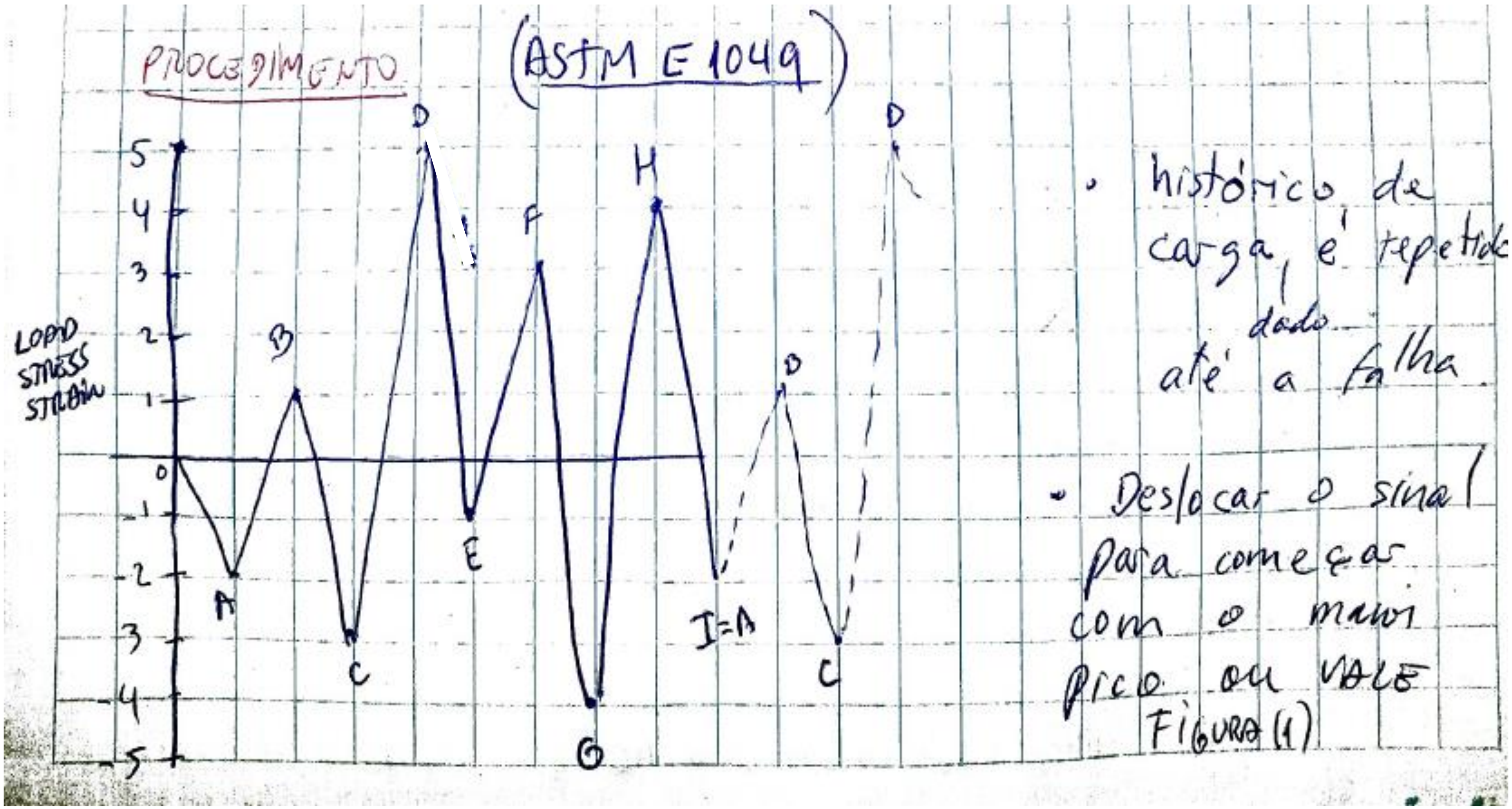
Procedure must start from the highest peask or lowest valley

Exemplo

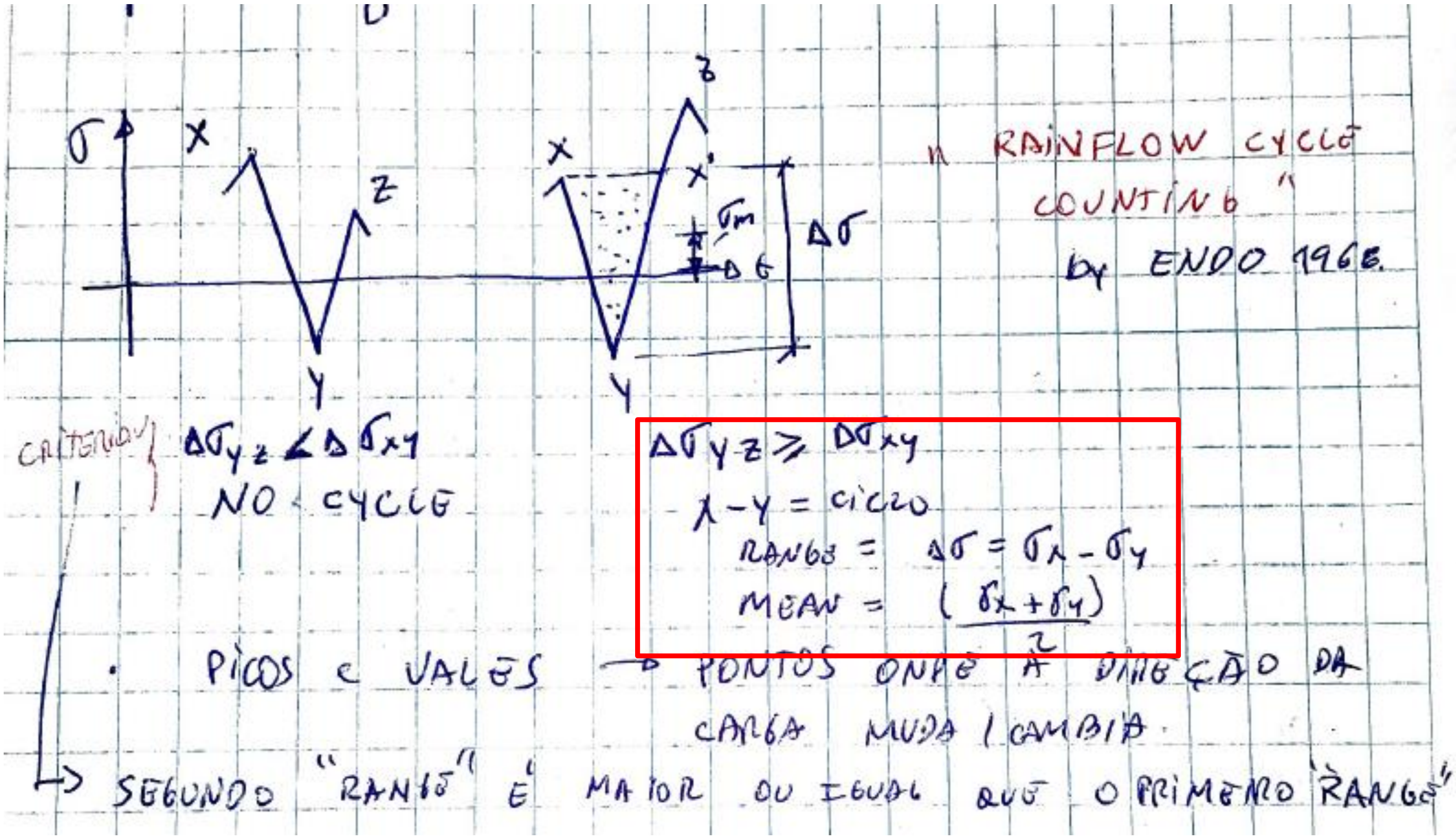


σ
X
Y
Z
X'
σm
Δσ
"RAINFLOW CYCLE COUNTING"
by ENDO 1968.
CRITERION
Δσy-z < Δσxy
NO CYCLE
Δσy-z ≥ Δσxy
X-Y = CICLO
RANGE = Δσ = σx - σy
MEAN = (σx + σy) / 2
• PICOS E VALES → PONTOS ONDE A DIREÇÃO DA CARGA MUDA / CAMBIA
→ SEGUNDO "RANGE" É MAIOR OU IGUAL QUE O PRIMEIRO "RANGE"

Exemplo


PROCEDIMENTO
(ASTM E1049)
LOAD
STRESS
STRAIN
5
4
3
2
1
0
-1
-2
-3
-4
-5
A
B
C
D
E
F
G
H
I=A
• histórico de carga é repetido até a falha
• Deslocar o sinal para começar com o maior pico ou VALE
FIGURA (1)

Exemplo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CRITERION
ΔσYZ < ΔσXY
NO CYCLE
ΔσY-Z ≥ ΔσXY
X-Y = CICLO
RANGE = Δσ = σX - σY
MEAN = (σX + σY)/2
• PICOS e VALES → PONTOS ONDE A DIREÇÃO DA CARGA MUDA / CAMBIA.
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Exemplo

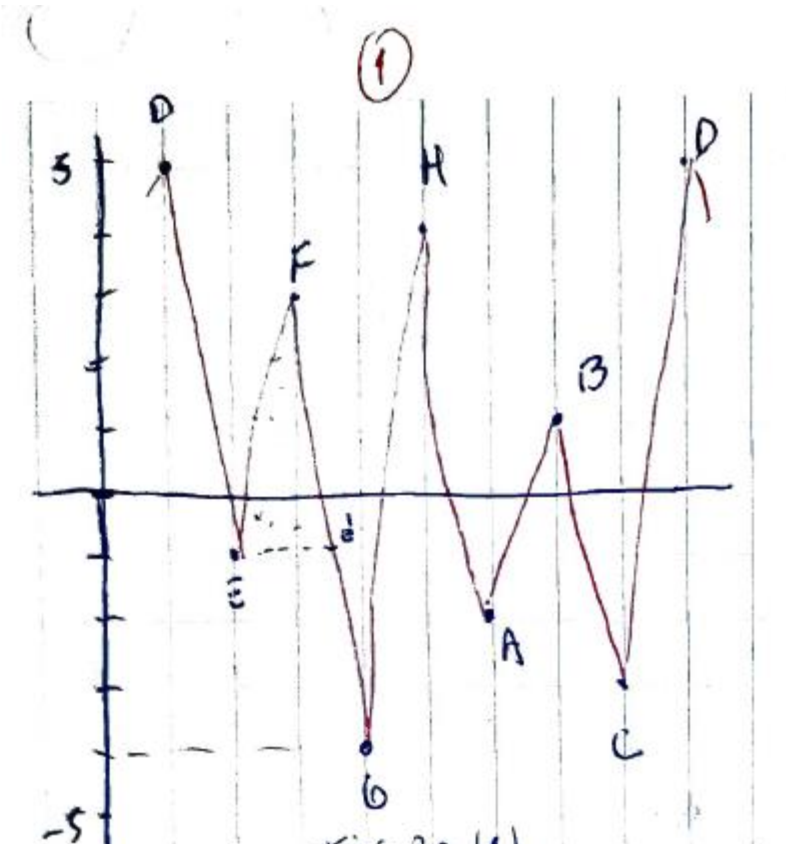


FIGURA (1)

CICLO

DE vs. EF ✗

EF vs. FG ✓

REDESENHAR O HISTÓRICO SEM CONSIDERAR O PRÉVIO CICLO E-F-E' FIGURA (2)

$\Delta\sigma_{DE} = 5-(-1) = 6$

$\Delta\sigma_{EF} = 3-(-1) = 4$

$\Delta\sigma_{DE} > \Delta\sigma_{EF}$ ✗

Exemplo

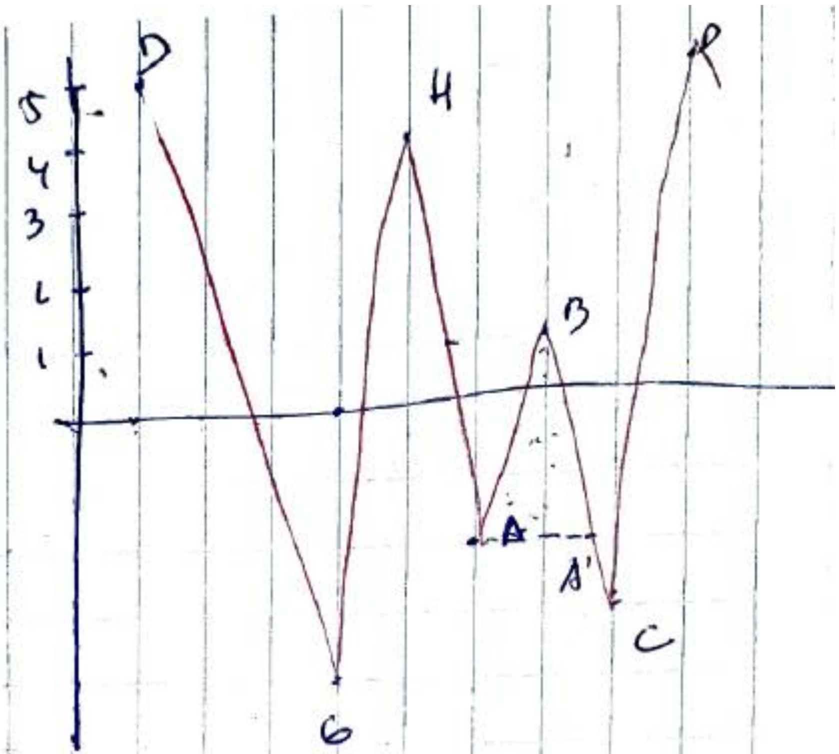


FIGURA (2)

DG VS. GH x

GH VS. HA x

HA VS. AB x

AB VS. BC ✓

REFAZER HISTÓRICO

DESCONSIDERANDO O CICLO AB FIGURA(3)

Exemplo

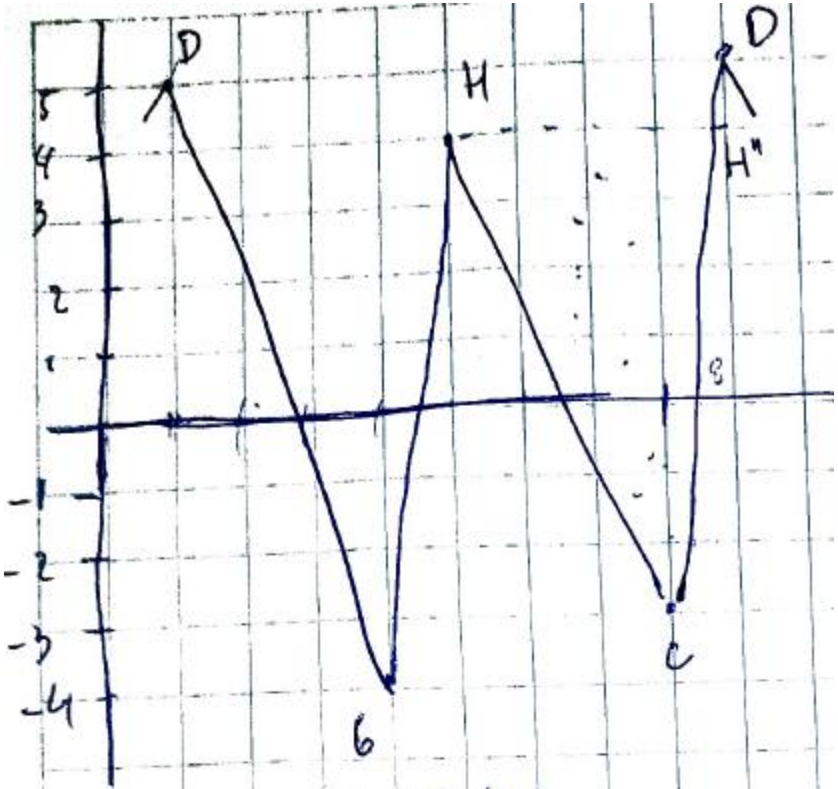
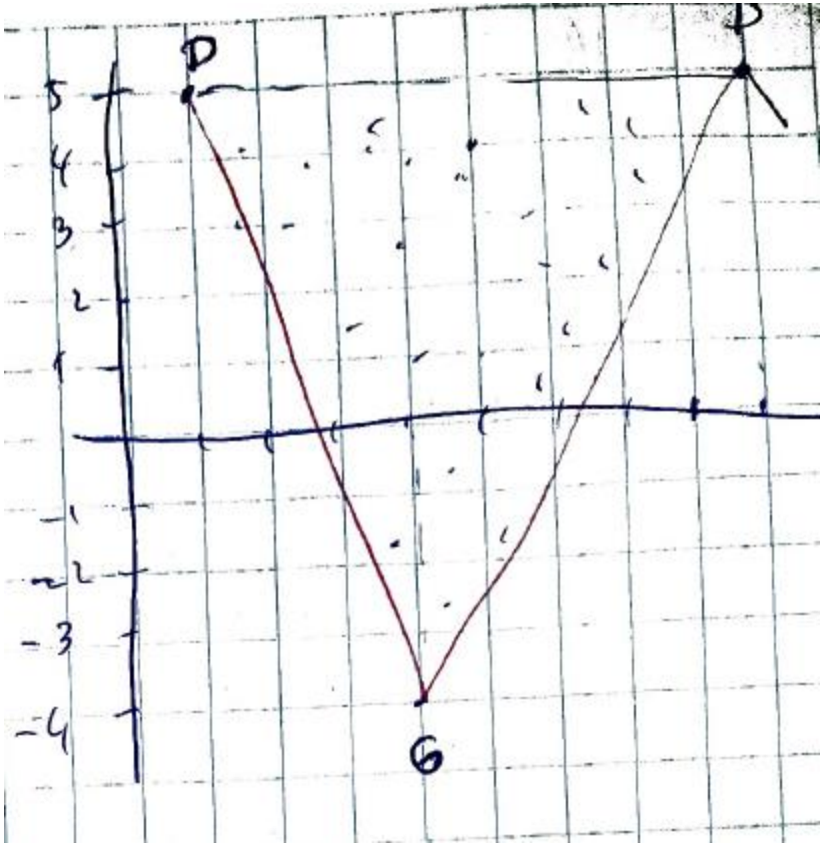


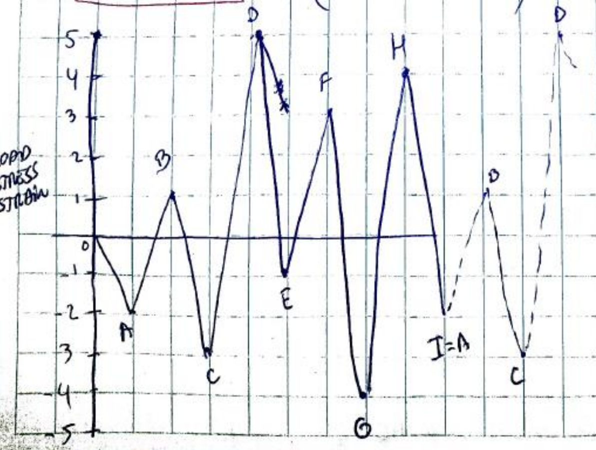
FIGURA (3)

DG vs. GH ✗
GH vs. HC ✗
HC vs. CD ✓

REFAZER HISTÓRICO SEM INCLUIR CICLO HC

Exemplo





Exemplo

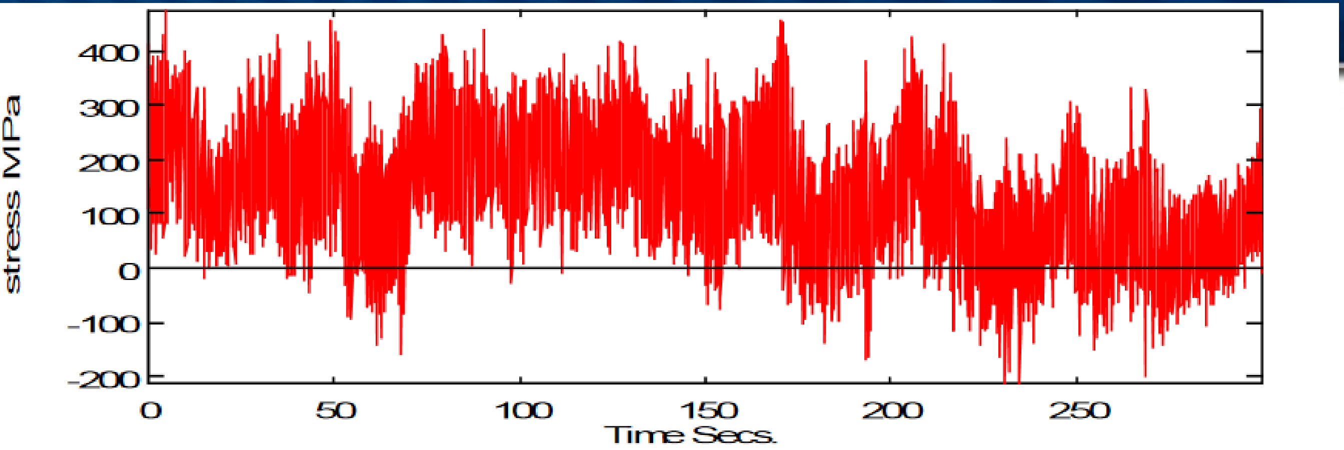
CONTAGEM

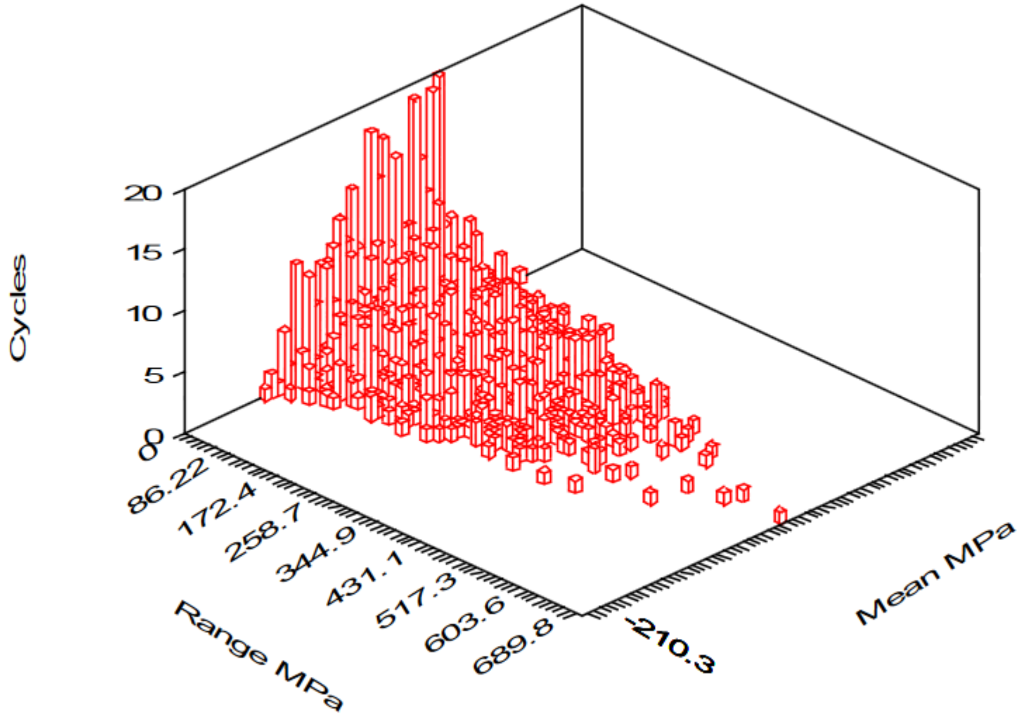
CICLO	RANGE	MEAN
E-F	4.0	1.0
A-B	3.0	-0.5 $\left(\frac{1-2}{2}\right) = -\frac{1}{2}$
H-C	7.0	0.5
D-G	9.0	0.5 → LARGEST RANGE

$$B_f \times \left[\sum \frac{n_i}{N_i} \right]_{\text{one repetition}} = 1$$

Repetições do bloco de carga.

Range-mean histogram by rainflow

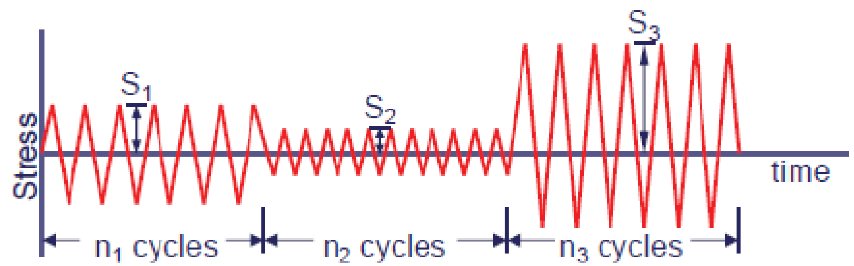




DAMAGE EVOLUTION

Palmgren-Miner Linear Damage Rule

- Failure is said to occur when the sum of all partial damage equals one



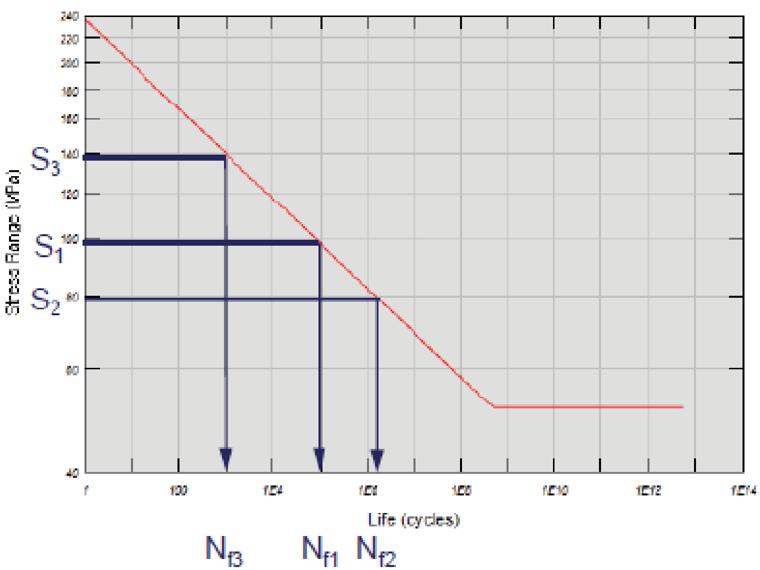
- Expect failure when:

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \geq 1$$

Miner's constant

$$\text{Partial damage} = \frac{n_i}{N_i}$$

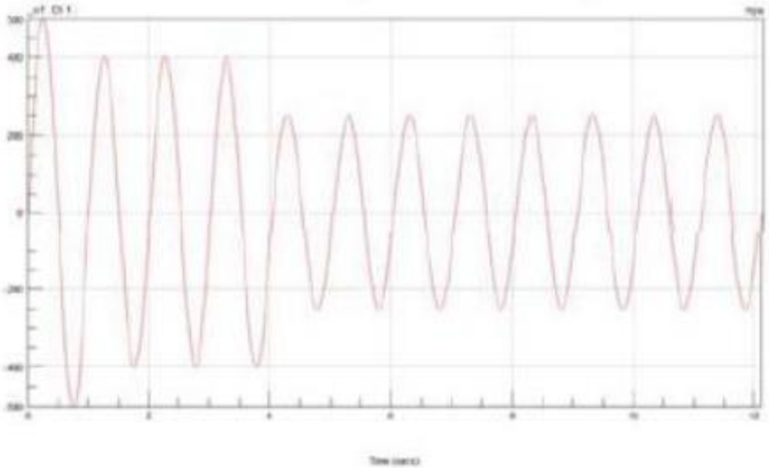
$$\frac{n_1}{N_{f1}} + \frac{n_2}{N_{f2}} + \frac{n_3}{N_{f3}} + \cdots = 1$$

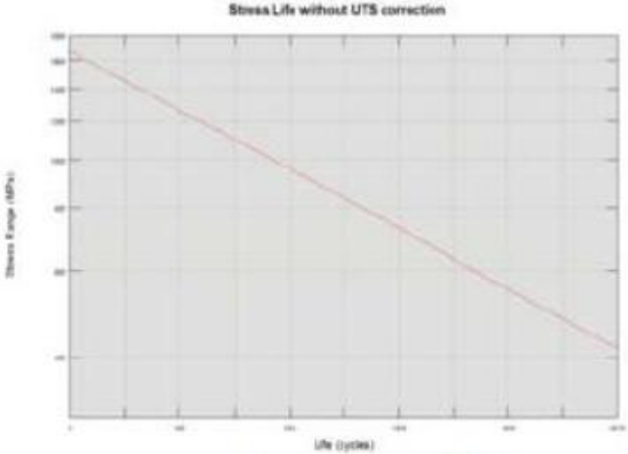


DAMAGE EVOLUTION & FATIGUE LIFE ESTIMATION

- Given
  - A landing gear component experiences varying stresses while landing
- Question
  - How long will the component last before fatigue failure?

Stress history from a landing

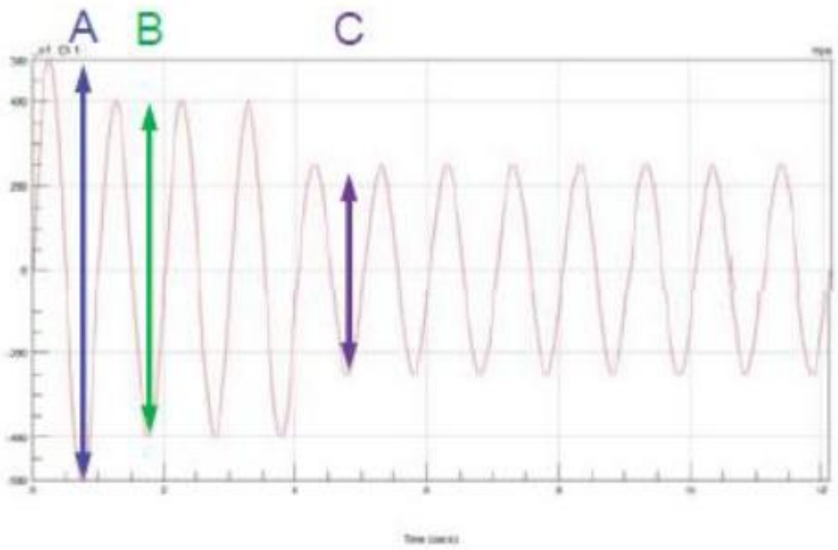




Material SN curve

DAMAGE EVOLUTION & FATIGUE LIFE ESTIMATION

stress history



Cycle	Max	Min	Range	# of cycles	Life (cycles)	Damage per cycle	Damage x cycles
A	500	-500	1000	1			
B	400	-400	800	3			
C	250	-250	500	8			
						Total Damage	

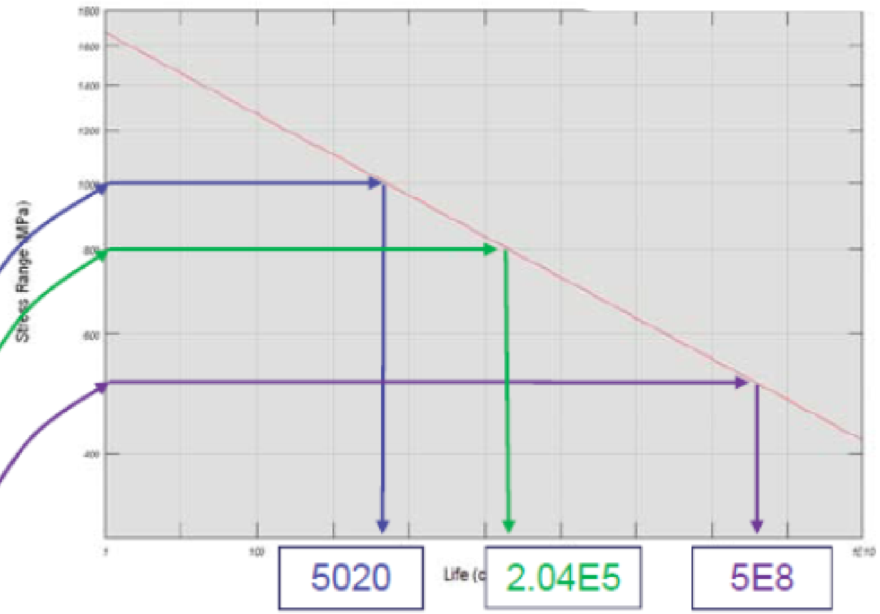
DAMAGE EVOLUTION & FATIGUE LIFE ESTIMATION

Calculating Partial Damage

- Each cycle consumes a bit of fatigue life

  or

- Causes some amount of fatigue damage



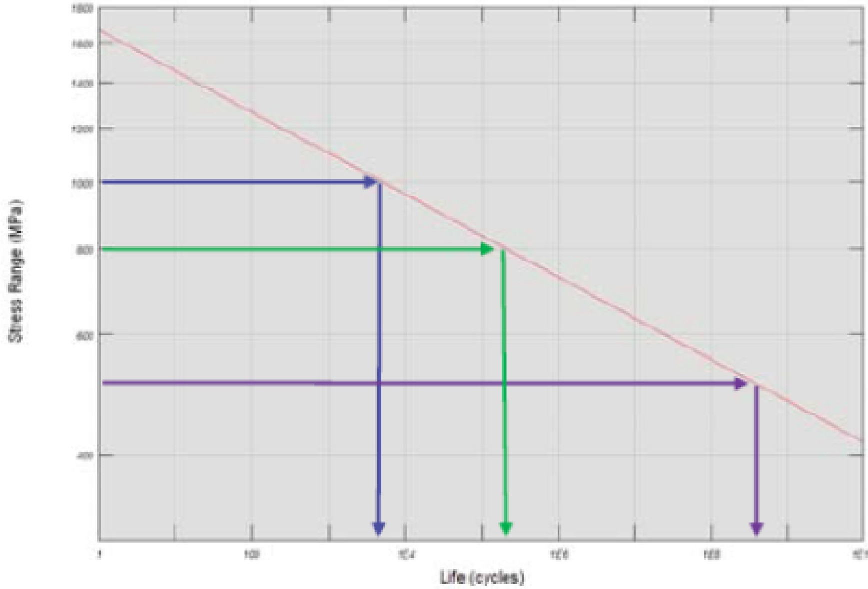
Cycle	Max	Min	Range	# of cycles	Life (cycles)	Damage per cycle	Damage x cycles
A	500	-500	1000	1	5020	1.99E-4	
B	400	-400	800	3	2.04E5	4.89E-6	
C	250	-250	500	8	5E8	2E-9	
						Total Damage	

DAMAGE EVOLUTION & FATIGUE LIFE ESTIMATION

Calculating Total Damage

- Miner's Rule:
- Total damage is the summation of damage from each cycle

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \geq 1$$

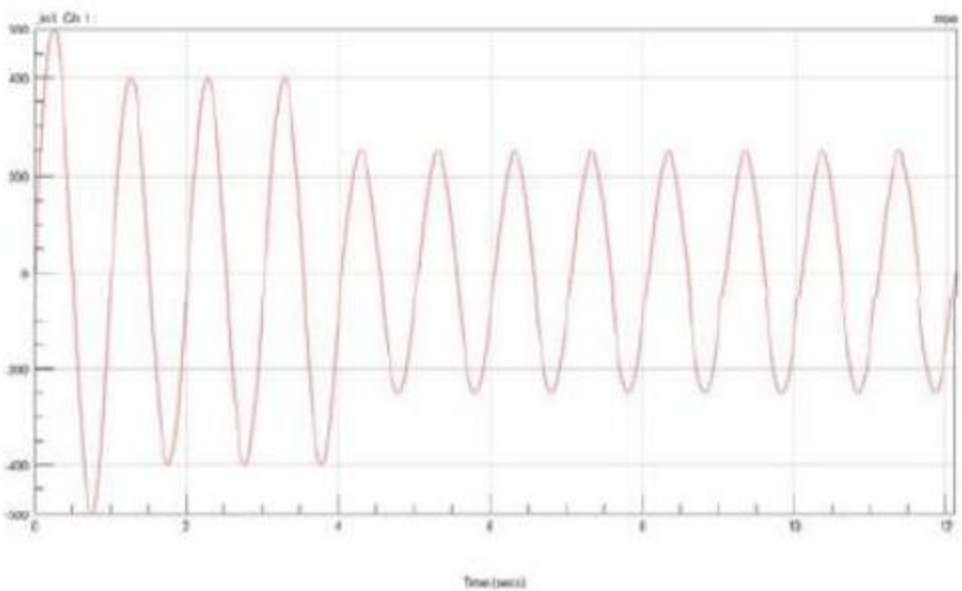


Cycle	Max	Min	Range	# of cycles	Life (cycles)	Damage per cycle	Damage x cycles
A	500	-500	1000	1	5020	1.99E-4	1.99E-4
B	400	-400	800	3	2.04E5	4.89E-6	1.47E-5
C	250	-250	500	8	5E8	2E-9	1.6E-8
						Total Damage	2.14E-4

DAMAGE EVOLUTION & FATIGUE LIFE ESTIMATION

Calculating Fatigue Life

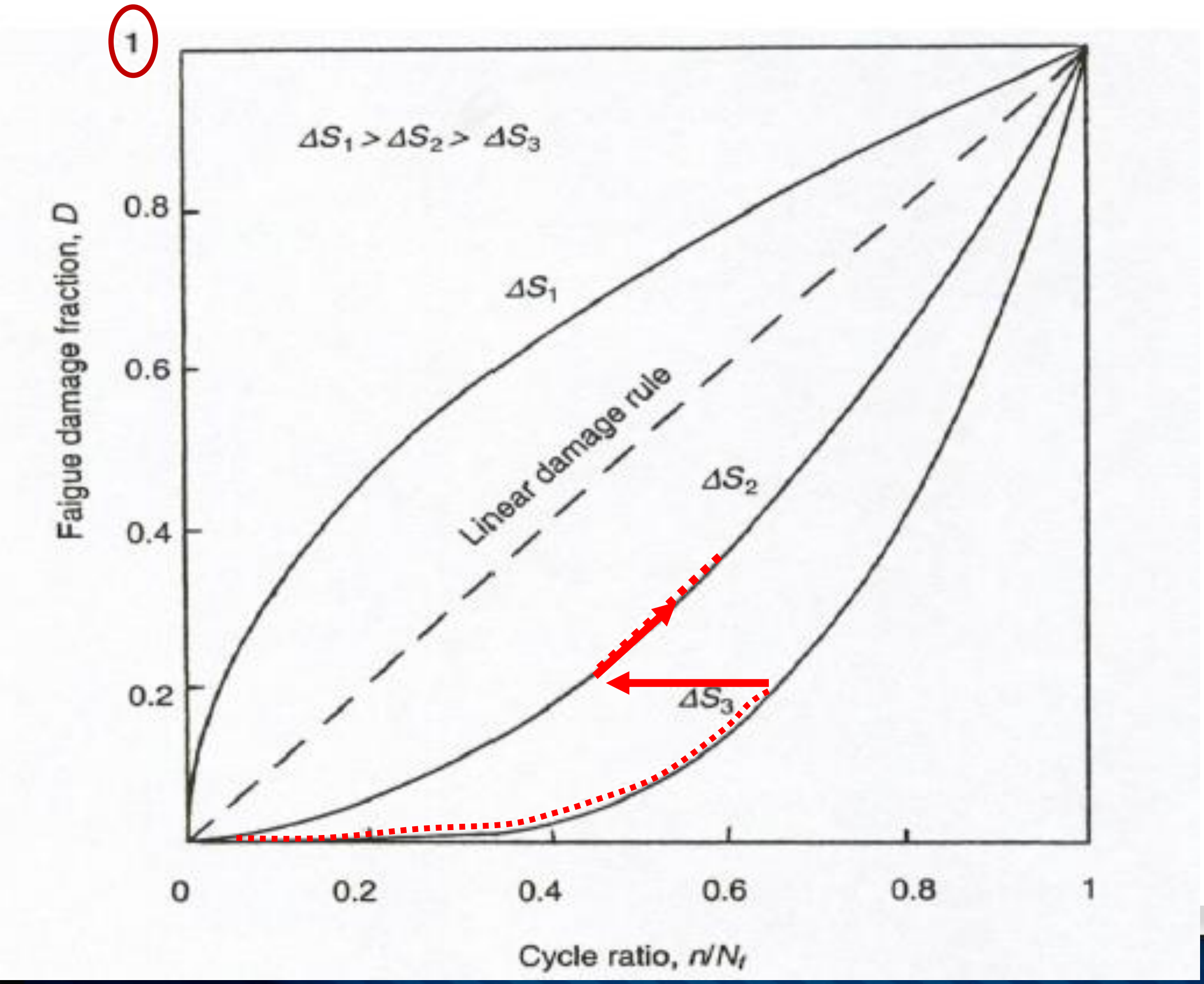
- Failure if total *damage* > 1
- If not, fatigue *life* = 1 / total damage
- So, fatigue *life* = 1 / 2.14E-4



- Estimated life is 4675 landings until fatigue failure

DAMAGE EVOLUTION

Nonlinear Damage Rule

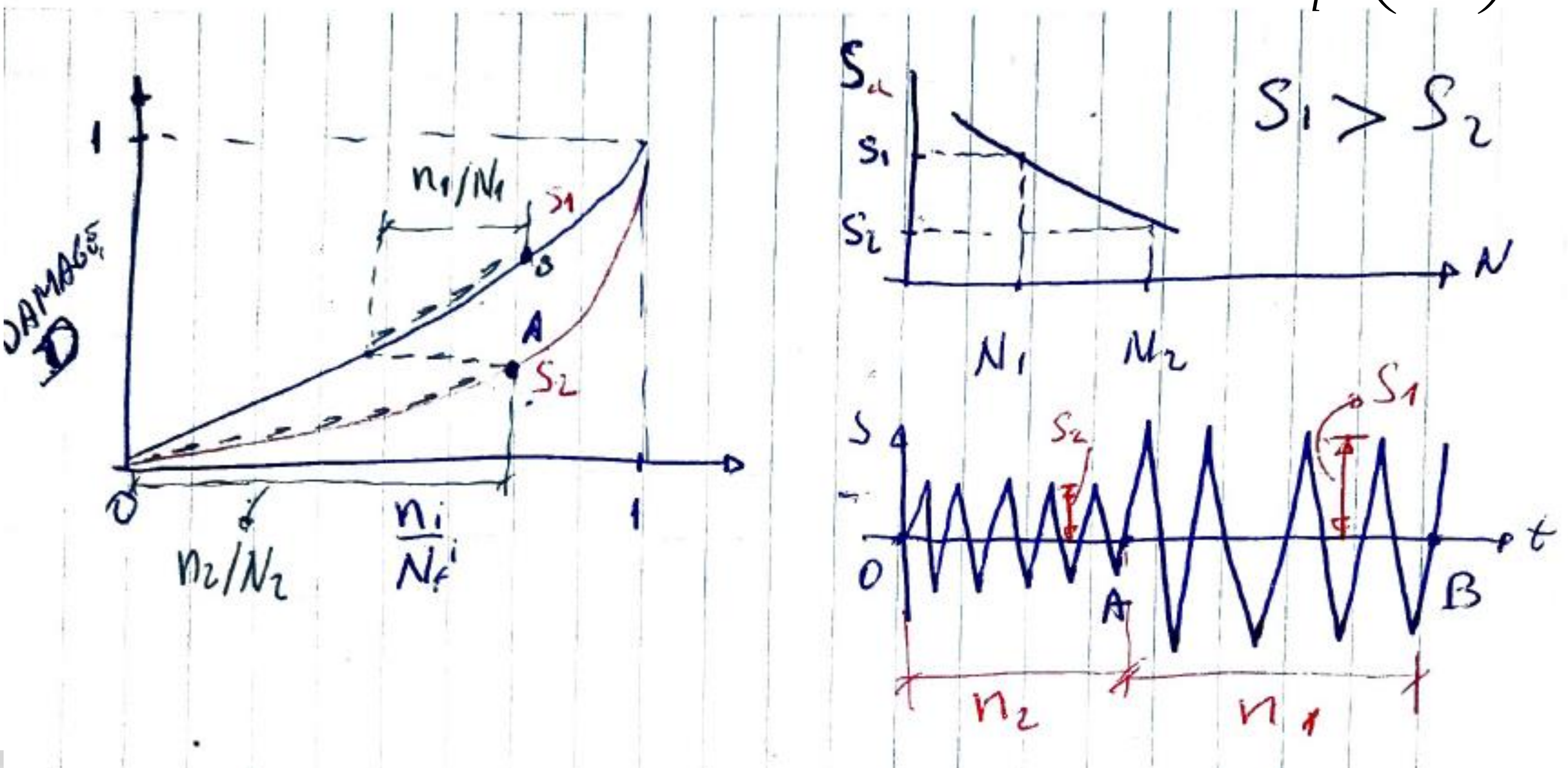


$$D = \sum_i \left(\frac{n}{N} \right)^{\alpha}$$

DAMAGE EVOLUTION

Nonlinear Damage Rule

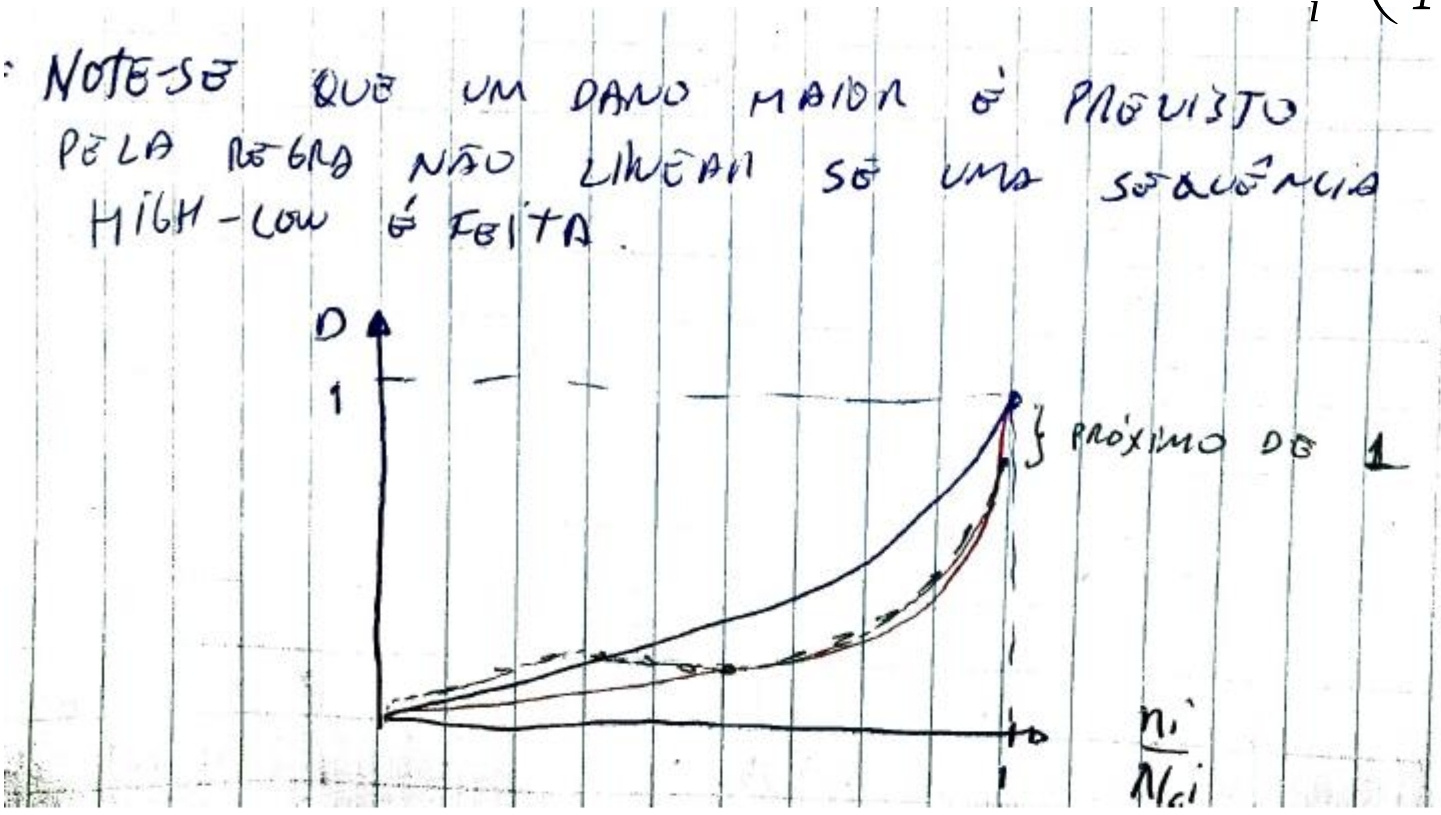
$$D = \sum_i \left(\frac{n}{N} \right)^{\alpha}$$



DAMAGE EVOLUTION

Nonlinear Damage Rule

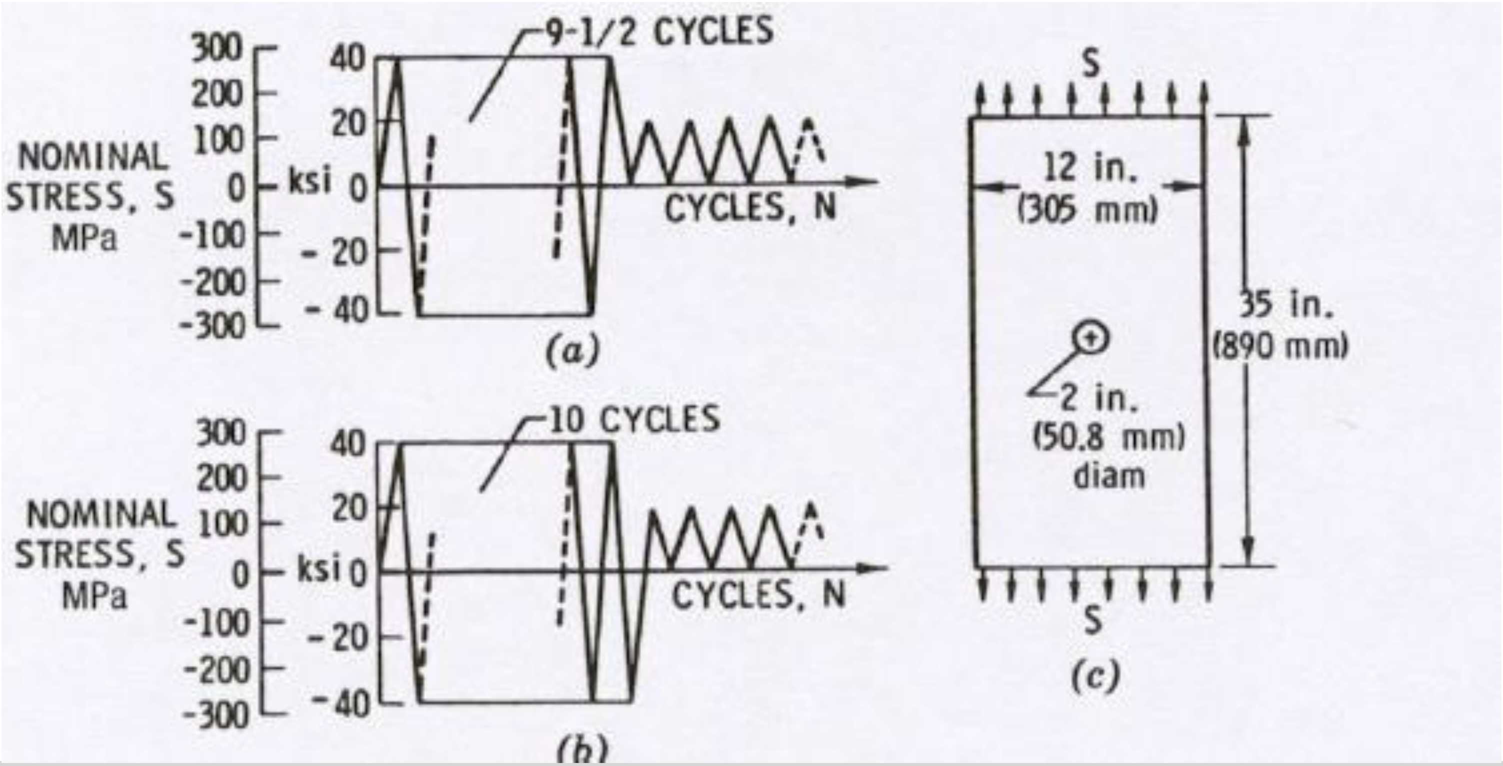
$$D = \sum_i \left(\frac{n}{N} \right)^{\alpha}$$



DAMAGE EVOLUTION

Nonlinear Damage Rule (Initiation)

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



Cycles

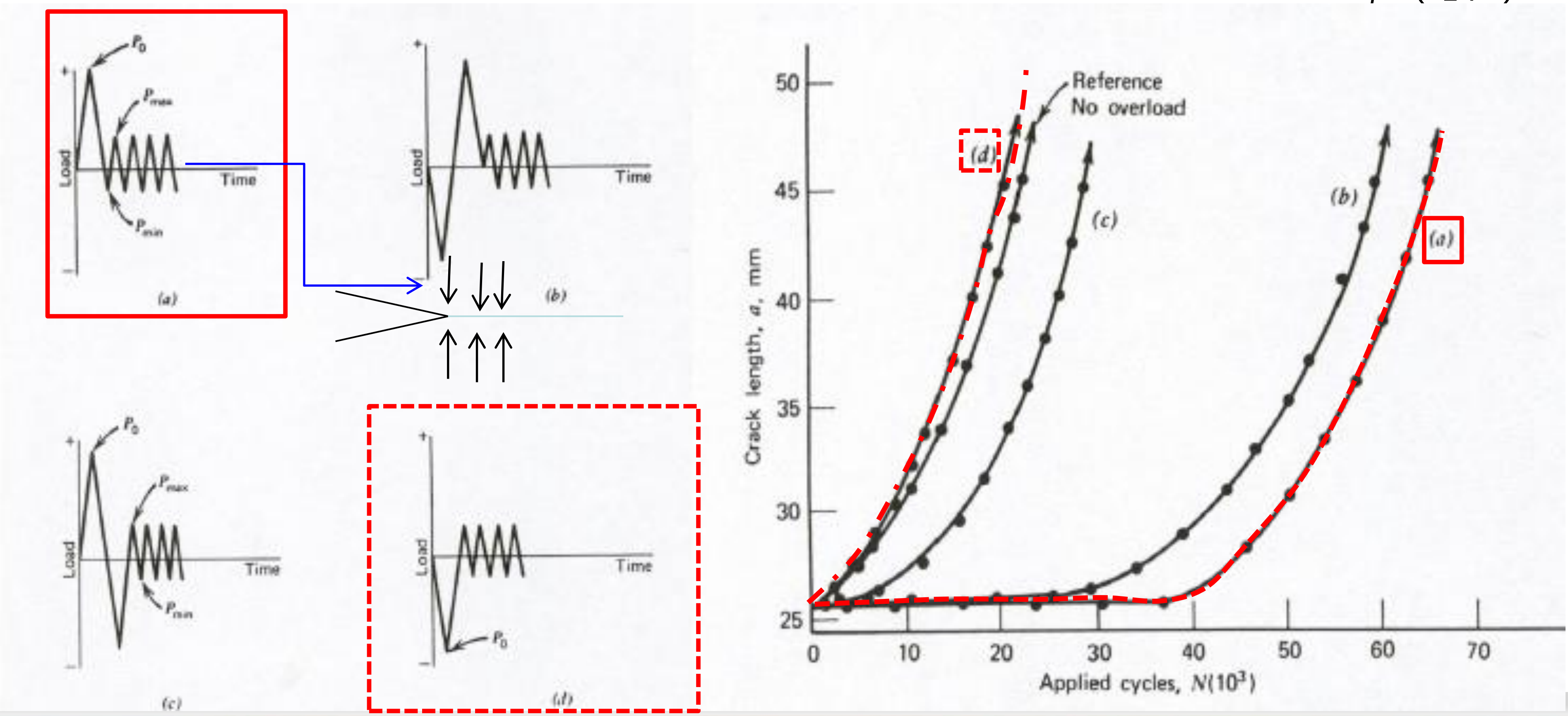
$$460 \times 10^3$$

$$63 \times 10^3$$

DAMAGE EVOLUTION

Nonlinear Damage Rule (Propagation)

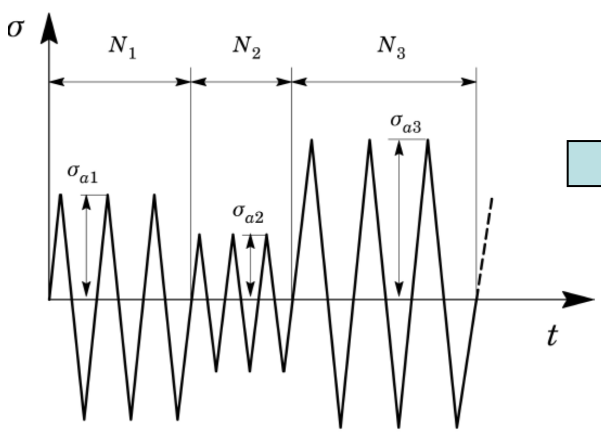
$$D = \sum_i \left(\frac{n}{N} \right)^{\alpha}$$

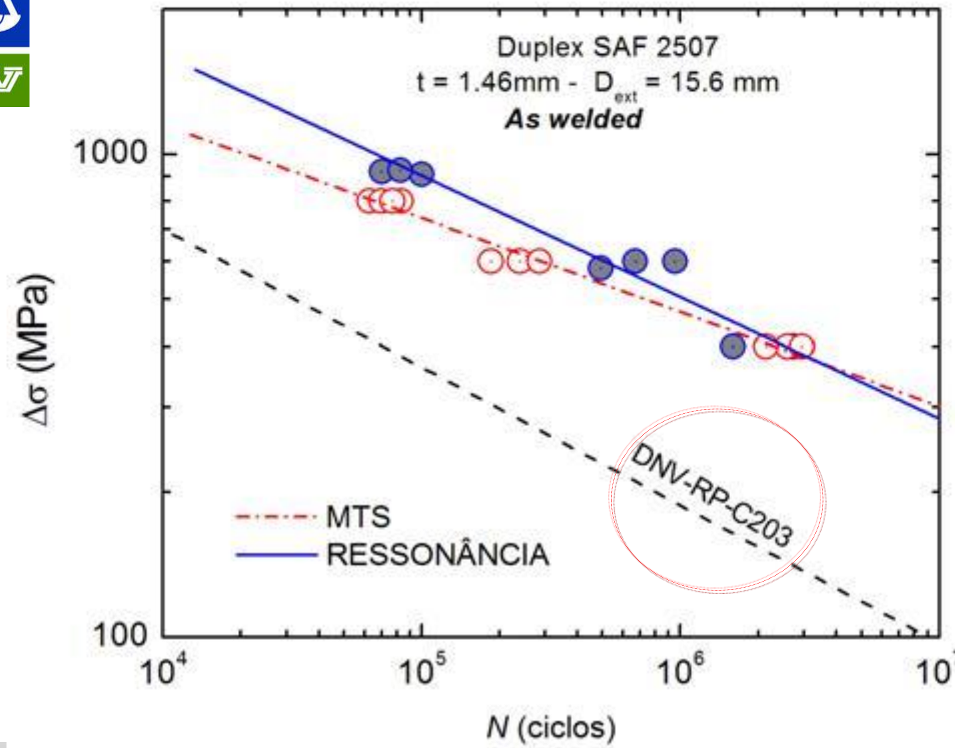


Rainflow + Damage

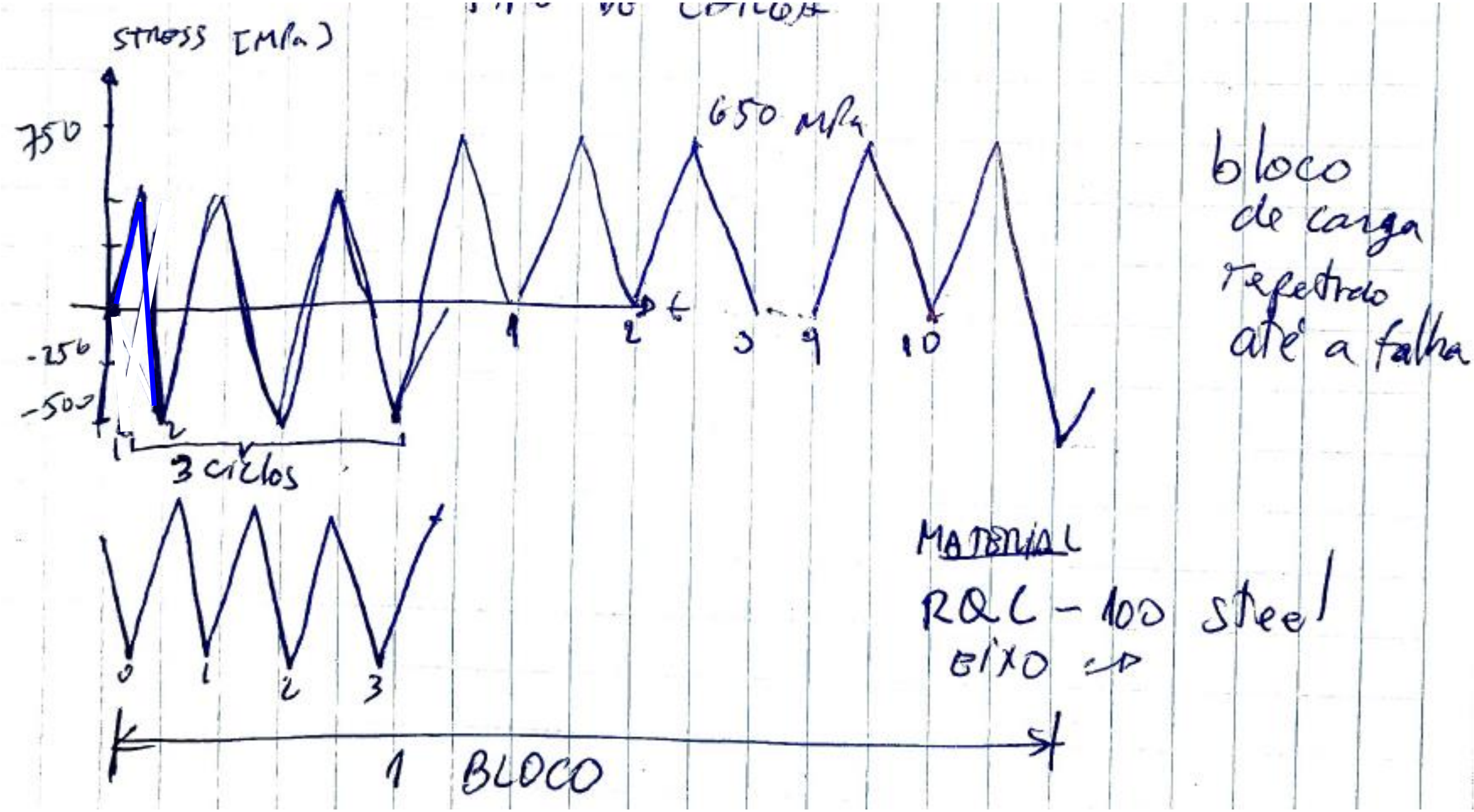
– Análise dos procedimentos correntes de avaliação usando normas de construção naval e de estruturas oceânicas.

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





Exemplo



STRESS [MPa]
750
-250
-500
650 MPa
3 ciclos
bloco de carga repetido até a falha
MATERIAL
RQC - 100 steel
eixo
1 BLOCO

Exemplo

a) EIXO SEM ENTALHES, POLIDO. QUANTOS BLOCOS PODEM SER APLICADOS

ROUND SHAFT MADE RQC-100 steel

o OBSERVA-SE 3 INTERVALOS DE CARGA

Exemplo

a) EIXO SEM ENTALHES, POLIDO. QUANTOS BLOCOS PODEM SER APLICADOS

ROUND SHAFT MADE RQC-100 steel

o OBSERVA-SE 3 INTERVALOS DE CARGA

Exemplo

a) EIXO SEM ENTALHES, POLIDO. QUANTOS BLOCOS PODEM SER APLICADOS

ROUND SHAFT MADE RQC-100 steel

o OBSERVA-SE 3 INTERVALOS DE CARGA

Exemplo

SEGMENTO	Smin [MPa]	Smax [MPa]	Sa [MPa]	Sm [MPa]	ni ciclos
1	-500	500	500	0	3
2	-500	650	575	75	1
3	0	650	325	325	10

$$S_a = \sigma_f' (2N_f)^b$$

$$\sigma_a = S_a = 1240 (2N_f)^{-0.07}$$

Exemplo

EFEITOS DA TENSÃO MÉDIA

GOODMAN

$$\frac{S_a}{S_{ar}} + \frac{S_m}{S_u} = 1 \quad ; \quad S_u = 931\ MPa$$

* CARREGAMENTOS COMPLETAMENTE REVERSOS EQUIVALENTES.

$$\frac{S_a}{\frac{575}{S_{ar}}} + \frac{75}{931} = 1 \rightarrow S_{ar} = 1.088\, S_a$$

$$S_{ar} = 1.088 \cdot (575)$$

$$\frac{325}{S_{ar}} + \frac{325}{931} = 1 \Rightarrow S_{ar} = 1.536\, S_a$$

$$1.536(325)$$

Exemplo

SEGMENTO	Sa	Sar	Nf	n	ni/Nf
1	500	500	215770	3	1.4×10^{-5}
2	575	625	8815	1	1.13×10^{-4}
3	325	499	219630	10	4.6×10^{-5}

$$\sigma_a = S_a = 1240(2N_f)^{-0.07}$$

$$\sum \frac{n_i}{N_f} = 1.73 \times 10^{-4}$$

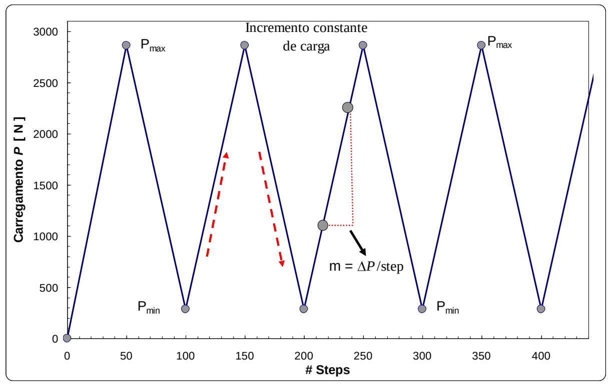
$$\#\ \text{BLOCOS} \times \left(\sum \frac{n_i}{N_f}\right)_{1\ \text{REP.}} = 1$$

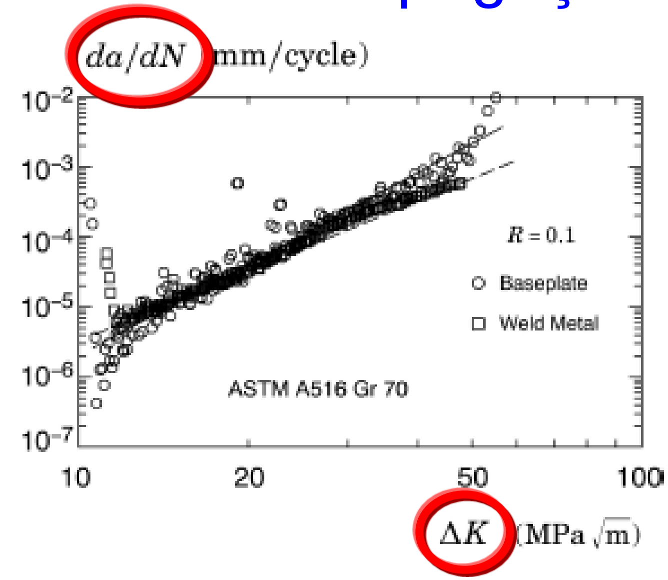
$$\Downarrow$$

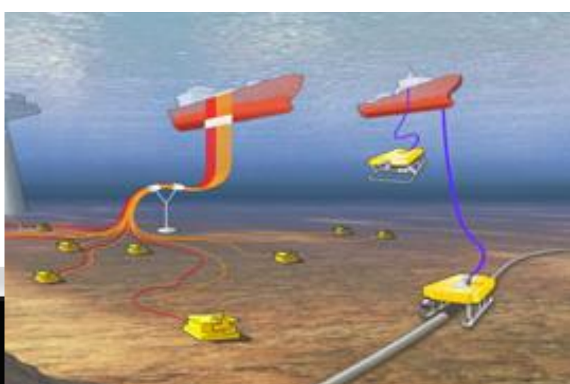
$$\#\ \text{BLOCOS} = \frac{1}{1.73 \times 10^{-4}} = 5782\ \text{blocos}$$

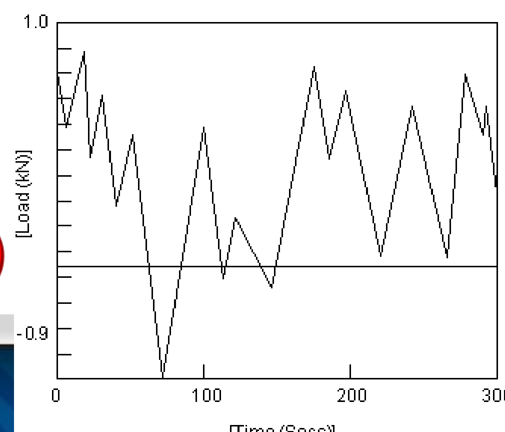
Rainflow + Damage

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









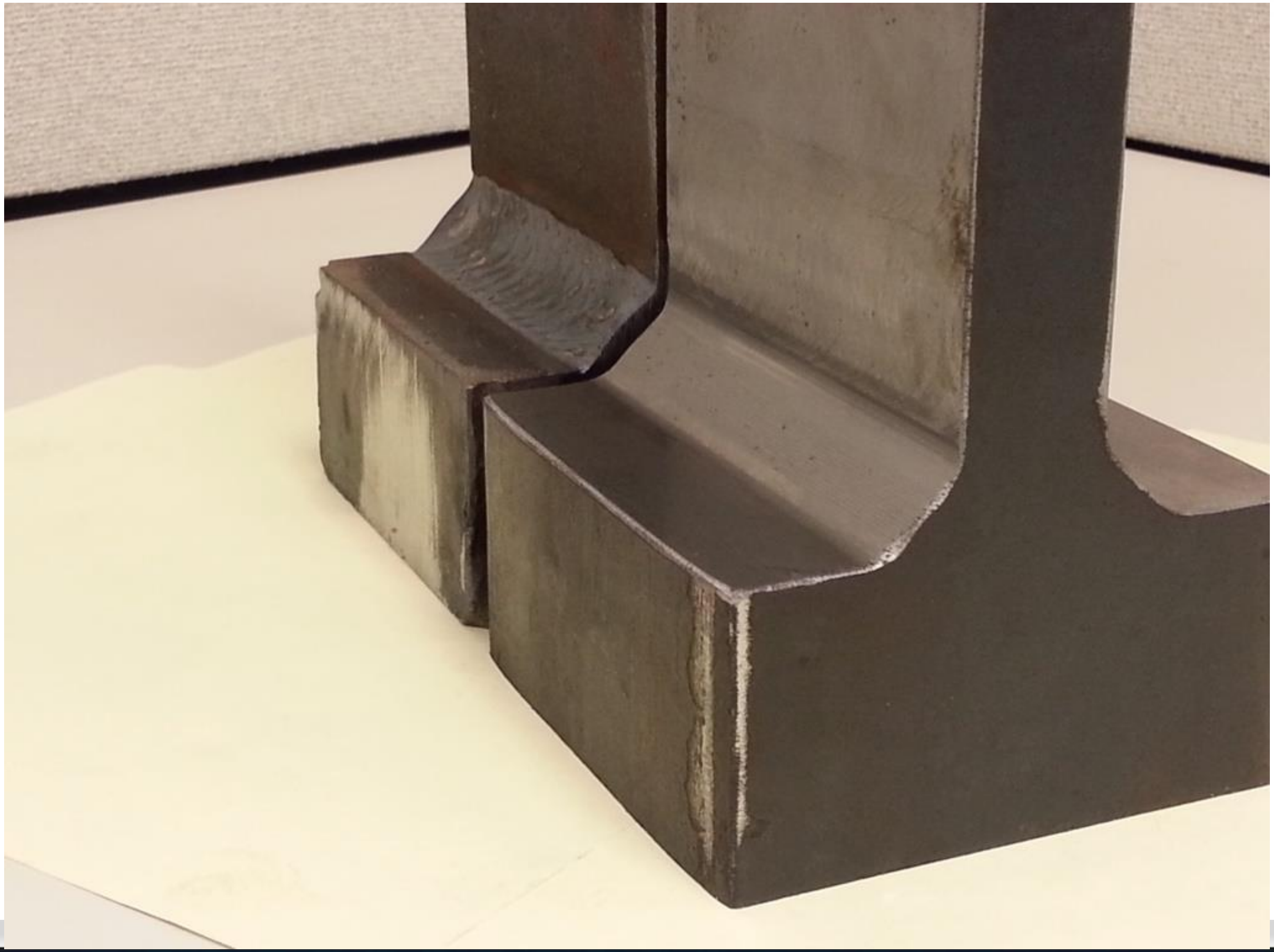
AGENDA

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)*

Fatigue of Welds

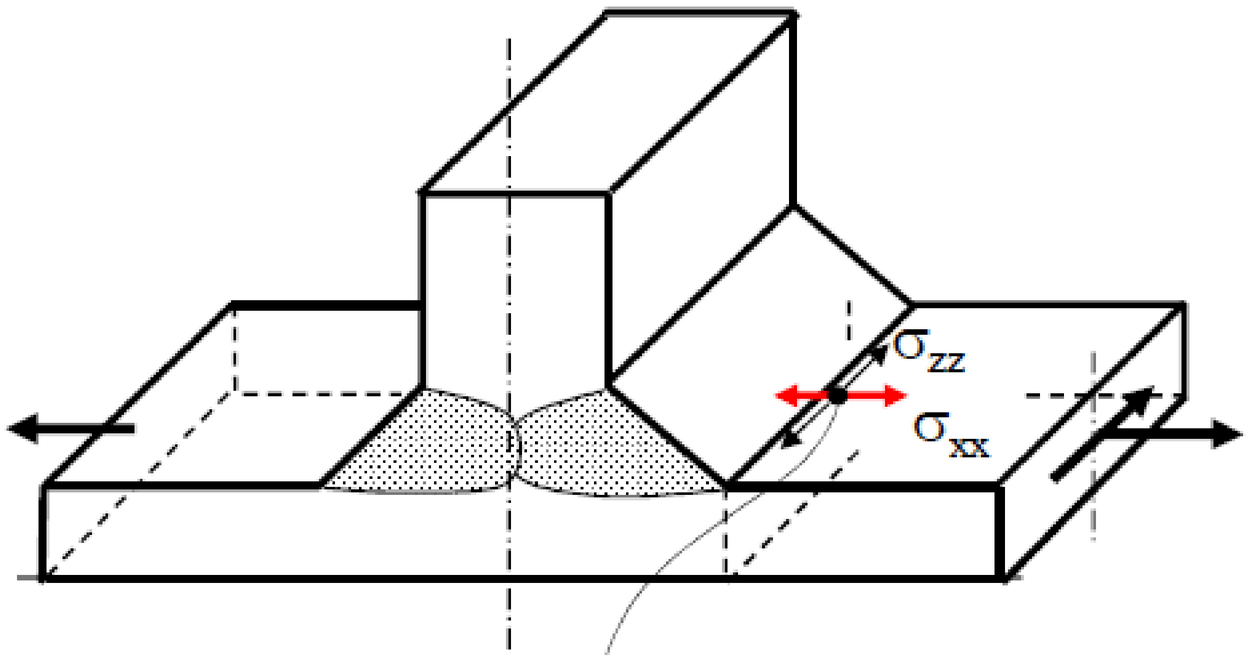
Weld Problems

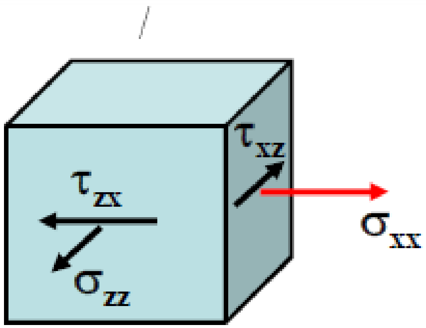
Fatigue of Welds



Fatigue of Welds

Stress State

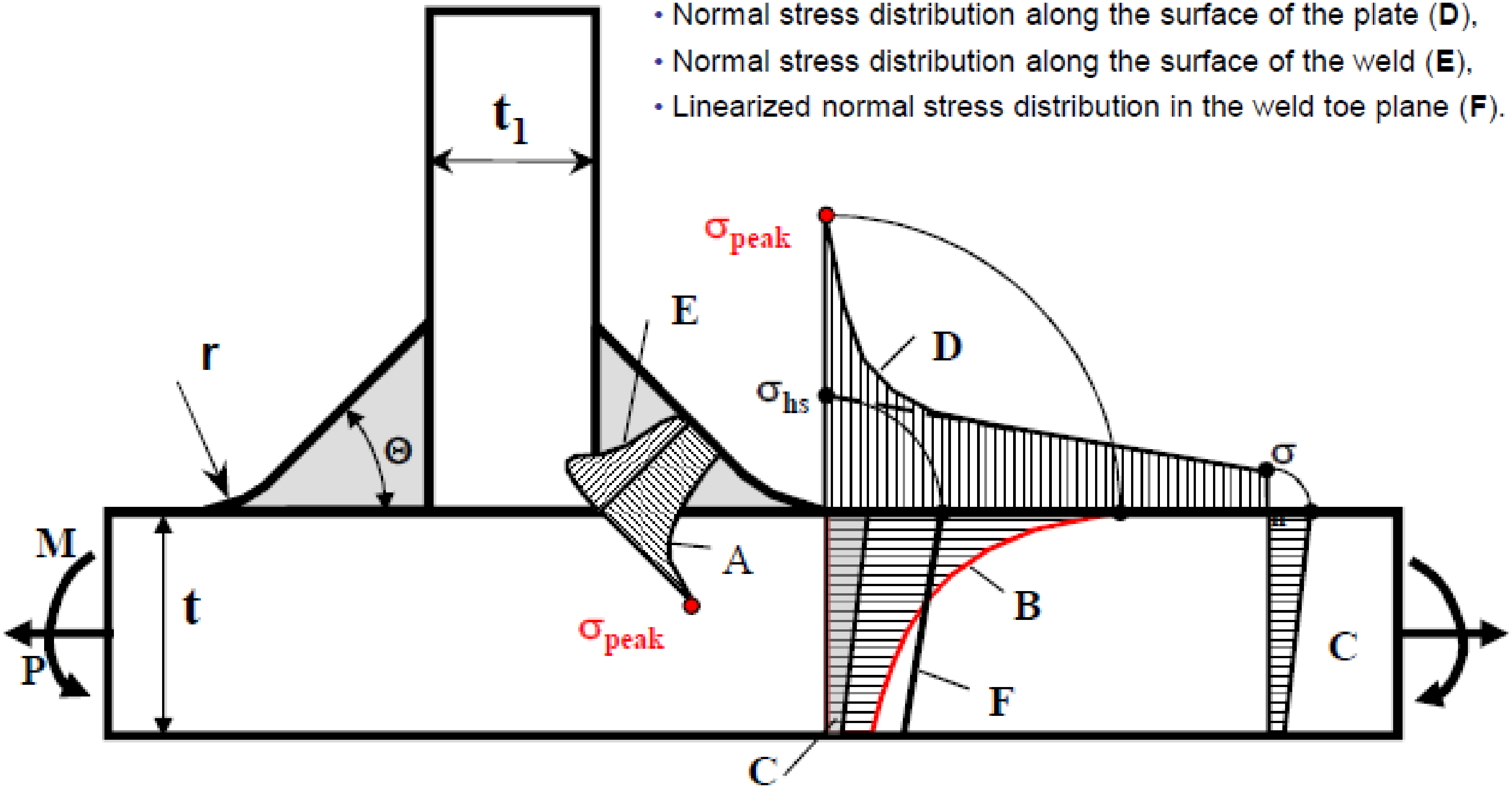




- Multiaxial State of Stress at the weld toe
- Due to notch σ_{xx} is the largest componente and responsible for fatigue damage

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**).

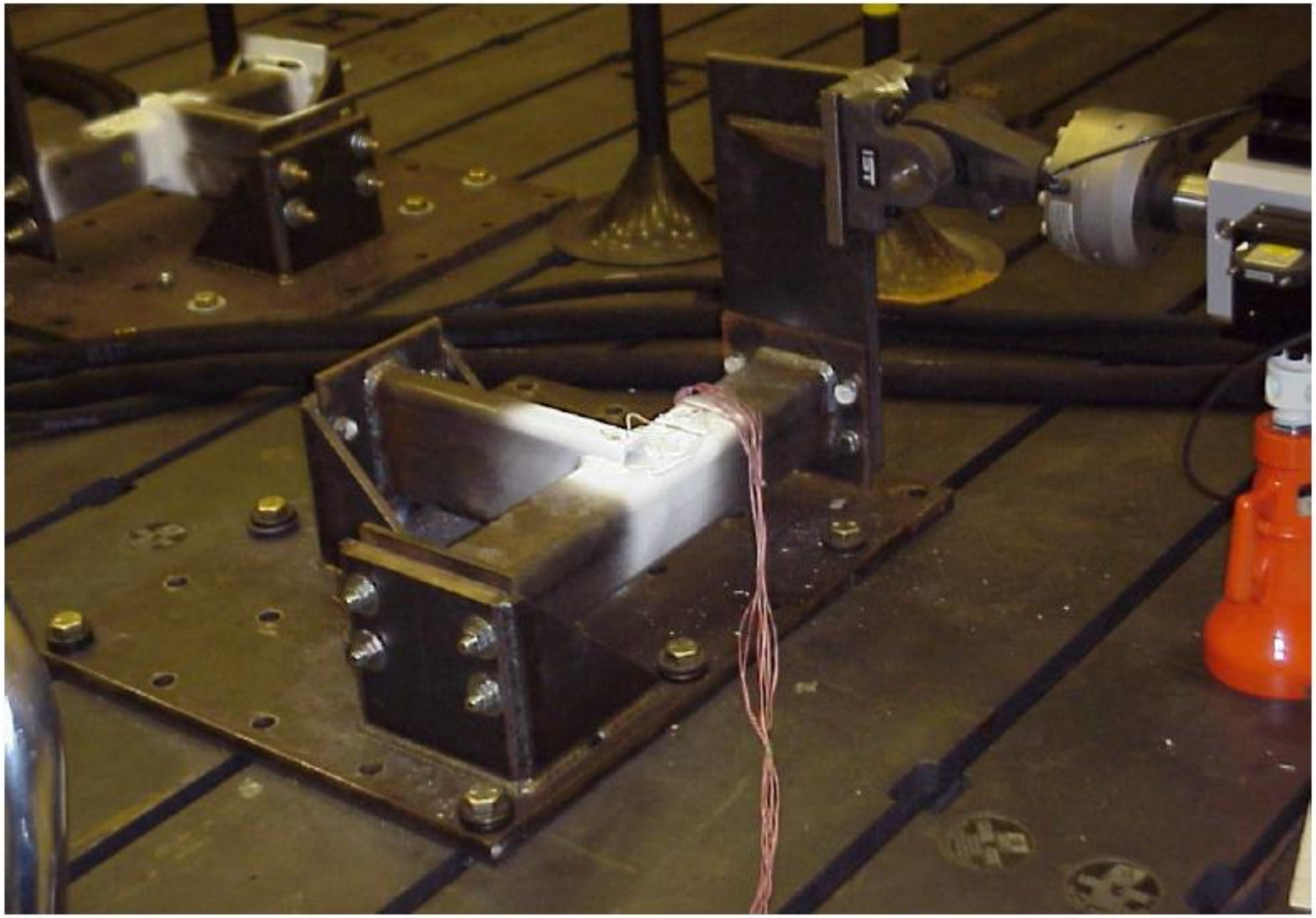


Various stress distributions in a T-butt weldment with transverse fillet welds;

2008 Grzegorz Glinka.

Design Fatigue Curves

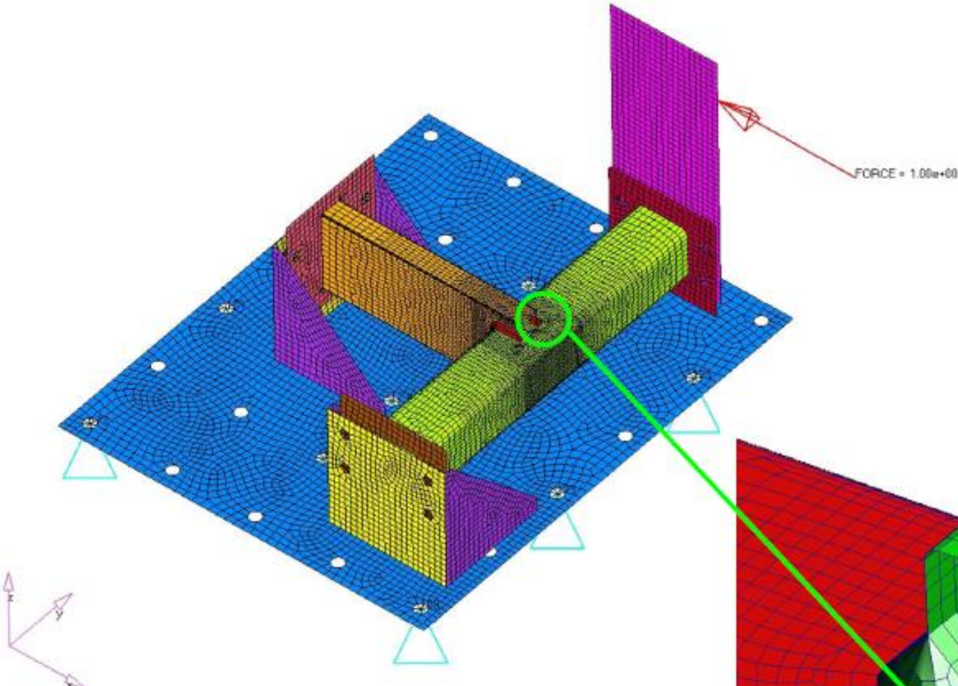
Tubular Welded Joint under Torsion and Bending



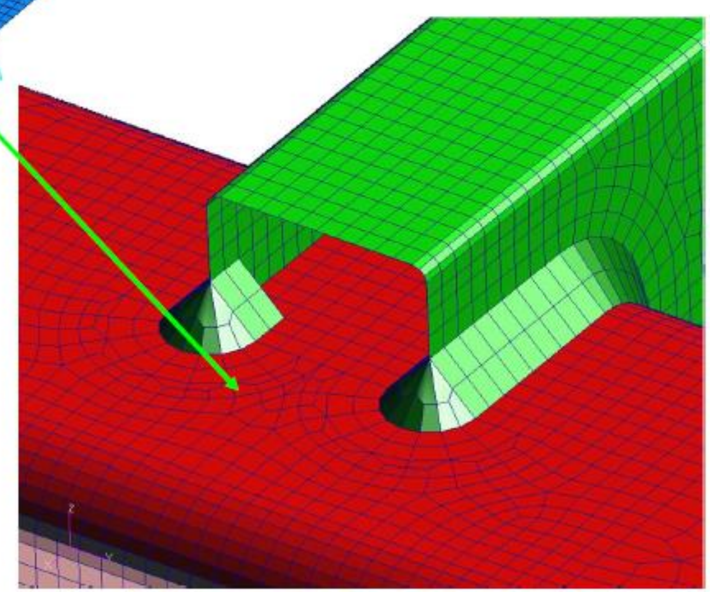
Courtesy of John Deere Co.

Design Fatigue Curves

Shell Element Model Details



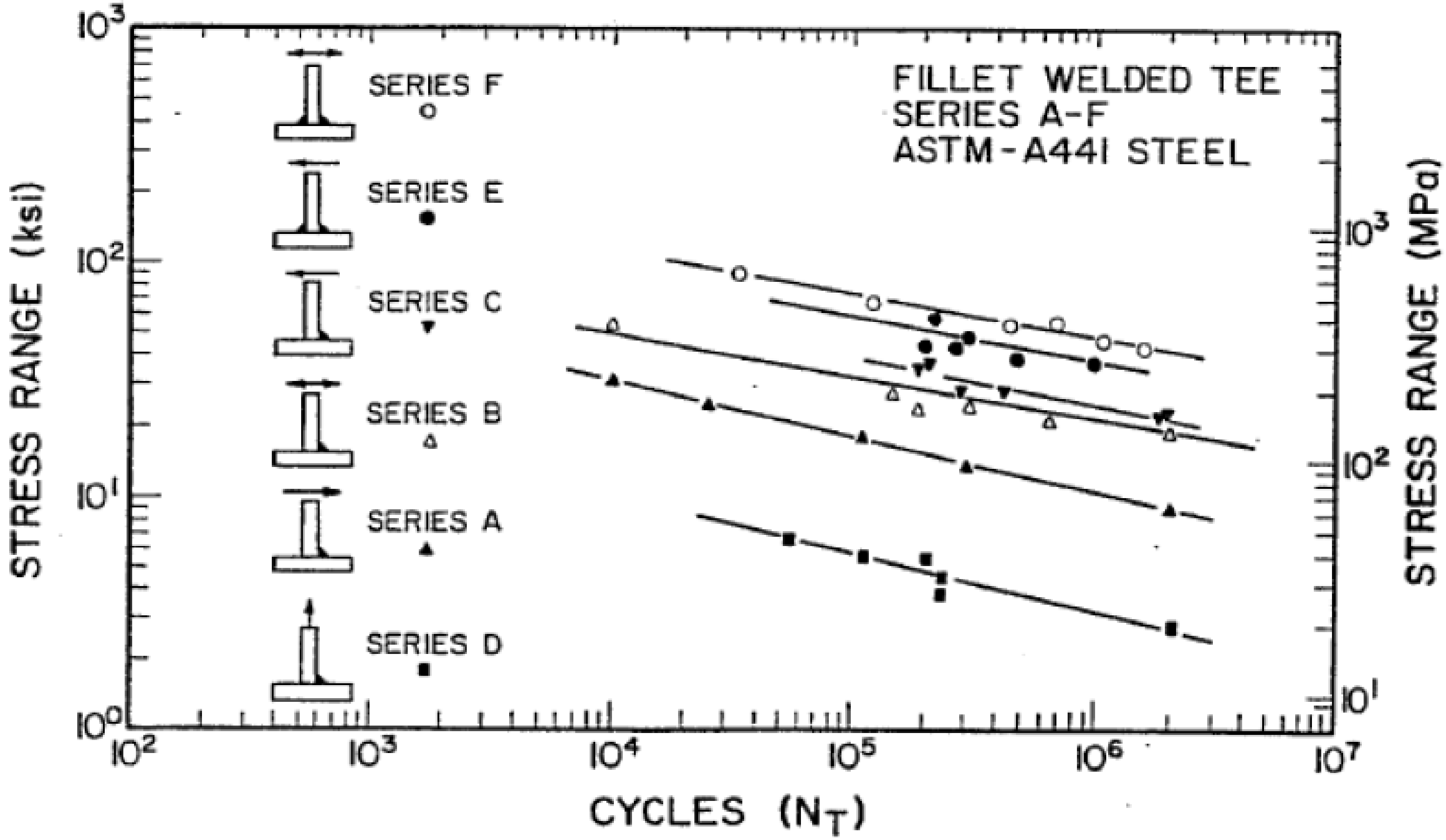
19197 nodes
18858 elements (linear quads)
114069 dof
Follows GY-2 modeling practice



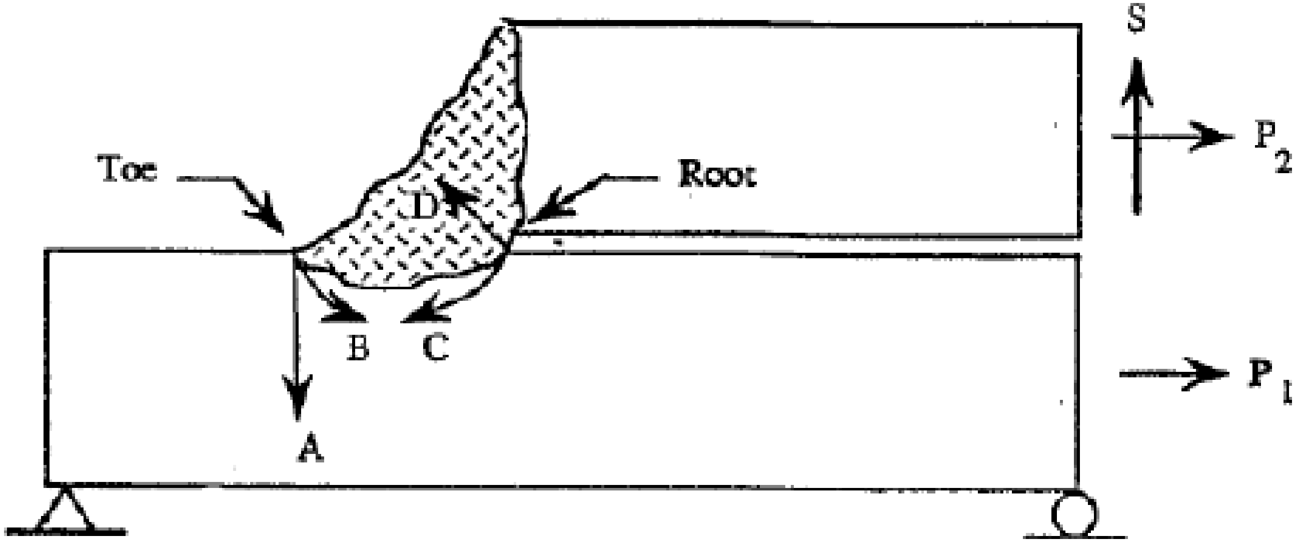
Material:
A22H Steel (ASTM A500 Cold Formed Steel for Structural Tubing)

Courtesy of John Deere Co.

Design Curves



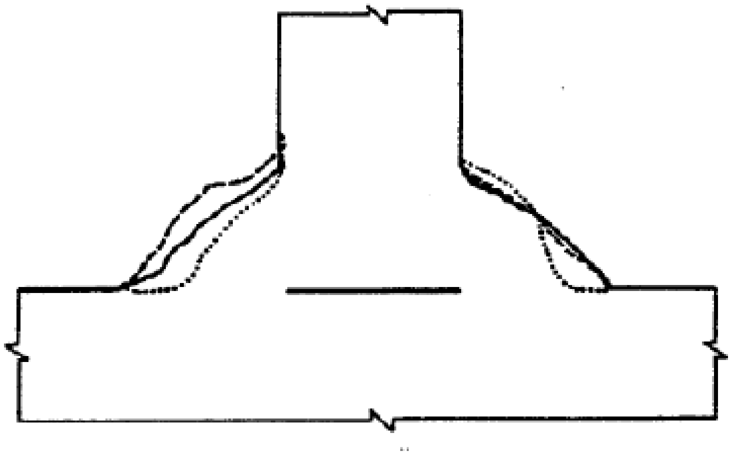
Failure Locations

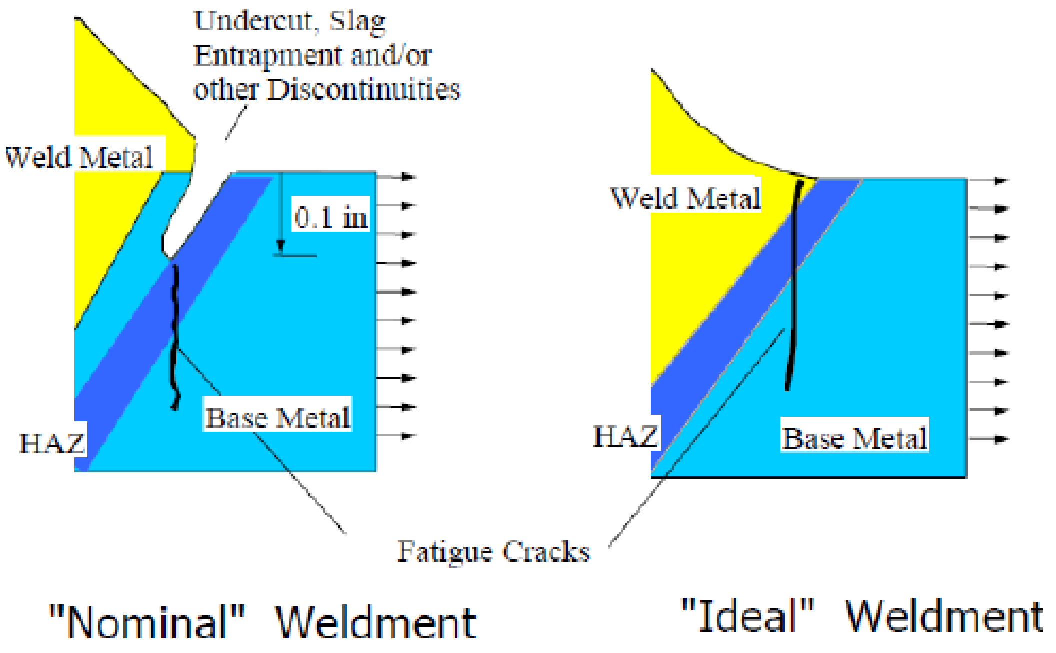


Fatigue of Welds

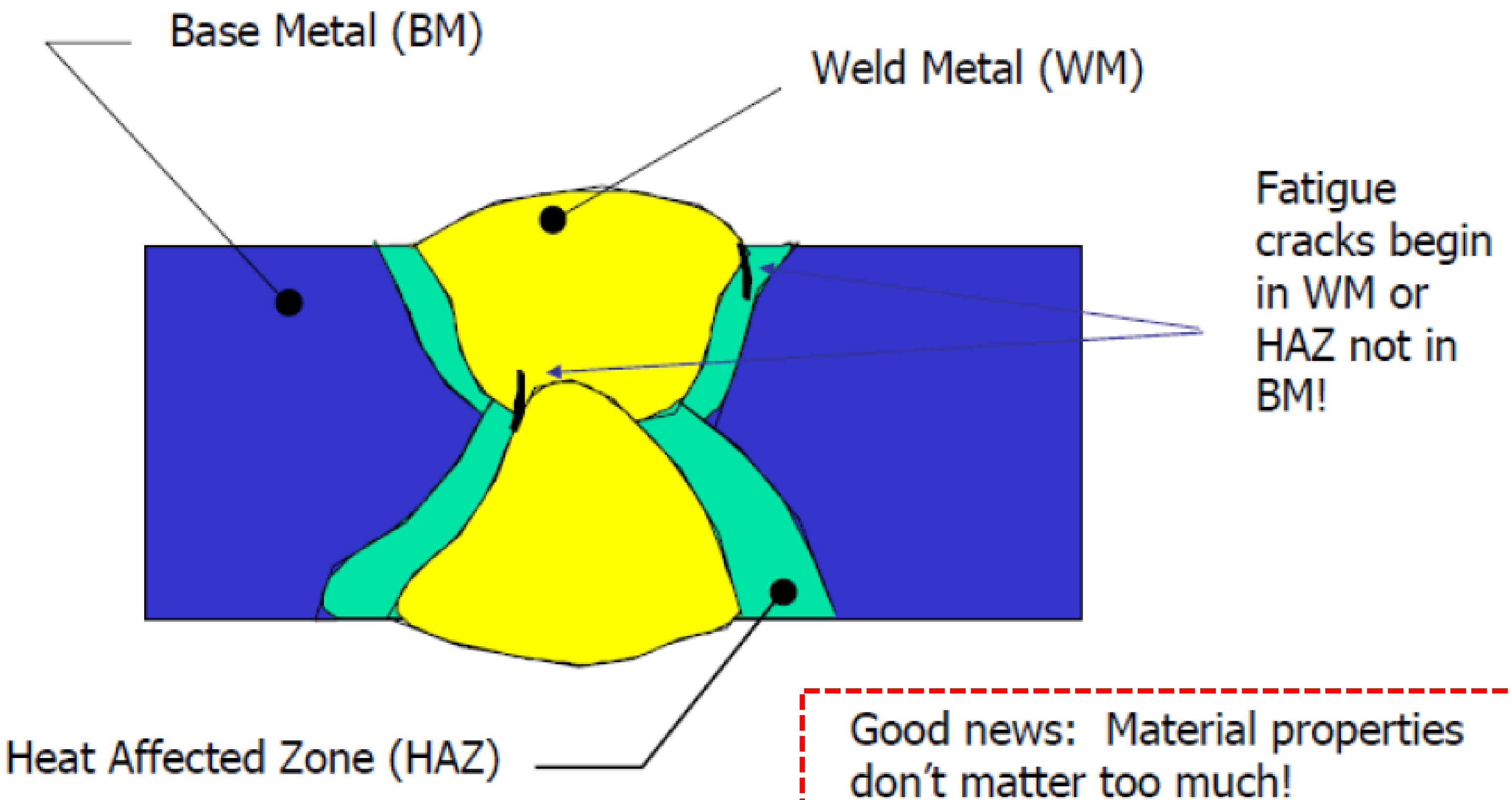
Weld Shape?

Weld Quality?





Material Properties



Good news: Material properties don't matter too much!

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.

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.

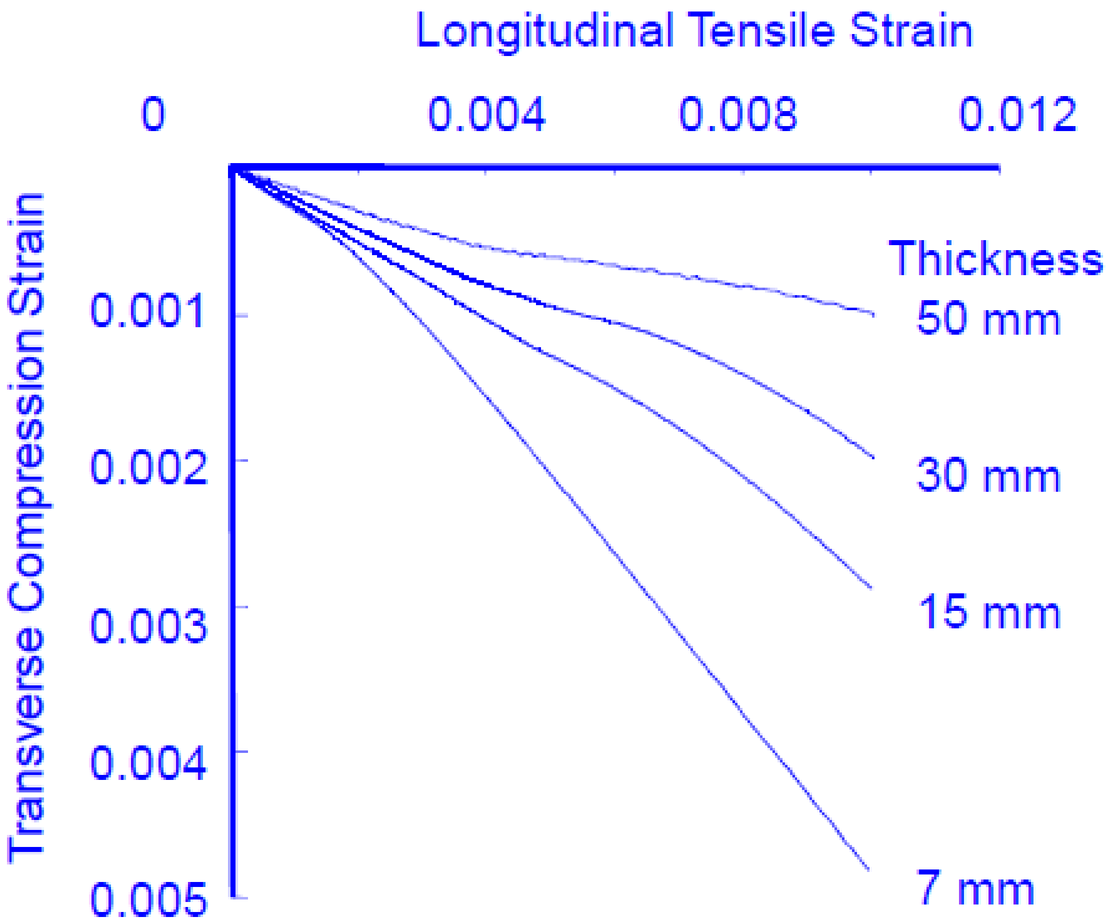
AGENDA

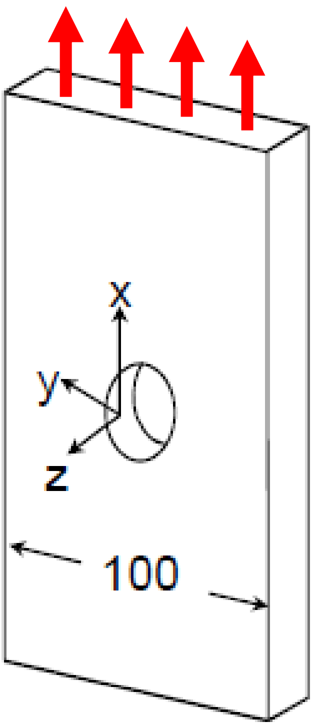
4. *Metodologias para Avaliação da Vida à Fadiga (Fatigue Methodologies)*
   - *Carregamento Constante (Constant Amplitude)*
     - *S-N*
     - *e-N*
     - *da/dN-DK*
   - *Efeitos de Entalhes (Notches)*
   - *Carregamento Variável (Variable Amplitude Loading)*
     - *Contagem de Ciclos (Cycle Counting)*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

dsarzosa@usp.br

Multiaxial Fatigue

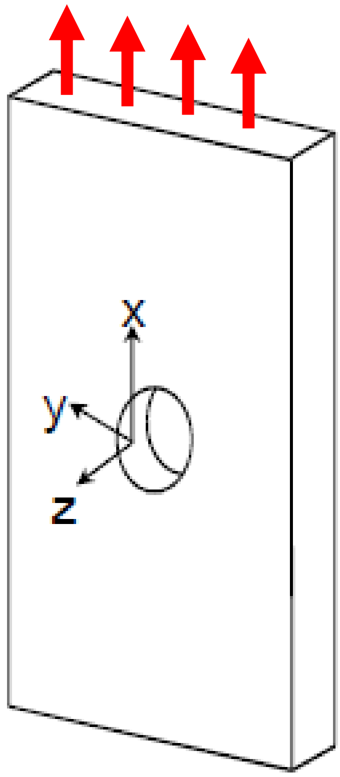
3D Stresses





Multiaxial Fatigue

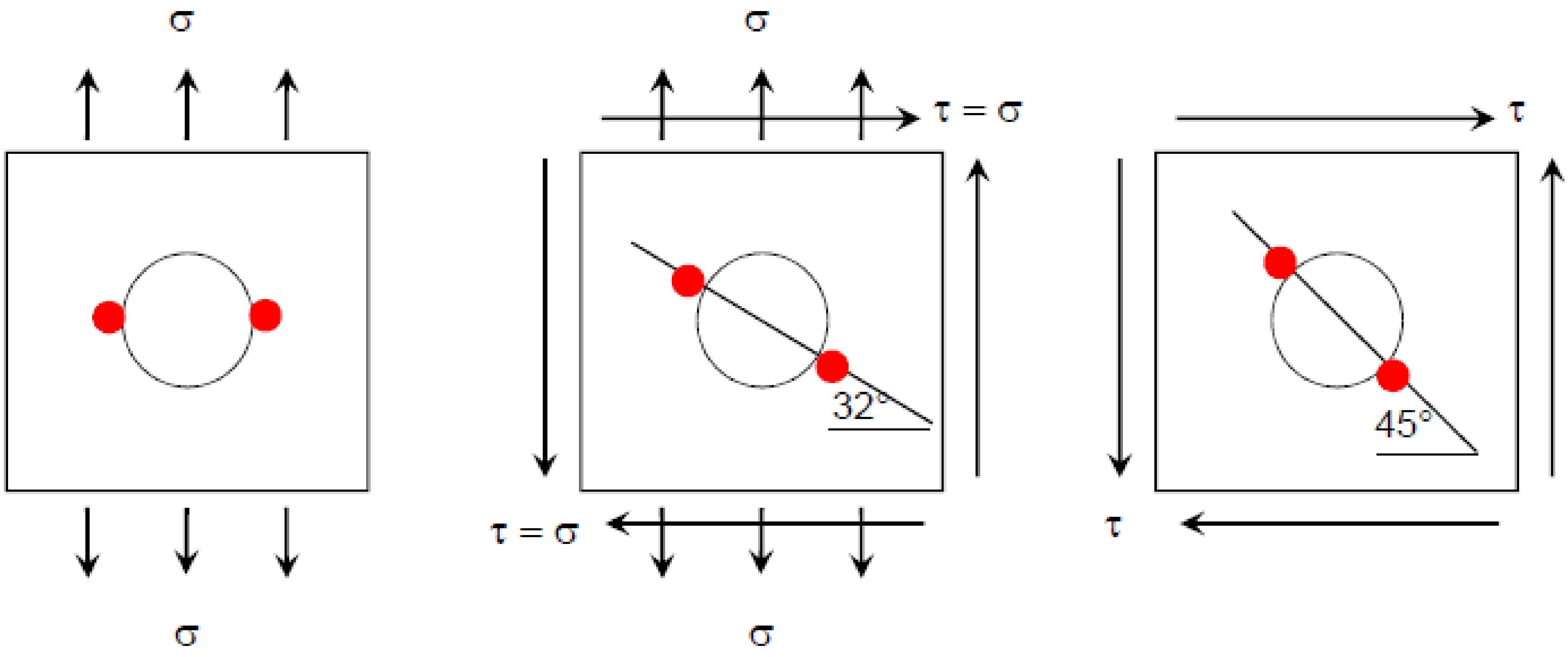
3D Stresses



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

Multiaxial Fatigue

Maximum Stress (Plane)

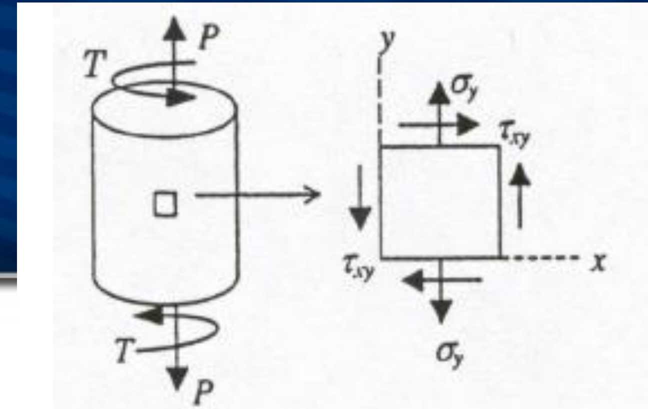


$K_t = 3$ $\sigma_1 = \sigma$

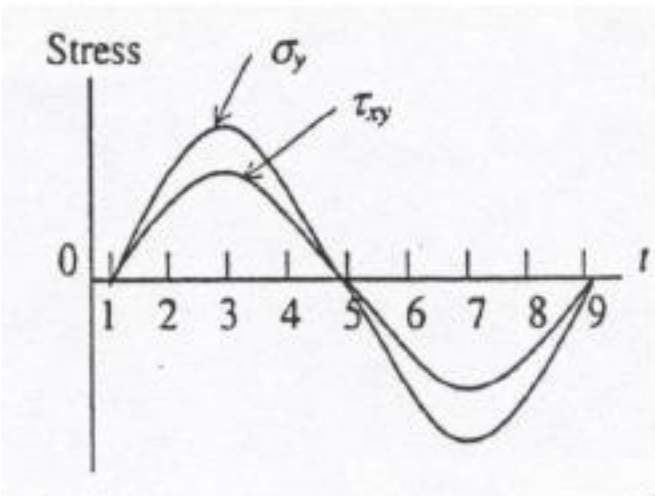
$K_t = 3.41$ $\sigma_1 = 1.72\sigma$

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

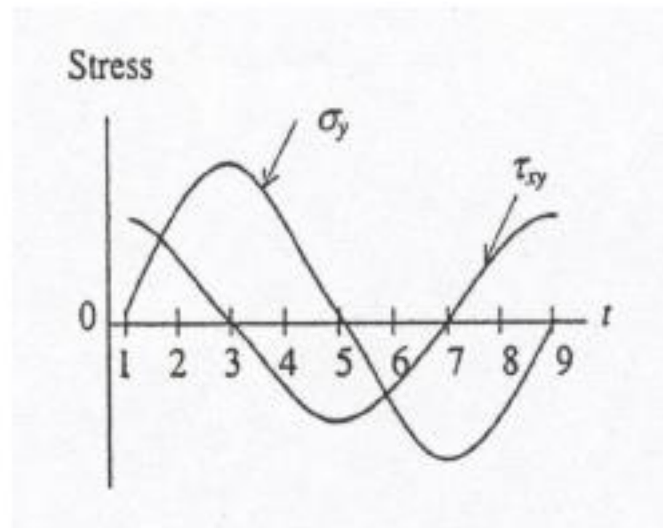
Multiaxial Fatigue

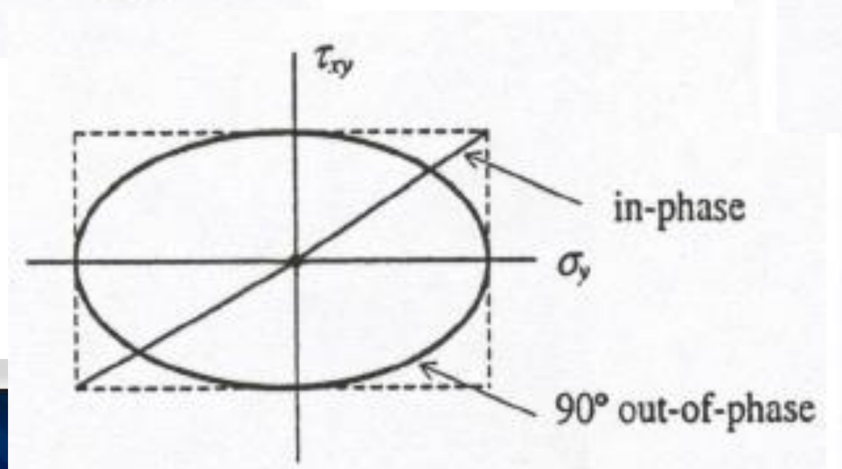


Proportional Loading



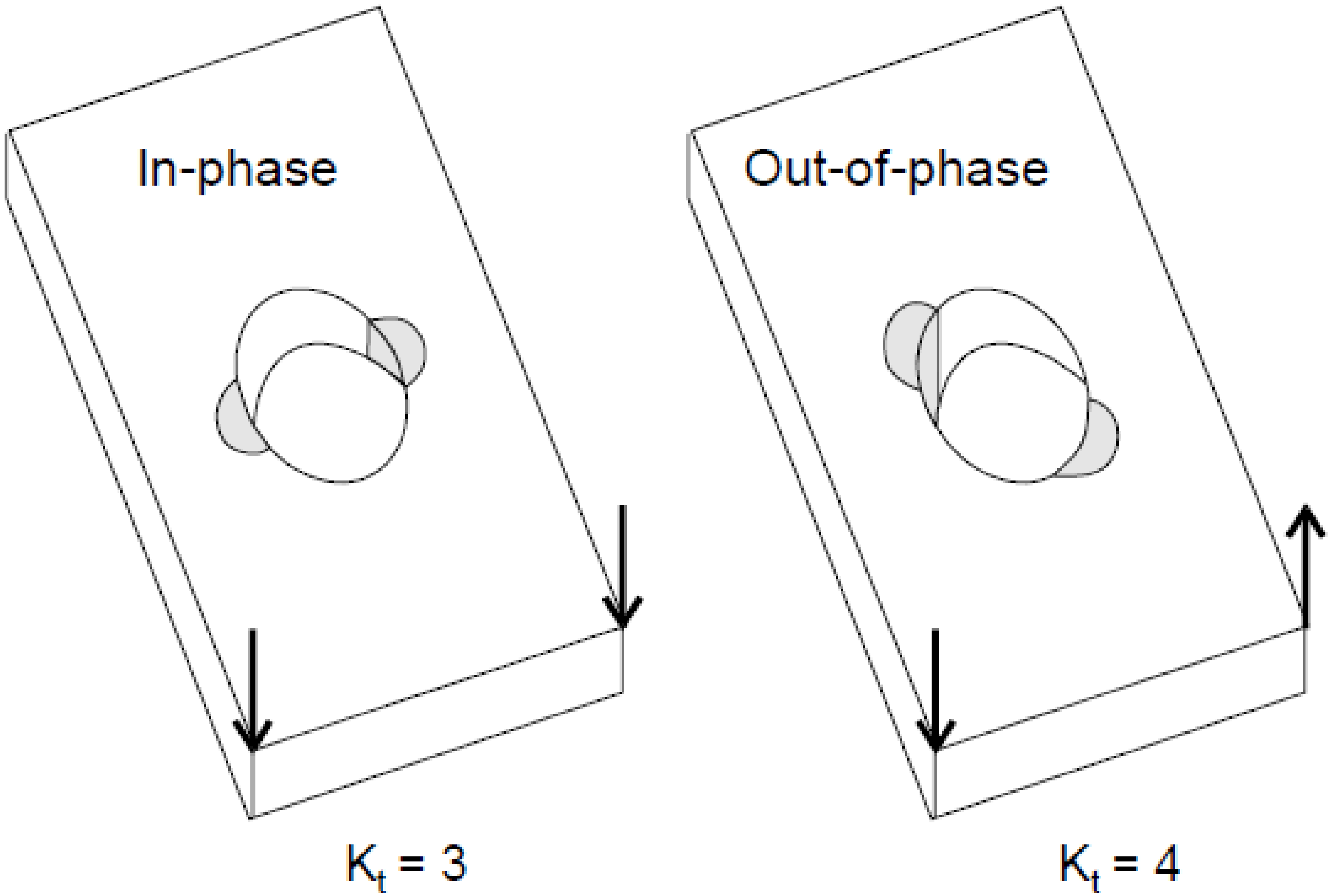
Nonproportional Loading





Out-of-phase

Multiaxial Fatigue



Damage location changes with load phasing

Obrigado!

Diego F. B. Sarzosa
Universidade de São Paulo - USP