Fadiga de Materiais Estruturais: Fundamentos e Aplicações
Metodologia S-N
(Strain-based Methodology)

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AGENDA

1. *Introdução (Introduction)*
2. *Comportamento do Material (Material Behavior)*
3. *Curvas de Fadiga ε-N (Strain-Life Curve)*
4. *Determinação das Propriedades (Fatigue Properties Determination)*
5. *Tensão Média (Mean Stress)*
6. *Fatores que Afetam a Vida à Fadiga (Factors Influencing ε-N Response)*

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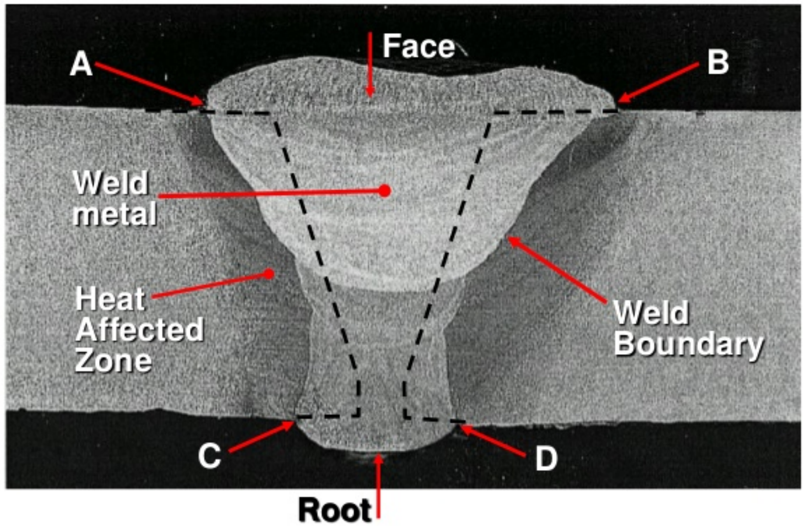
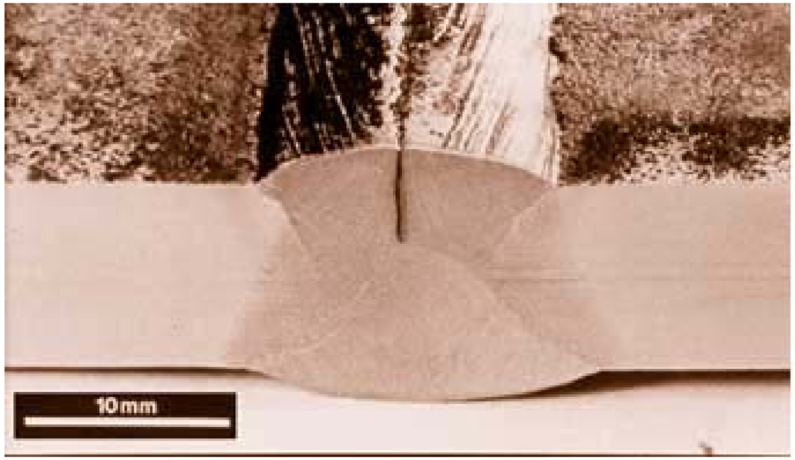
Introduction

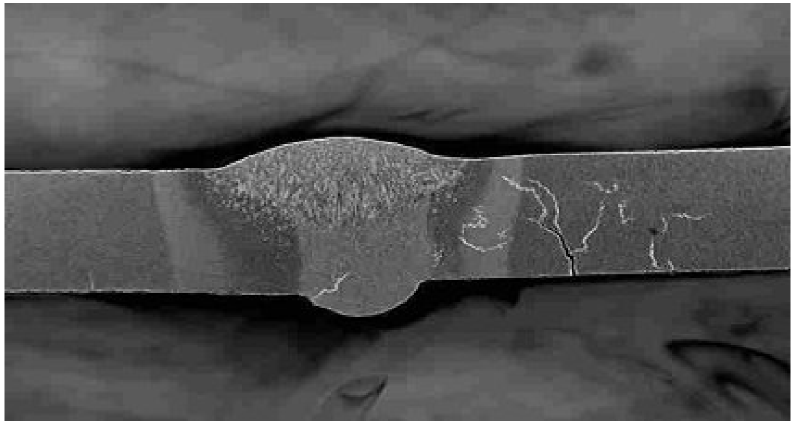
- ***Butt Weld – V Joint***

Weld Zone Terminology 2.5



A, B, C & D = Weld Toes

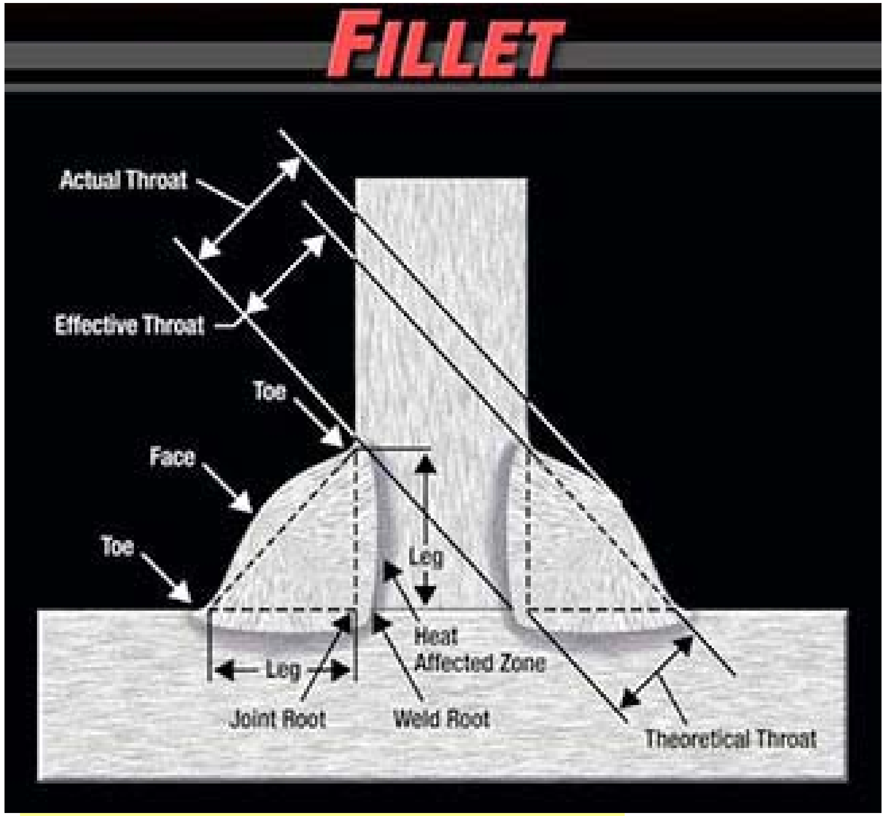




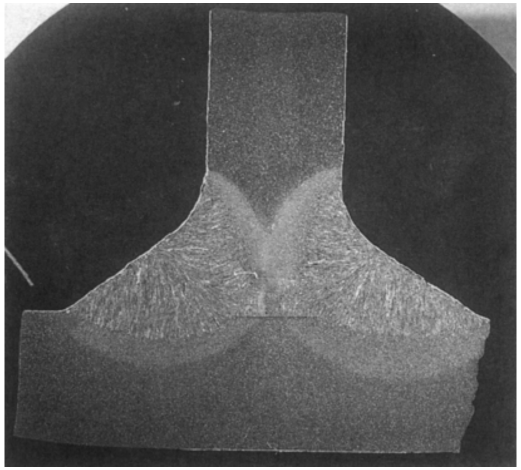
Notches = stress raisers

Introduction

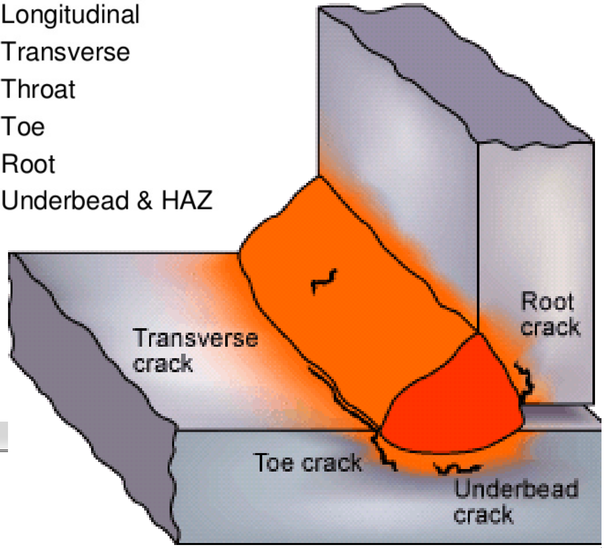
- ***Fillet T Weld***



Notches = stress raisers

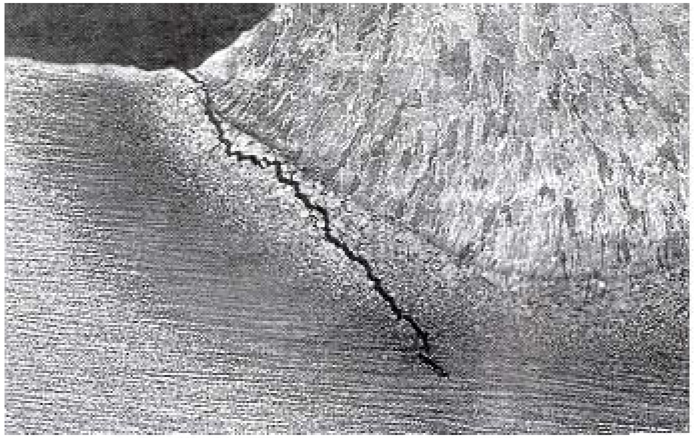


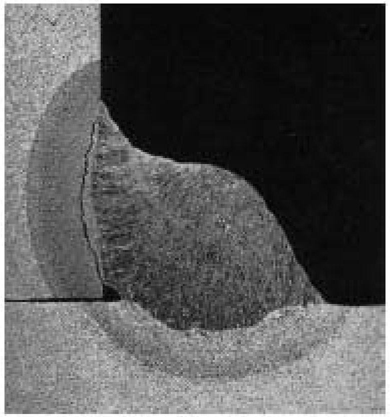
- Longitudinal
- Transverse
- Throat
- Toe
- Root
- Underbead & HAZ

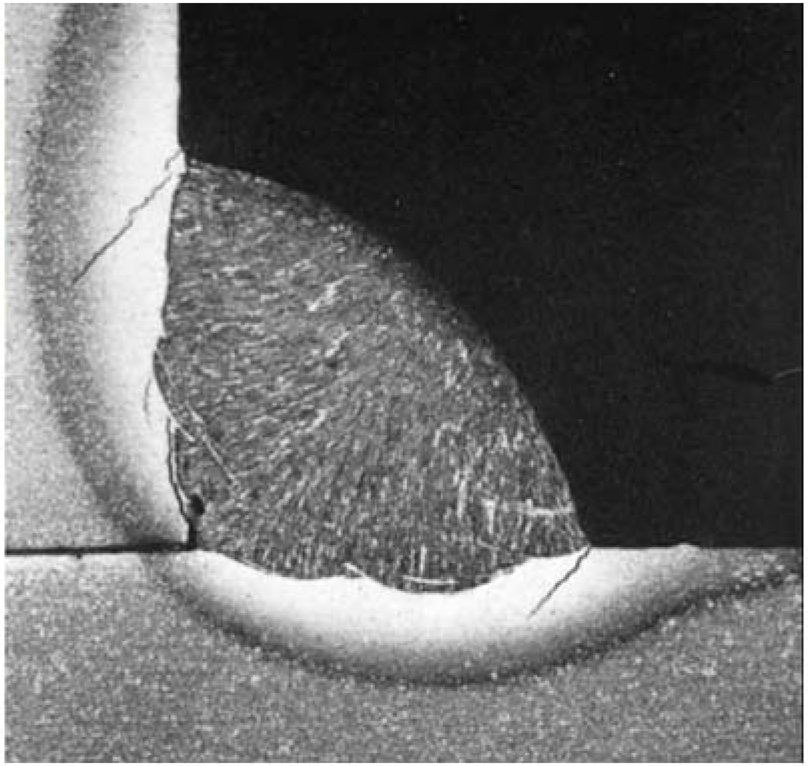


Introduction

- ***Fillet T Weld***





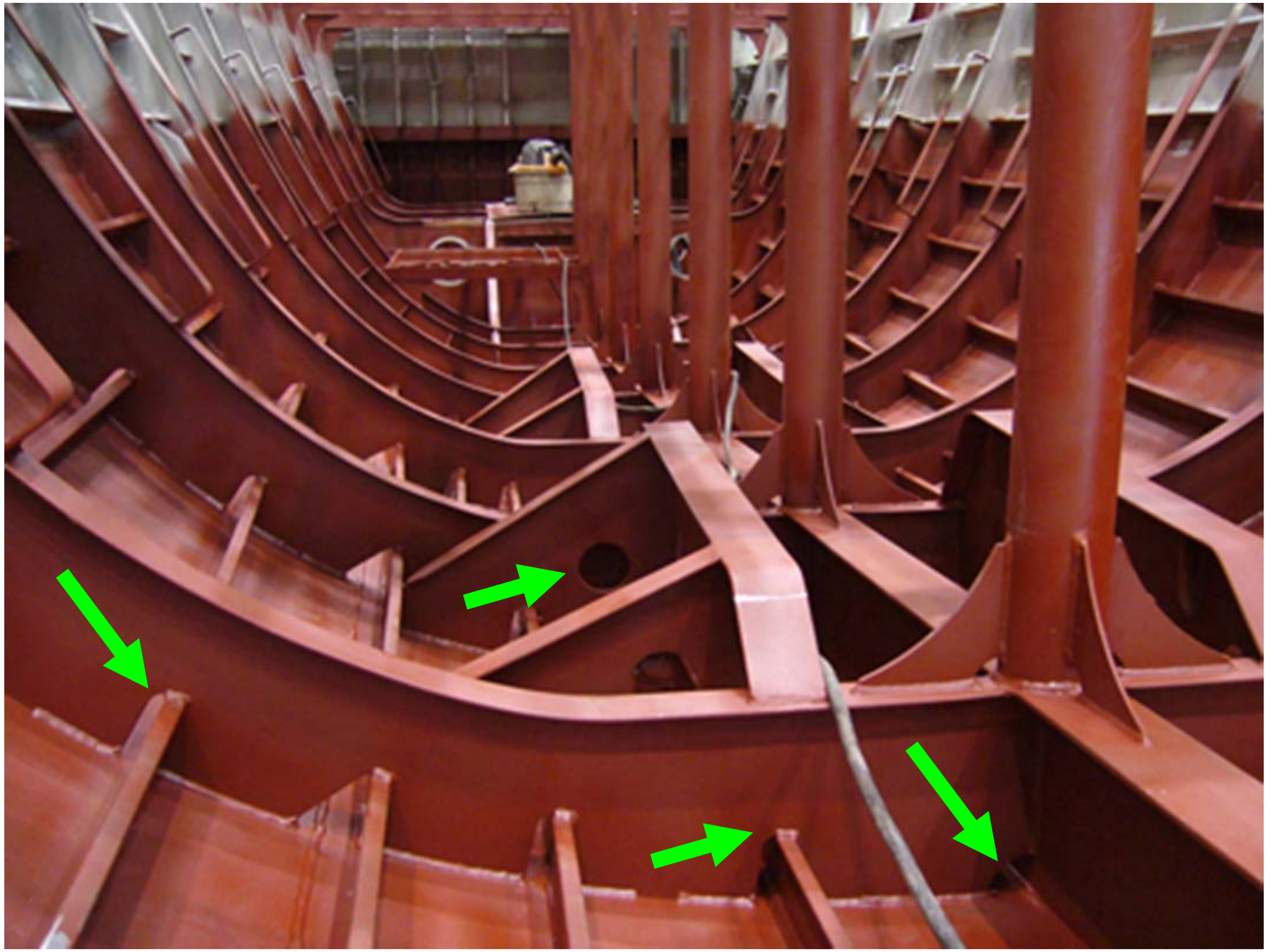


Notches = stress raisers

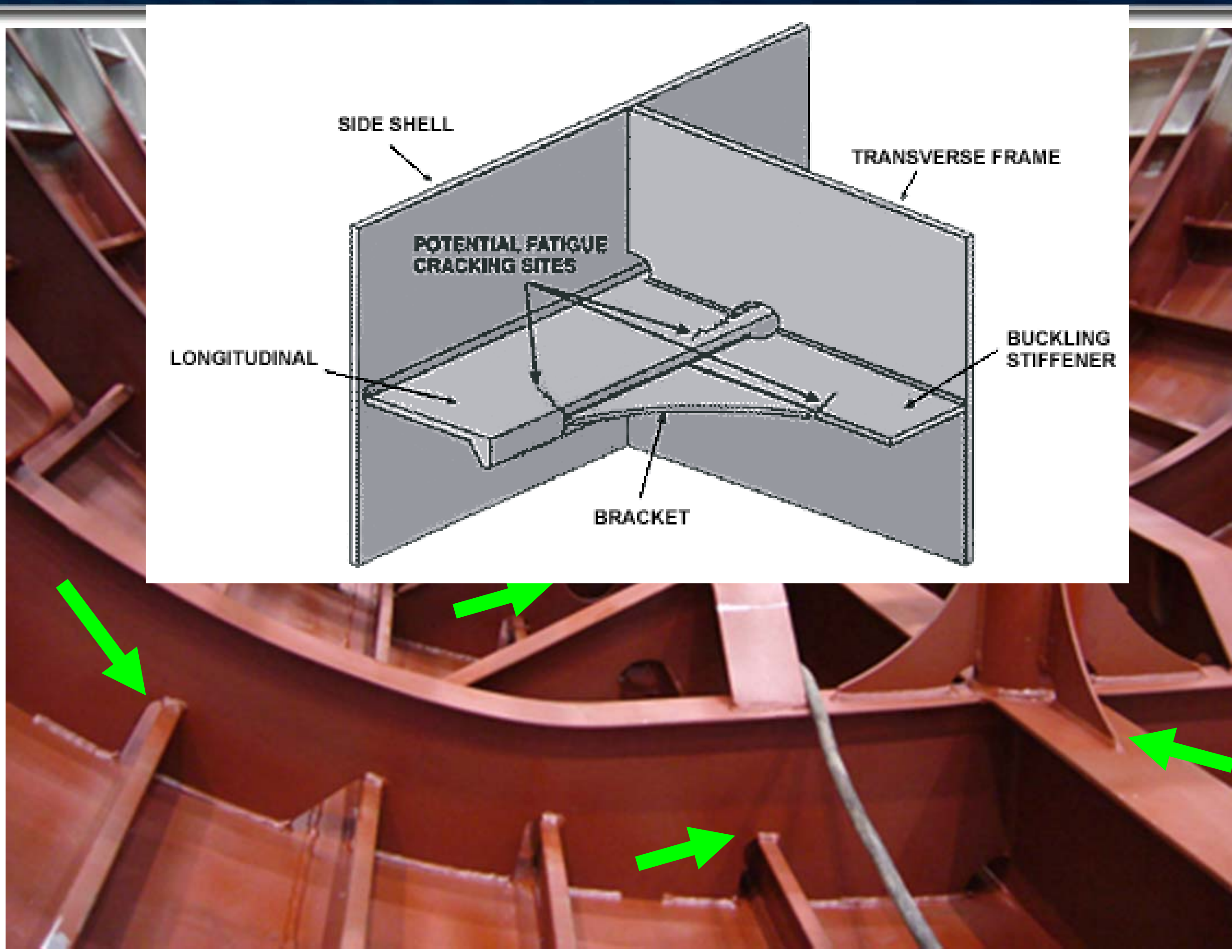
Opening (Notch)

Notches = stress raisers

Entalhes (Notches)

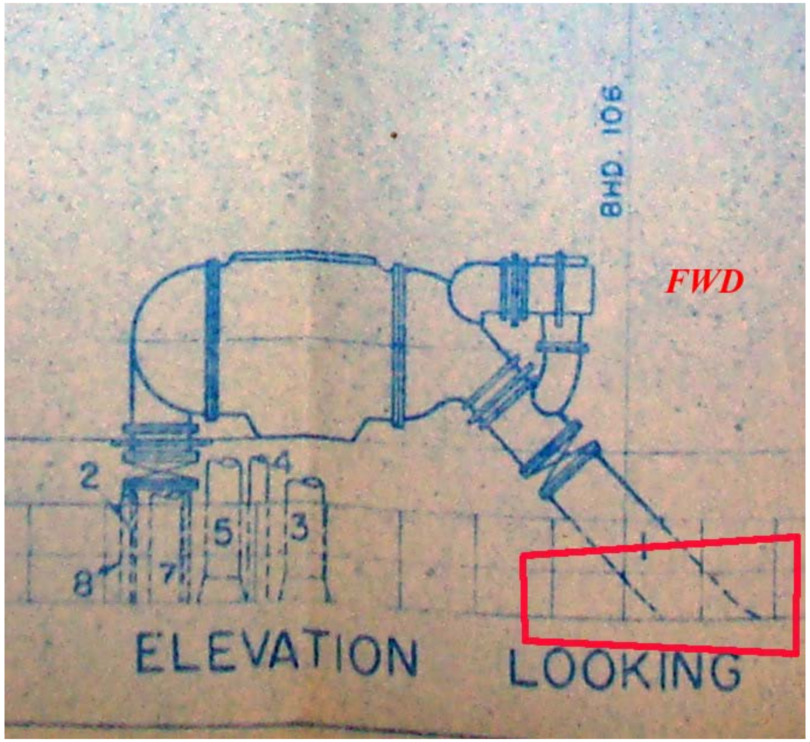


Entalhes (Notches)



Opening (Notch)

caixa de mar (sea chests)

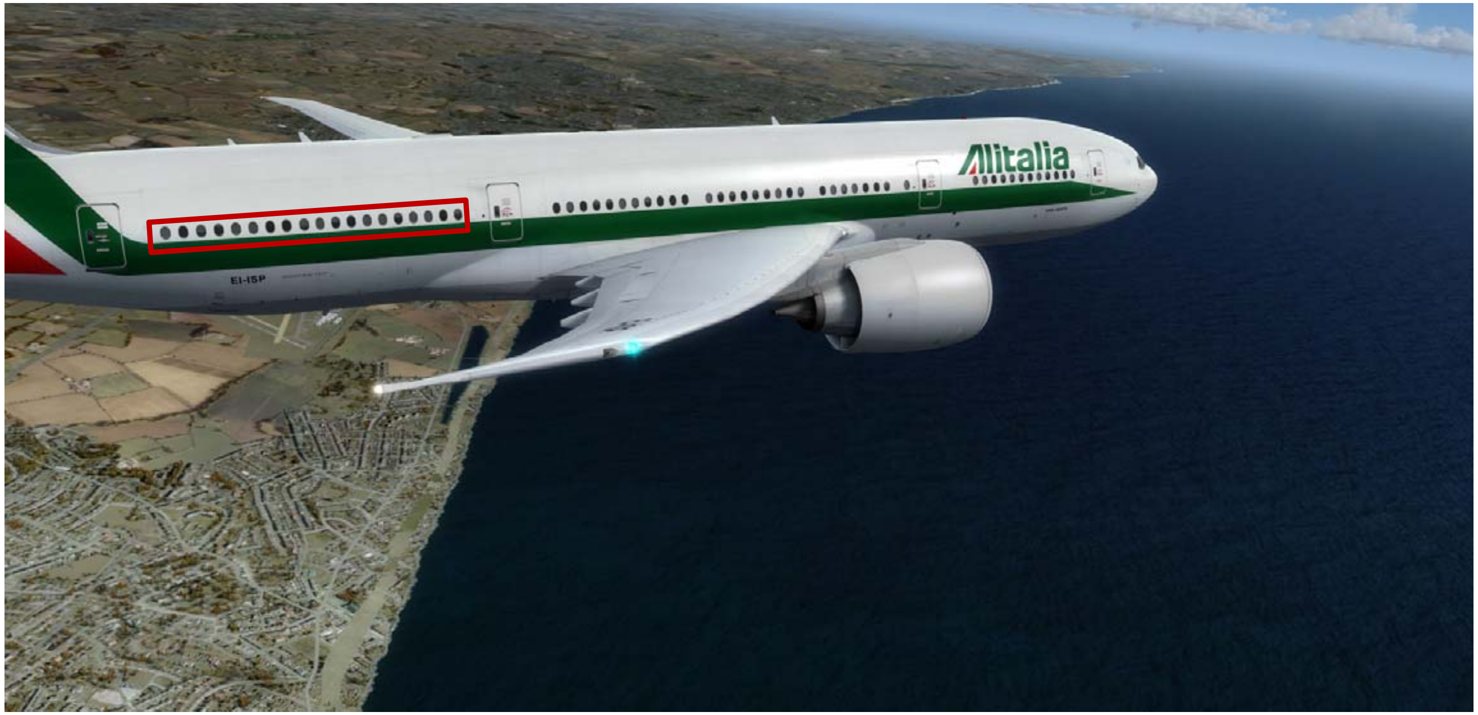


Sea Chest ----A compartment through which sea water is admitted or discharged.

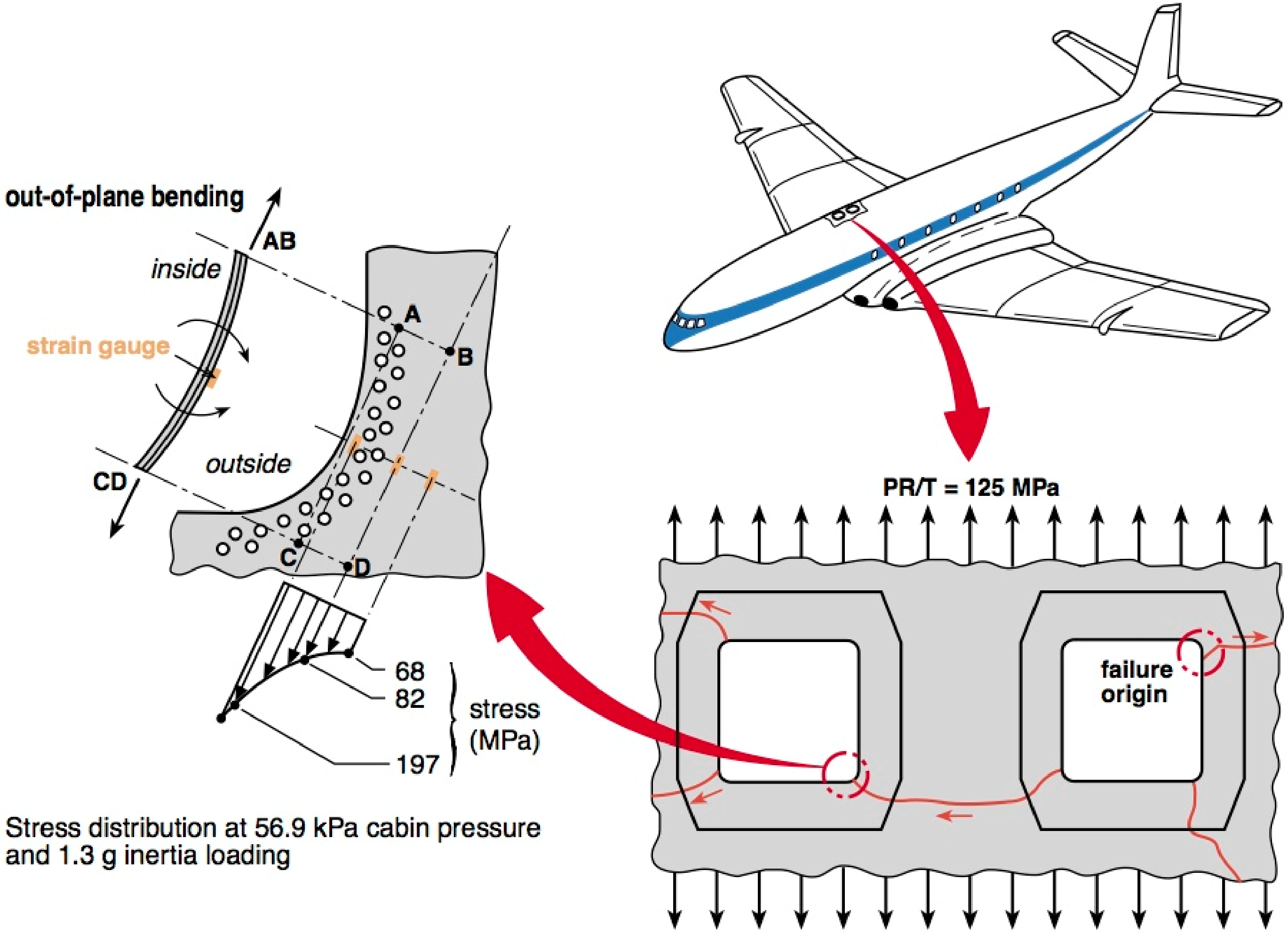
Entalhes (Notches)

Entalhes (Notches)

Entalhes (Notches)



Entalhes (Notches)

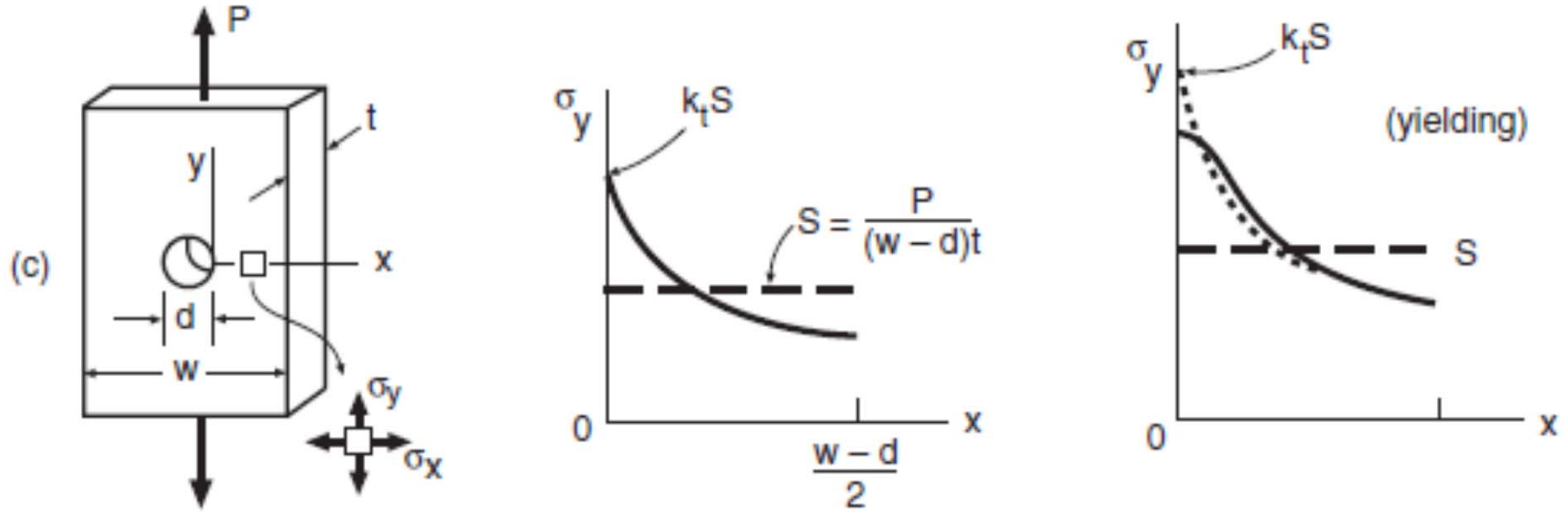


Stress distribution at 56.9 kPa cabin pressure
and 1.3 g inertia loading

Tensão no ponto versus Tensão Nominal

- Notched member
  - Área neta = (w-d)t

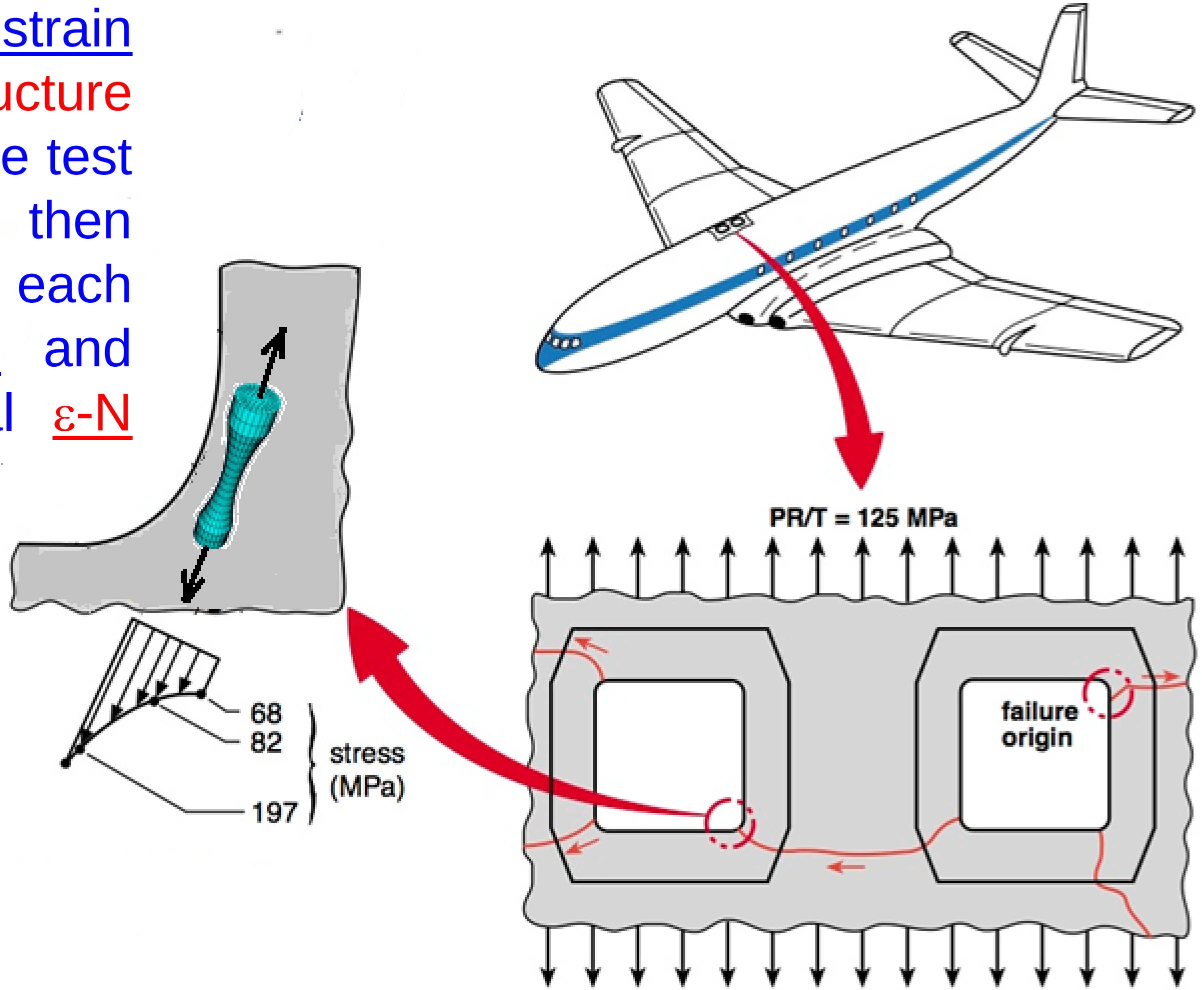
$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix} \longleftrightarrow S = \frac{P}{((w-d)\times t)}$$



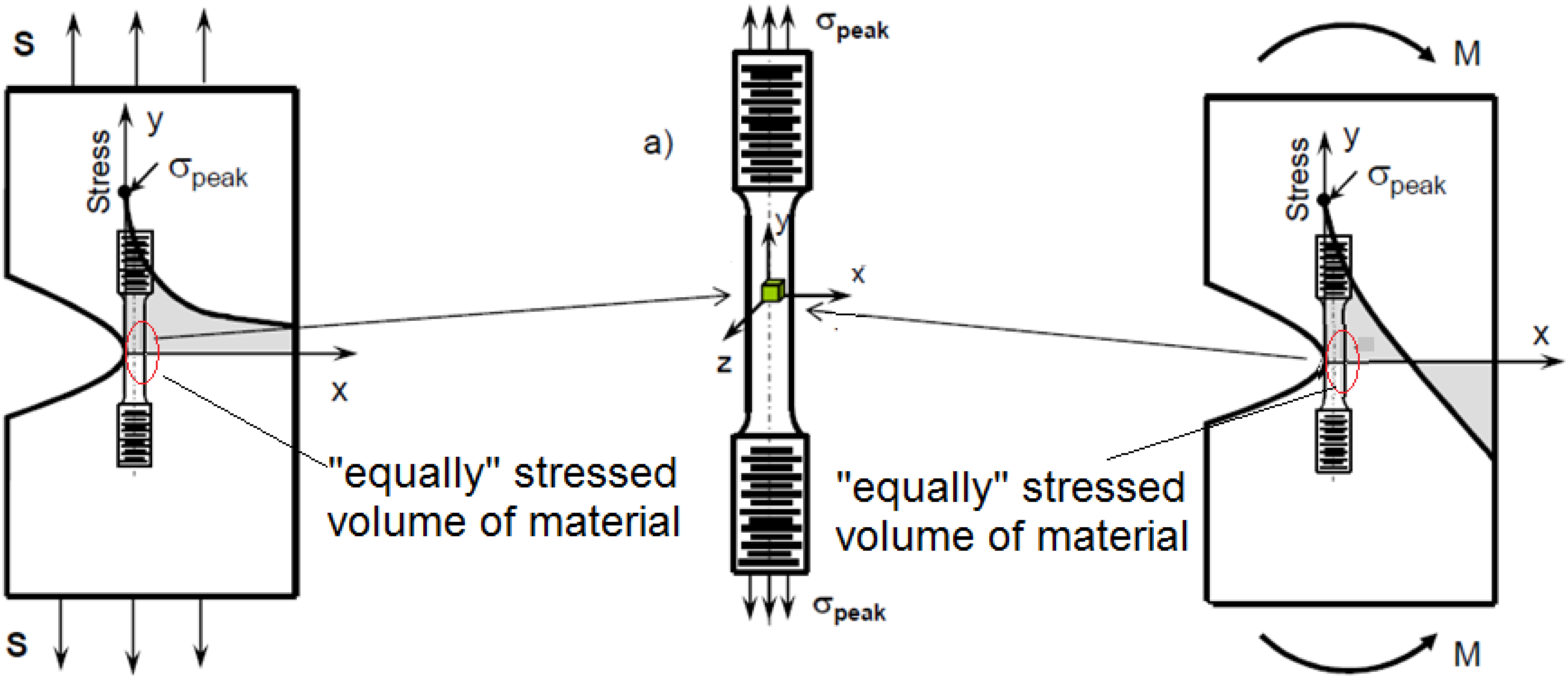
Notch= stress raiser (holes, grooves, fillets, etc)

Princípio de Similaridade (Similitude)

- If the local notch-tip strain history at the notched structure and the strain history in the test specimen are the same, then the fatigue response in each case will be the same and describe by the material ε-N curve.

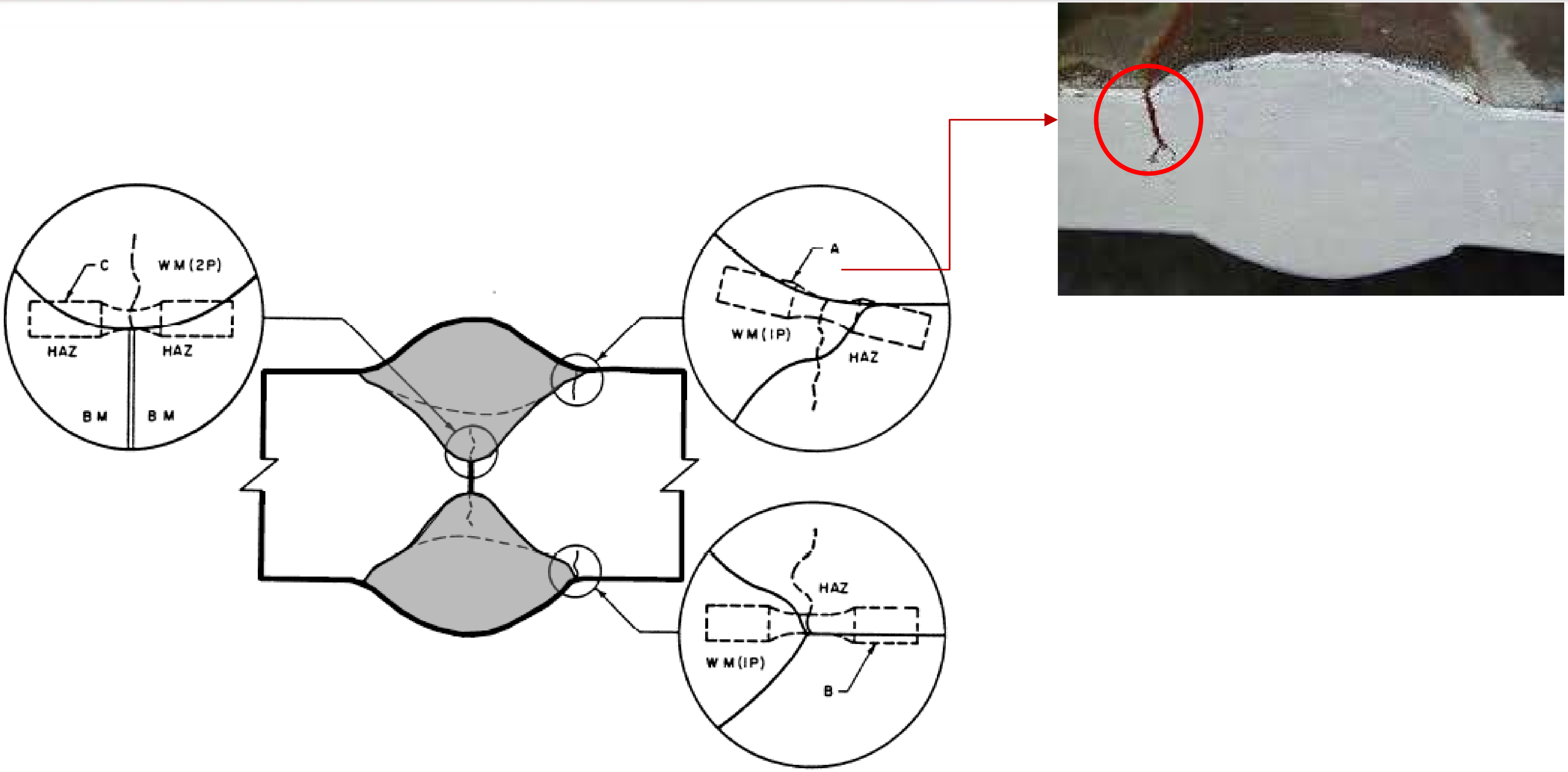


Princípio de Similaridade (Similitude)



Smooth specimen representing notched components

Princípio de Similaridade (Similitude)



Smooth specimen representing the critical regions of butt welded component

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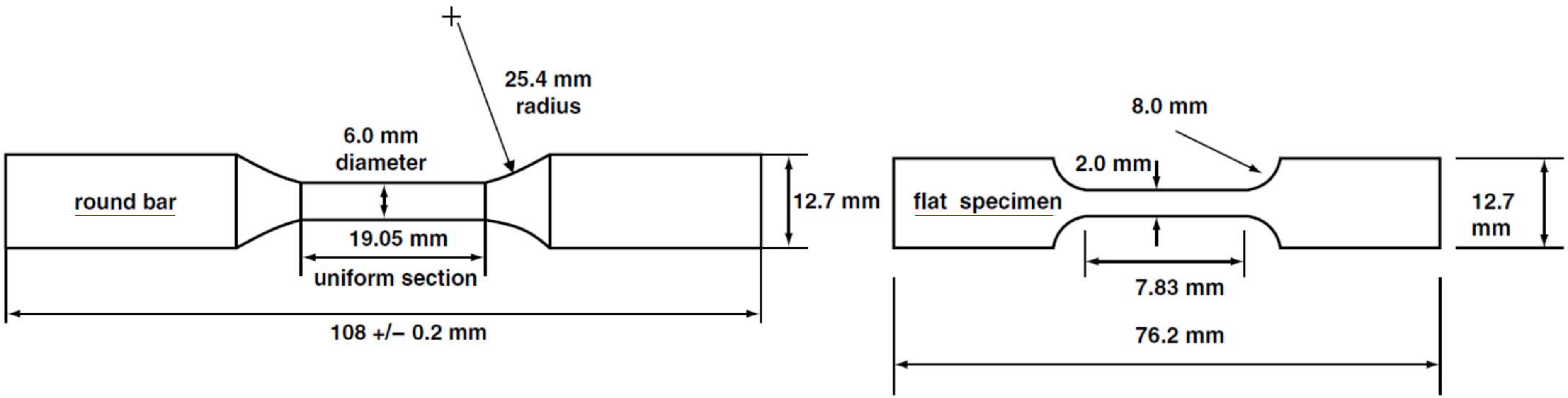
Monotonic Stress-Strain Behavior

ASTM E8M

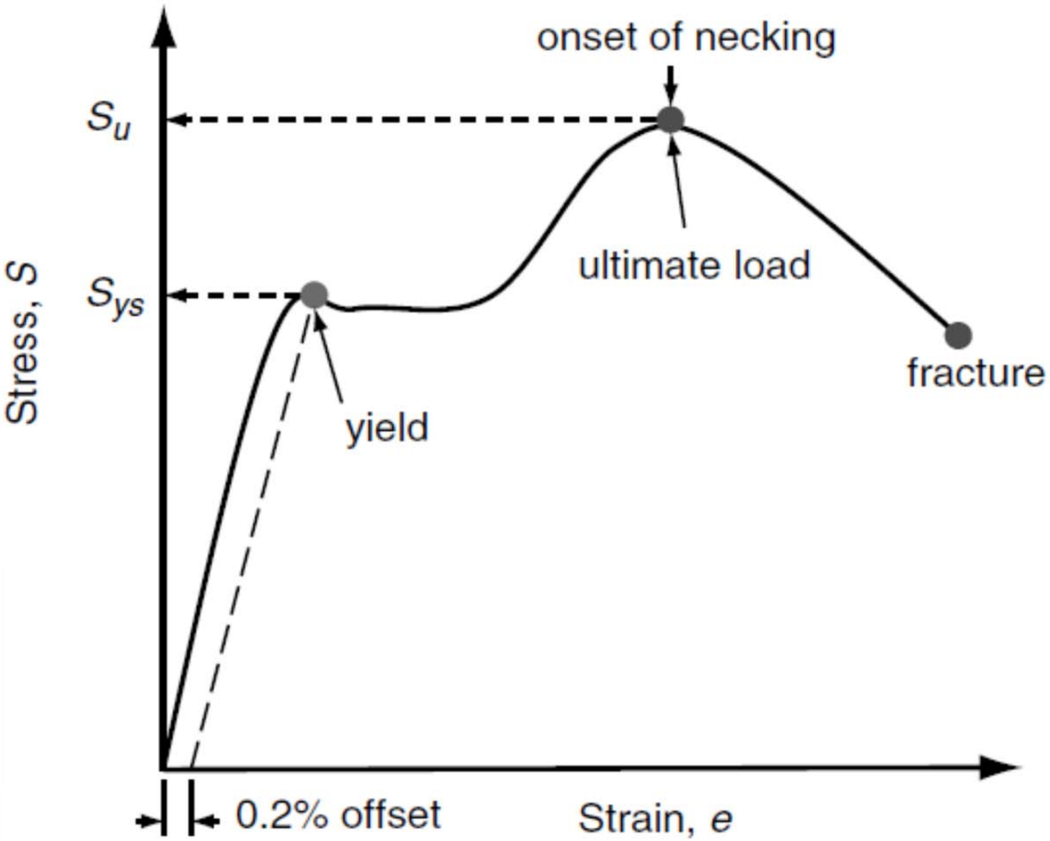
- Cilindrical specimens ϕ ~6 mm – 12 mm
- Flat specimens may also be used



Monotonic Stress-Strain Behavior

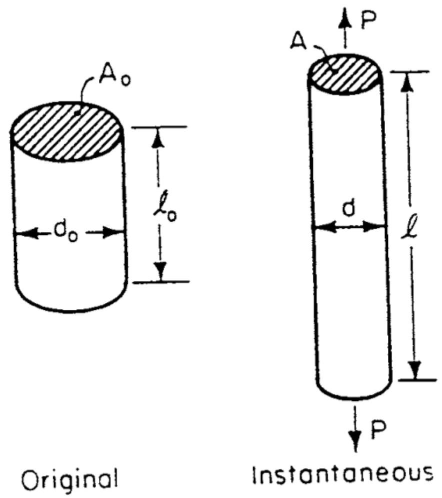
ASTM E8M

Engineering stress-strain curve



$$S = \text{engineering stress} = \frac{P}{A_0}$$

$$e = \text{engineering strain} = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0}$$

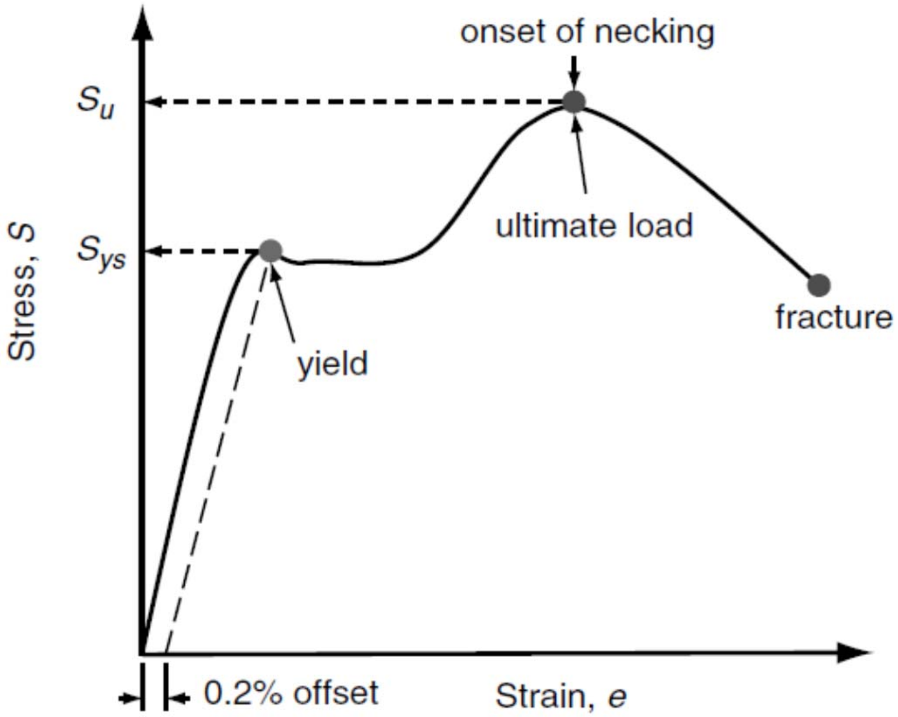


Four parameters can be measured directly from test: S_{ys}, S_u, %El, %RA

Monotonic Stress-Strain Behavior

ASTM E8M

Engineering stress-strain curve



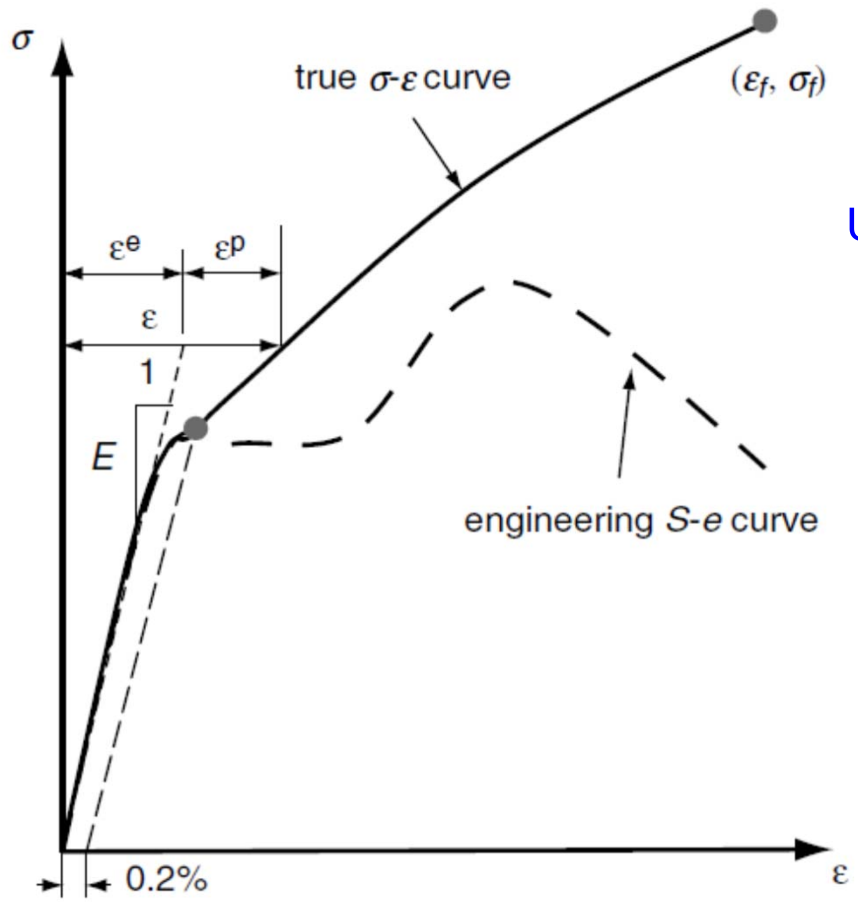
$$S_u = \frac{P_{max}}{A_o}$$

$$\%EI = 100 \times \frac{l_f - l_o}{l_o}$$

$$\%RA = 100 \times \frac{A_f - A_o}{A_o}$$

Ductility

Monotonic Stress-Strain Behavior



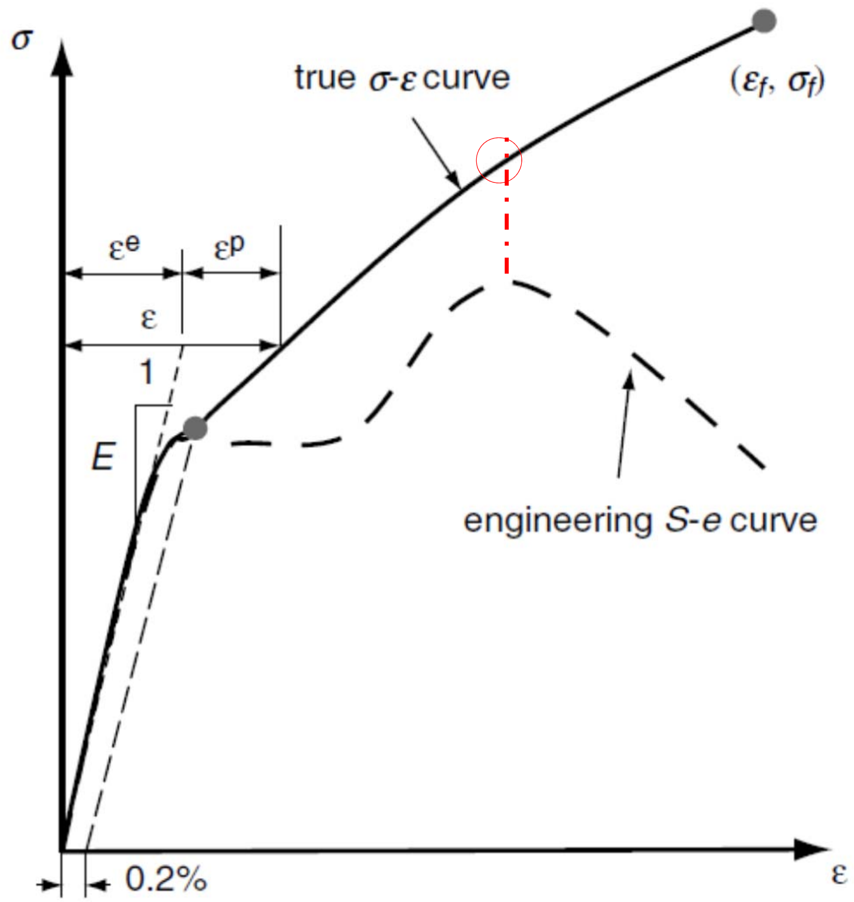
True stress- true strain curve

Use of instantaneous area (A) and length (l)

$$\sigma = \frac{P}{A}$$

$$\varepsilon = \int_{l_o}^{l} \frac{dl}{l} = \ln \frac{l}{l_o}$$

Monotonic Stress-Strain Behavior



Engineering stress-strain curve

True stress- true strain curve

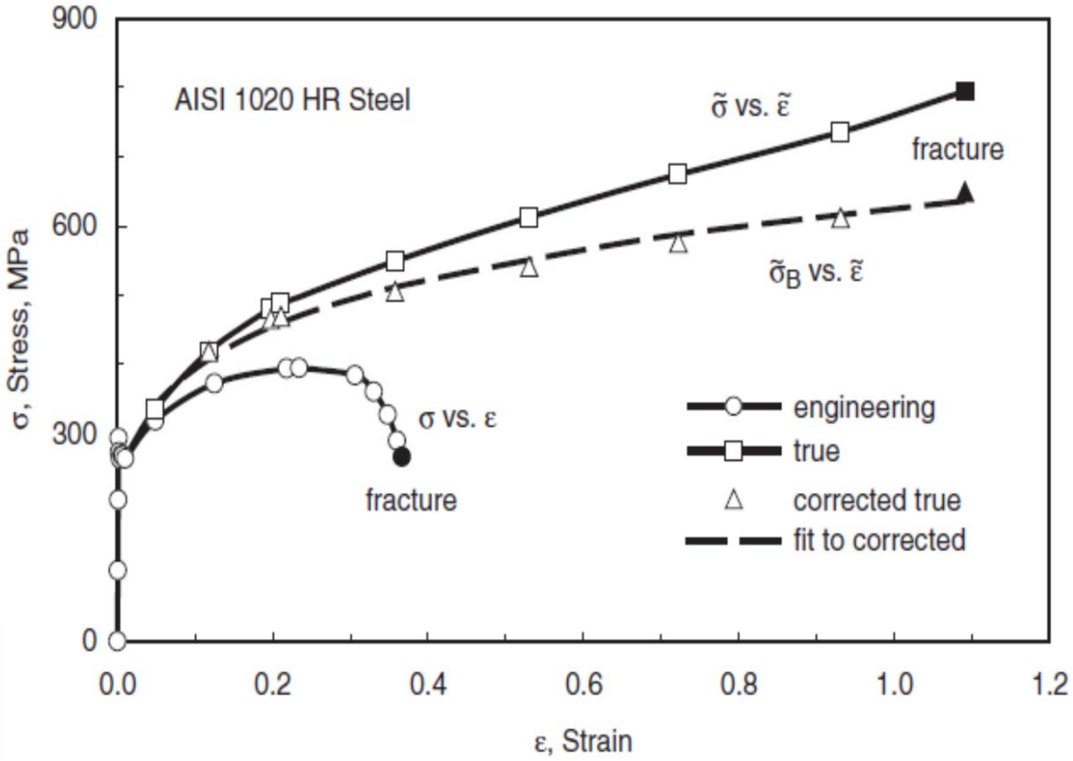
$$\sigma = S(1 + e)$$

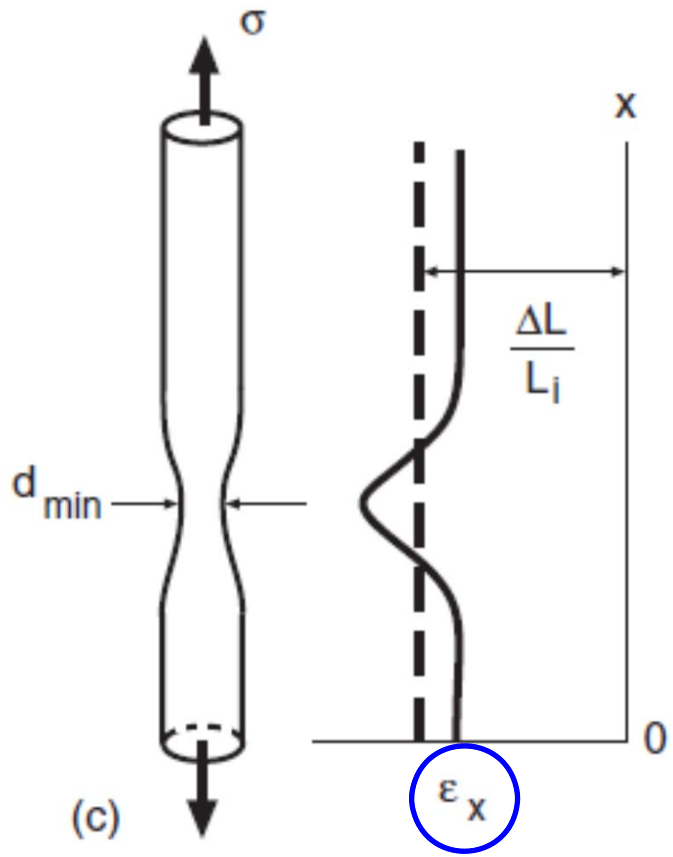
$$\varepsilon = \ln(1 + e)$$

- Assumption of constant volume
- Valid up to the onset of necking

Monotonic Stress-Strain Behavior

Empescoçamento (Necking)

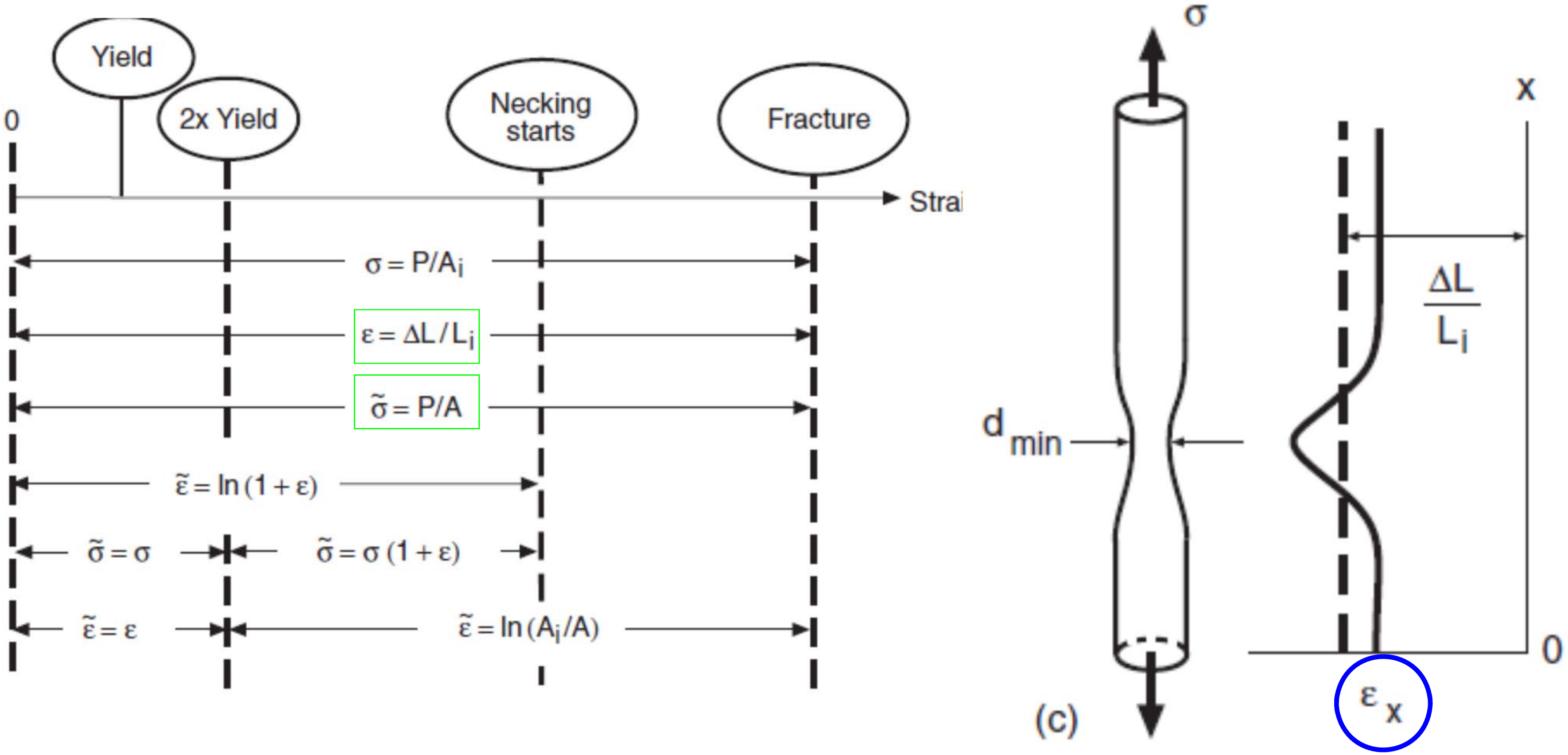




Decrease in force is a consequence of cross-sectional area rapidly decrease

Monotonic Stress-Strain Behavior

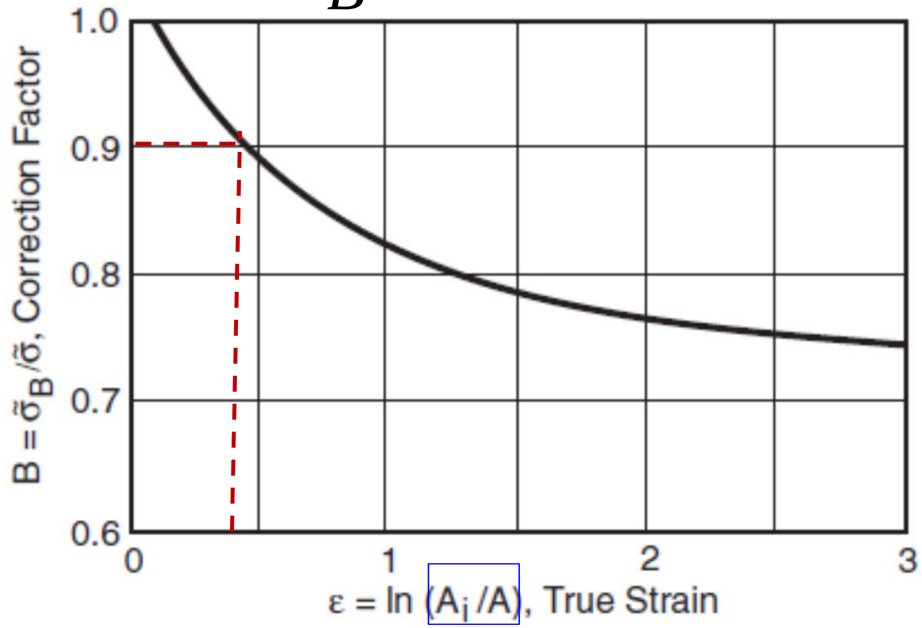
Limitations on True Stress –StrainEequations



Monotonic Stress-Strain Behavior

Bridman Correction (Empirical)

Steels : $\tilde{\sigma}_B = B\tilde{\sigma}$

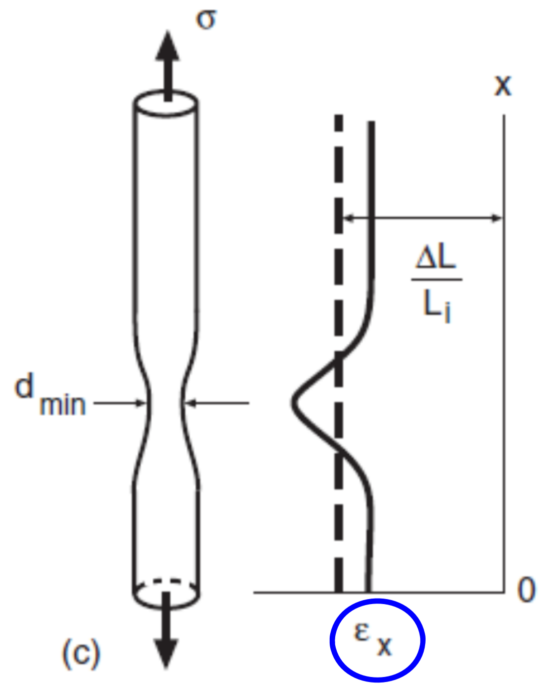


$$\tilde{\varepsilon} = \ln \frac{L}{L_i}$$

$$\tilde{\varepsilon} \approx 0.44$$

$$\downarrow$$

$$\frac{L}{L_i} = 1.55$$

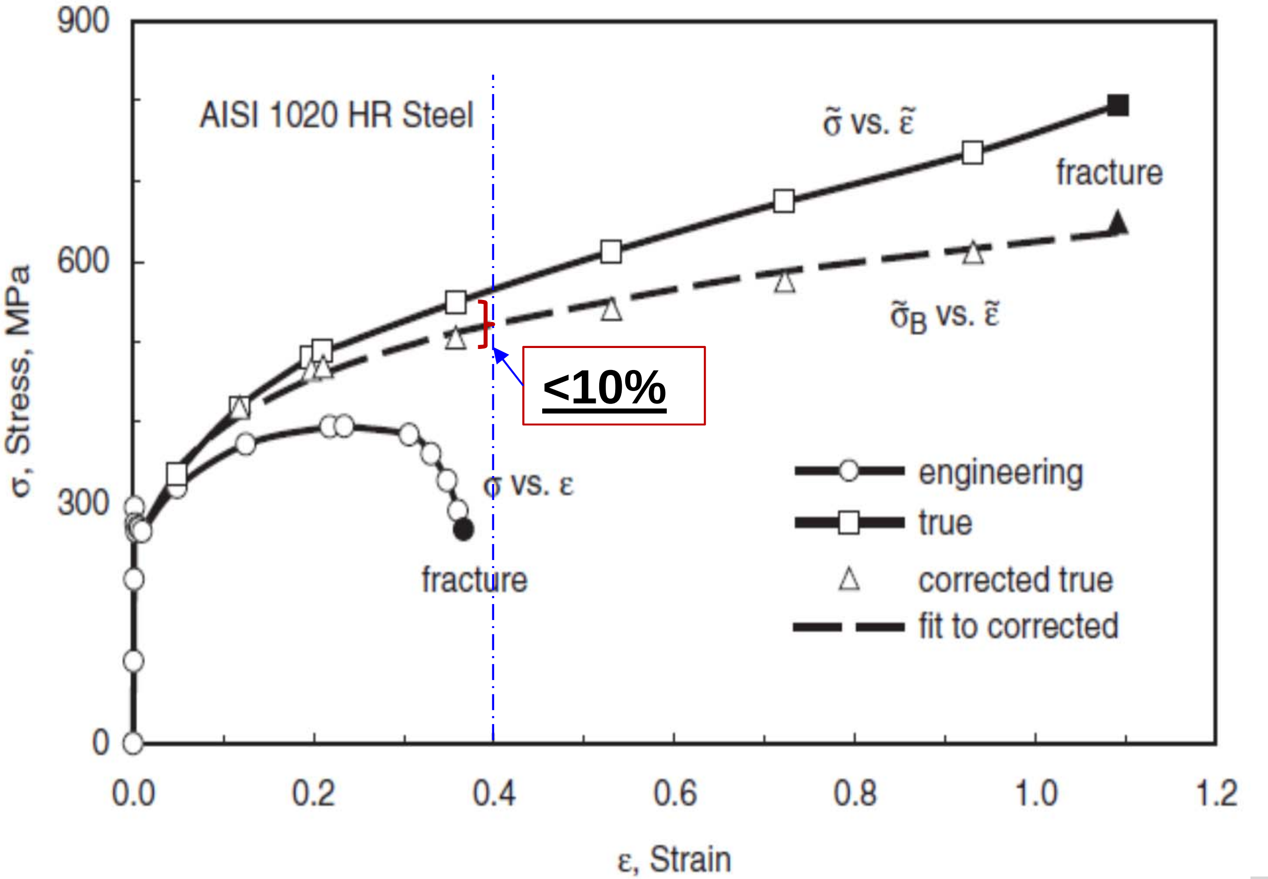


$$B = 0.0684(\log \tilde{\varepsilon})^3 + 0.0461(\log \tilde{\varepsilon})^2 - 0.205(\log \tilde{\varepsilon}) + 0.825$$

The correction is not need for true strain (Ai/A) < 0.12

Monotonic Stress-Strain Behavior

Limitations on True Stress –StrainEequations



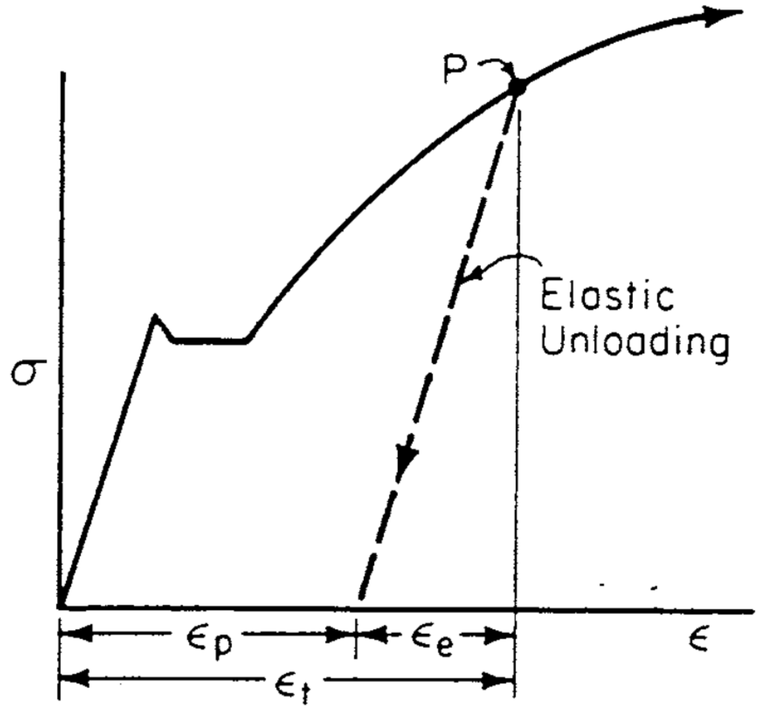
$$\tilde{\sigma}_B = B\tilde{\sigma}$$

$$B = 0.0684\left(\log\tilde{\varepsilon}\right)^3 + 0.0461\left(\log\tilde{\varepsilon}\right)^2 - 0.205\left(\log\tilde{\varepsilon}\right) + 0.825$$

Stress-Strain Relationships

Total deformation can be separated in two parts:

$$\varepsilon = \varepsilon_e + \varepsilon_p$$

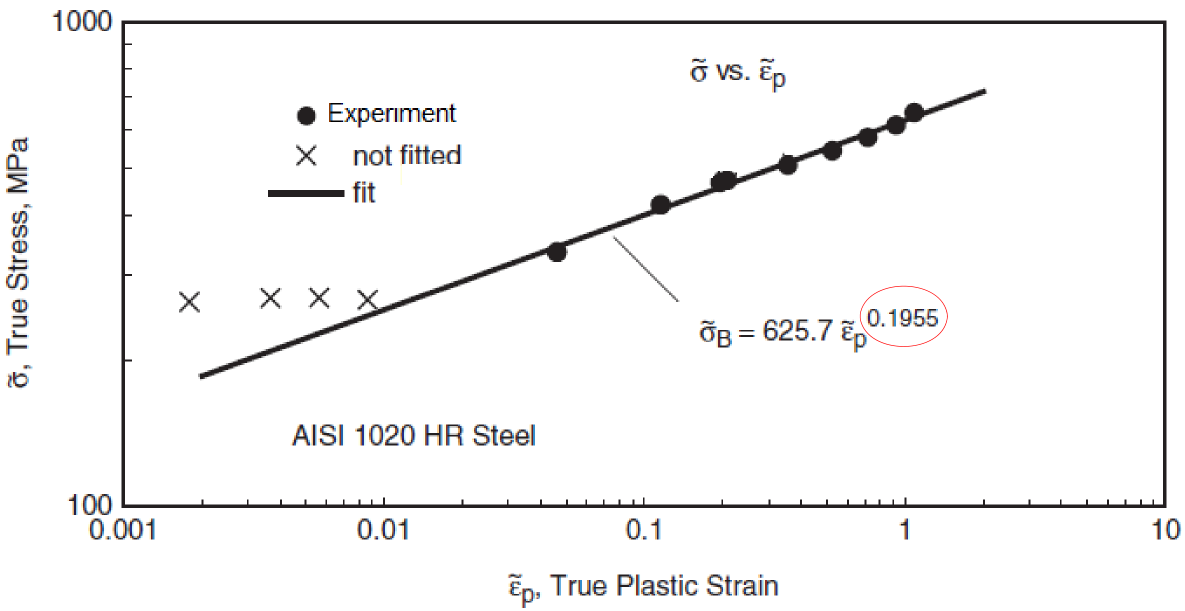


Recovered upon unloading

Can not be recovered upon unloading

Stress-Strain Relationships

For metals a log-log plot of experimental true stress versus true plastic strain often fits a straight line.



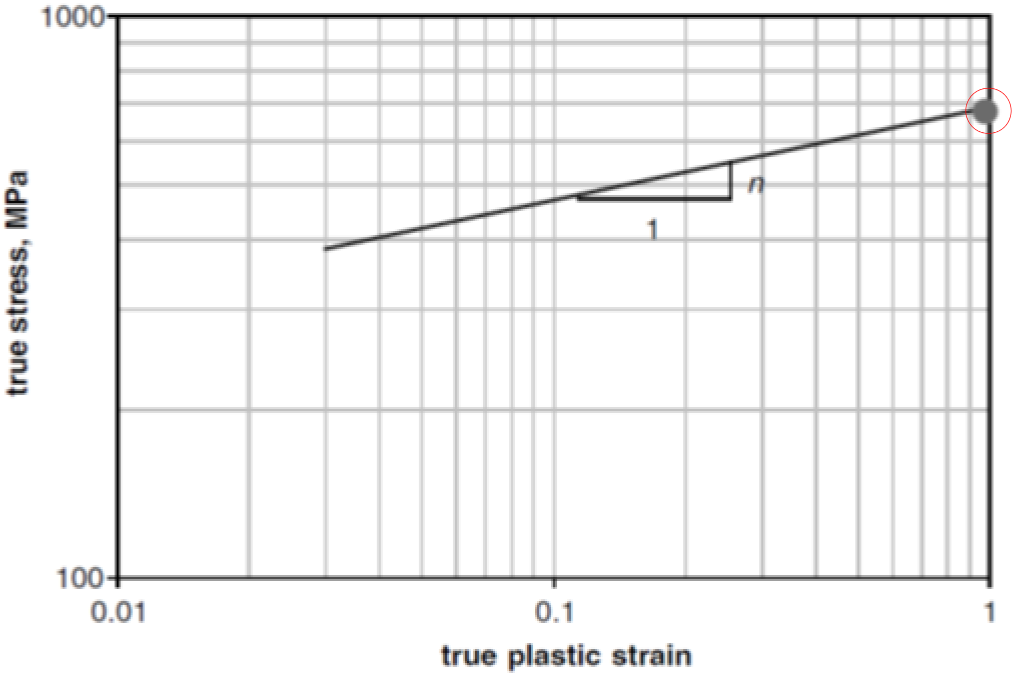
$$\tilde{\sigma} = H\,\tilde{\varepsilon}_p^{\,n}$$

n: strain hardening exponent (0<n<1)

H: strength coeficient (MPa)

Stress-Strain Relationships

For metals a log-log plot of experimental true stress versus true plastic strain often fits a straight line.



$$\tilde{\sigma} = H \tilde{\varepsilon}_p^n$$

$$\tilde{\varepsilon}_p = 1$$

$$\downarrow$$

$$\tilde{\sigma} = H$$

Table 4.6 True Stress–Strain Tensile Properties for Some Engineering Metals, and Also Hardness

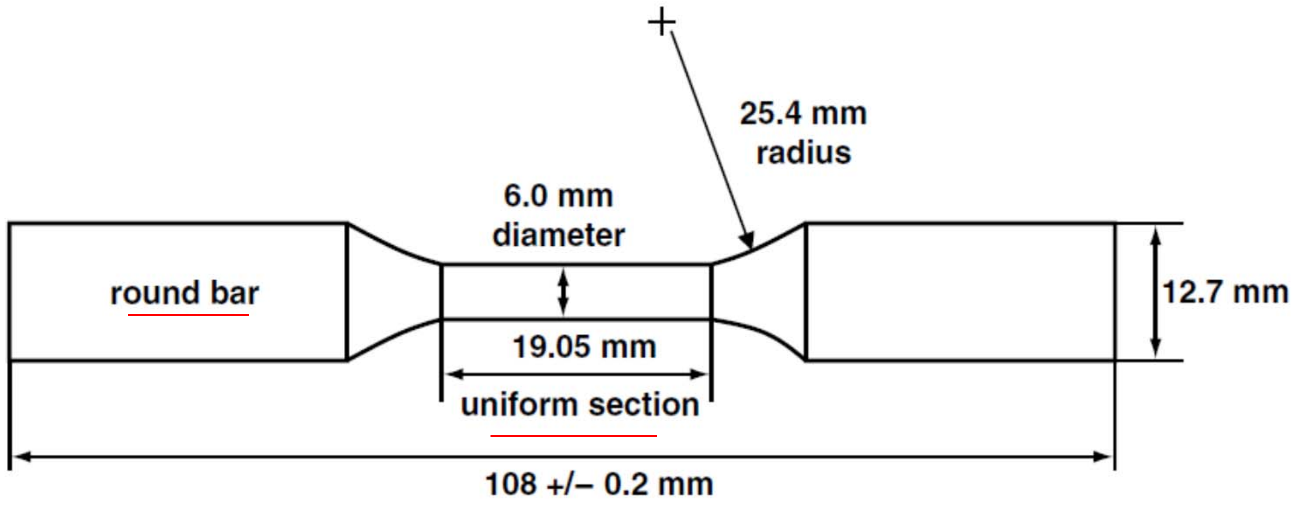
Material	True Fracture Strength $\tilde{\sigma}_{fB}$	True Fracture Strain $\tilde{\varepsilon}_f$	Strength Coefficient H	Strain Hardening Exponent n	Brinell Hardness[1] HB
	MPa (ksi)		MPa (ksi)		
Ductile cast iron A536 (65-45-12)	524 (76)	0.222	456 (66.1)	0.0455	167
AISI 1020 steel as rolled	713 (103)	0.96	737 (107)	0.19	107
ASTM A514, T1 structural steel	1213 (176)	1.08	1103 (160)	0.088	256
AISI 4142 steel as quenched	2580 (375)	0.060	—	0.136	670
AISI 4142 steel 205°C temper	2650 (385)	0.310	—	0.091	560
AISI 4142 steel 370°C temper	1998 (290)	0.540	—	0.043	450
AISI 4142 steel 450°C temper	1826 (265)	0.660	—	0.051	380
18 Ni maraging steel (250)	2136 (310)	0.82	—	0.02	460
SAE 308 cast aluminum	232 (33.6)	0.009	567 (82.2)	0.196	80
2024-T4 aluminum	631 (91.5)	0.43	806 (117)	0.20	120
7075-T6 aluminum	744 (108)	0.41	827 (120)	0.113	150
AZ91C-T6 cast magnesium	137 (20)	0.004	653 (94.7)	0.282	61

Note: [1]Load 3000 kg for irons and steels, 500 kg otherwise; typical values from [Boyer 85] are listed in some cases.
Sources: Data in [Conle 84] and [SAE 89].

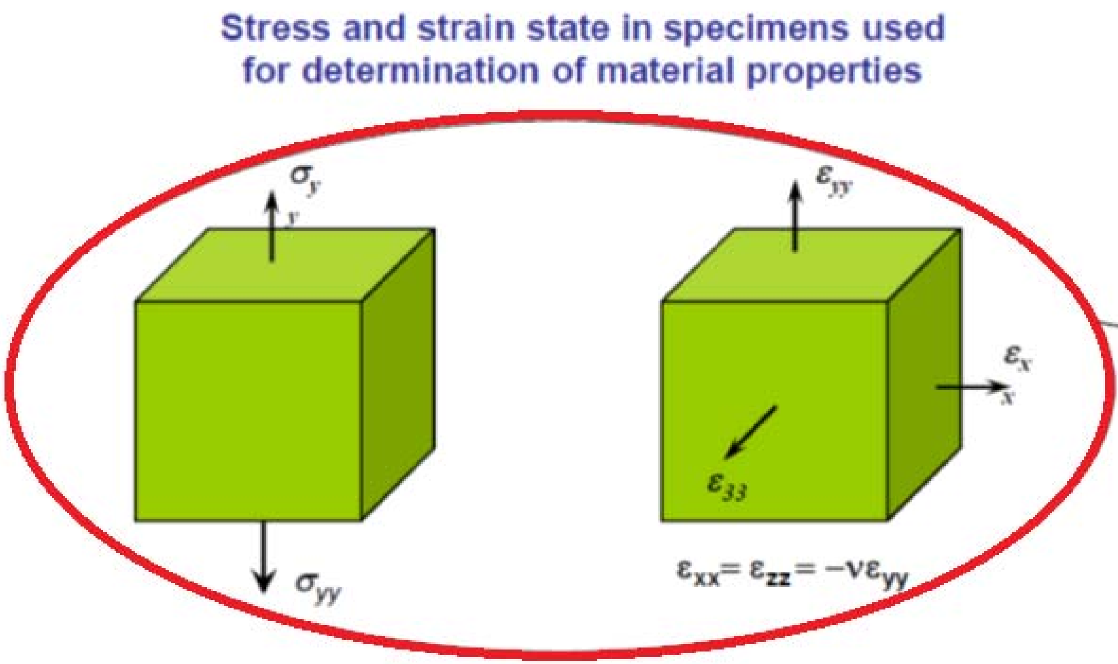
Cyclic Stress-Strain Behavior

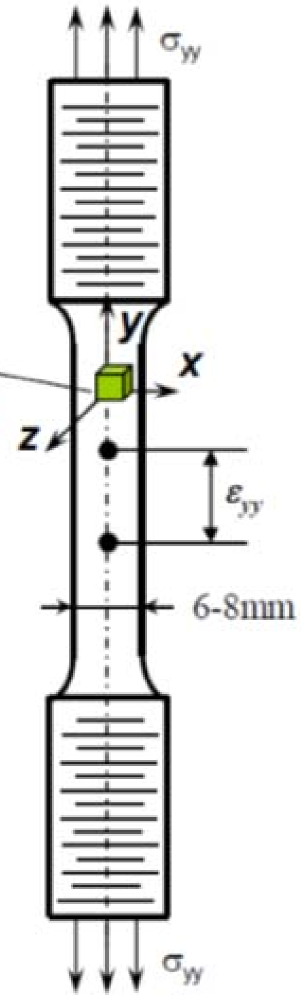
ASTM E466

- Cilindrical specimens ϕ ~6 mm – 12 mm



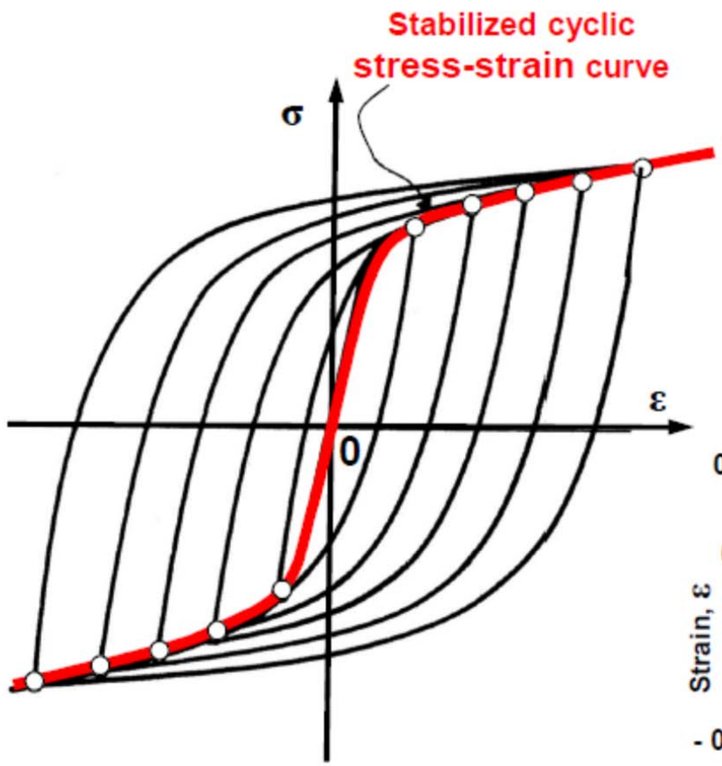
Smooth Specimen for σ–ε determination under monotonic and cyclic loading

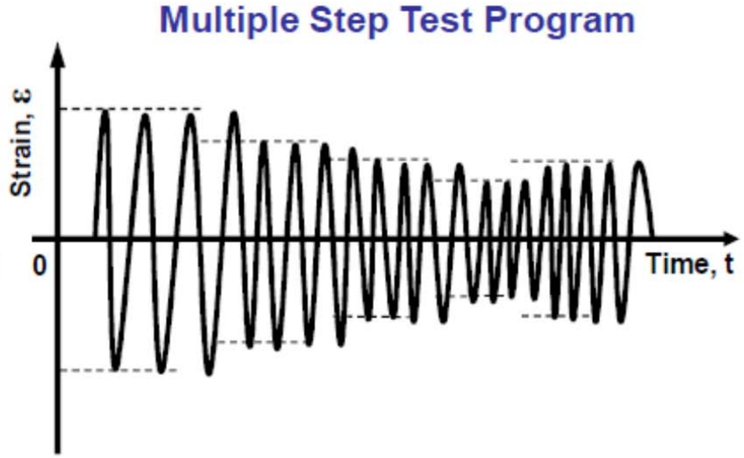


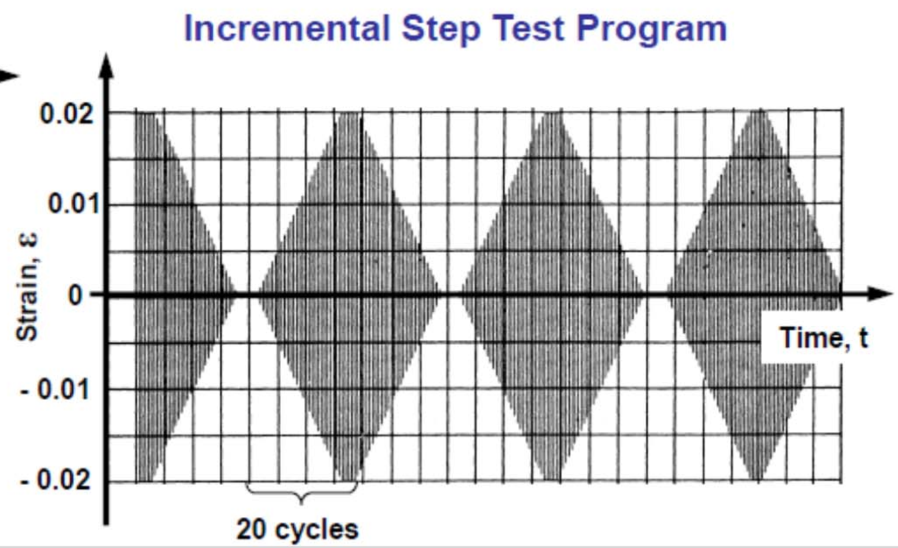


$$\sigma_{ij} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sigma_{yy} & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad \varepsilon_{ij} = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}$$

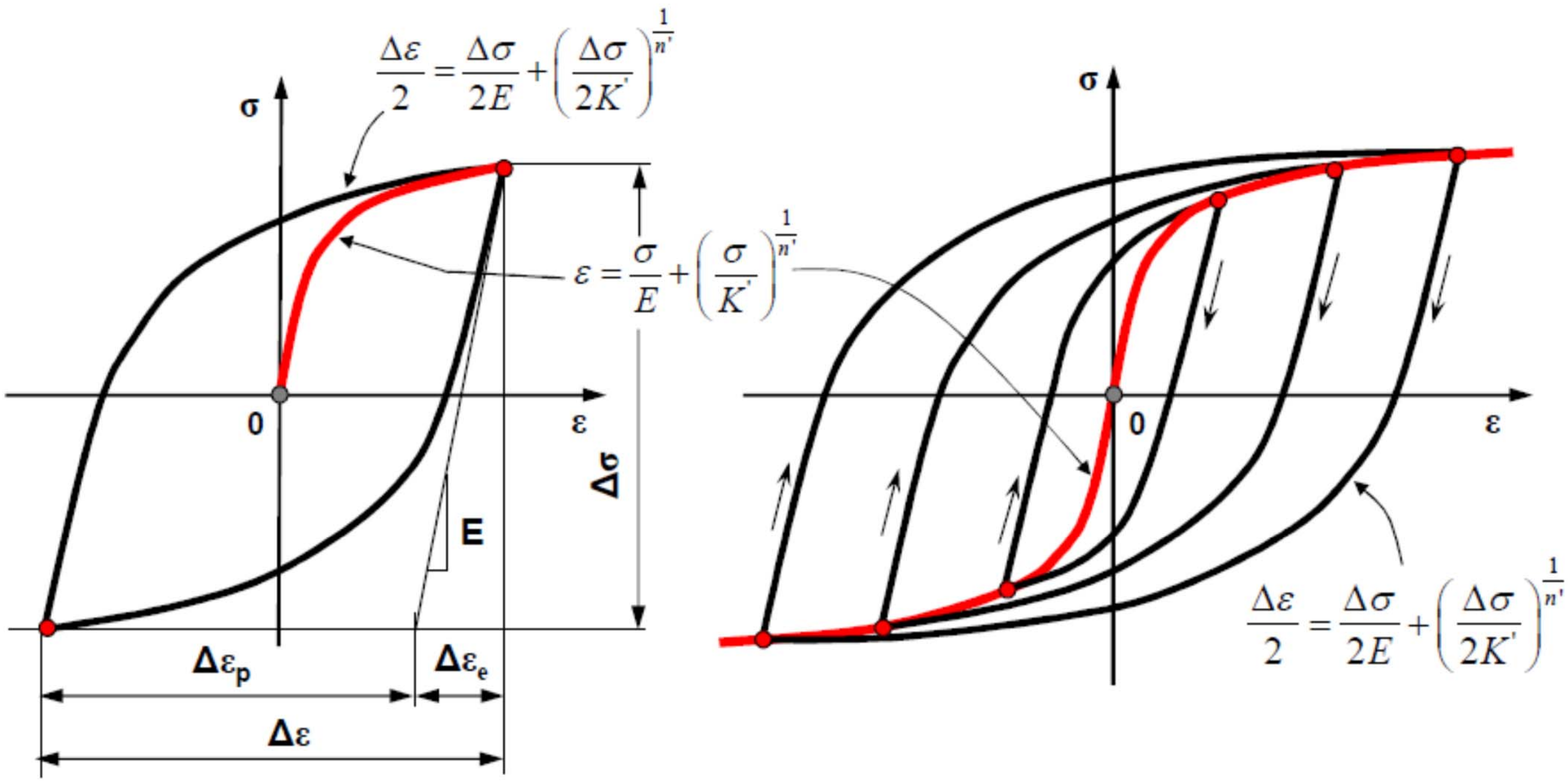
Cyclic Stress-Strain Behavior



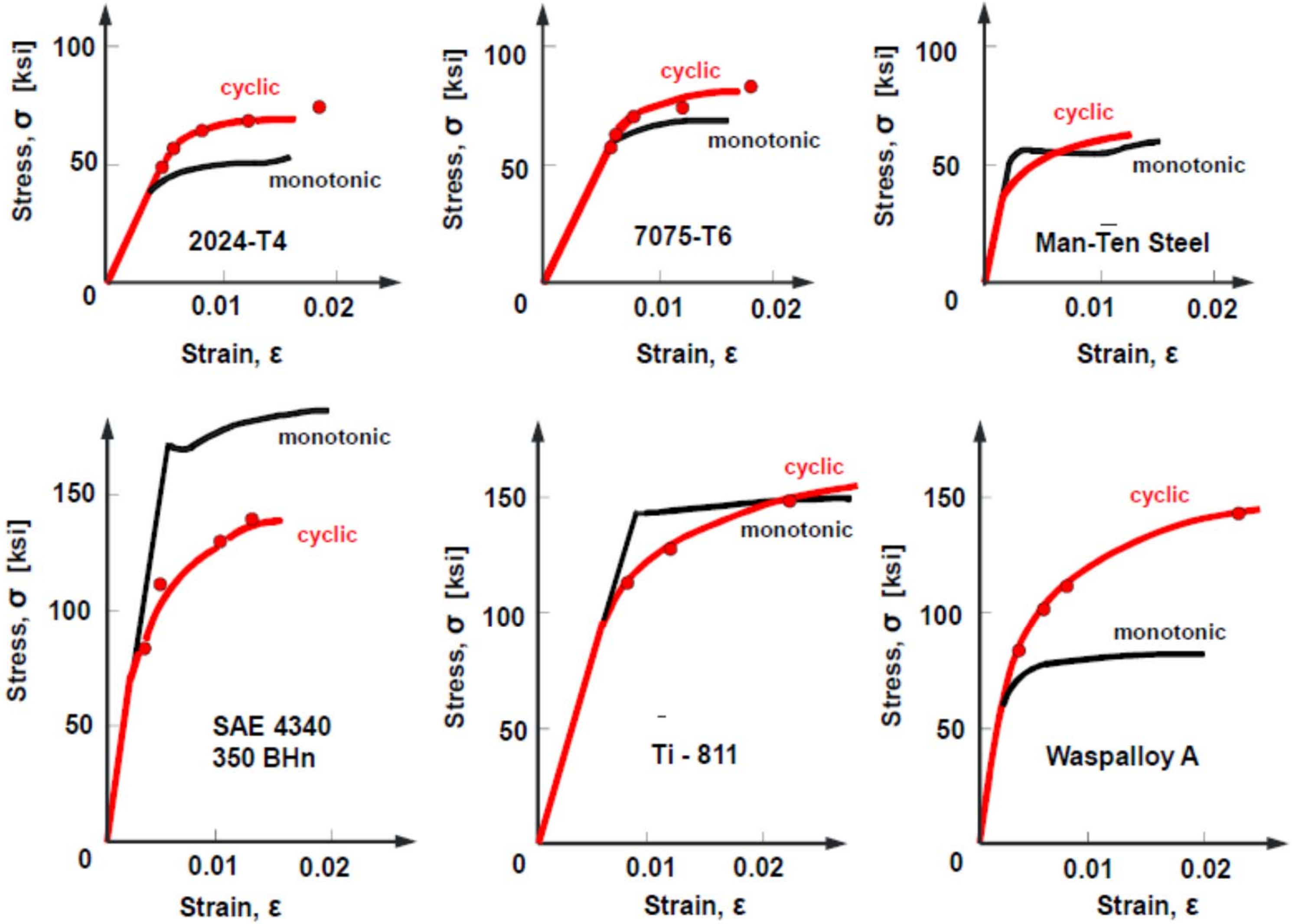




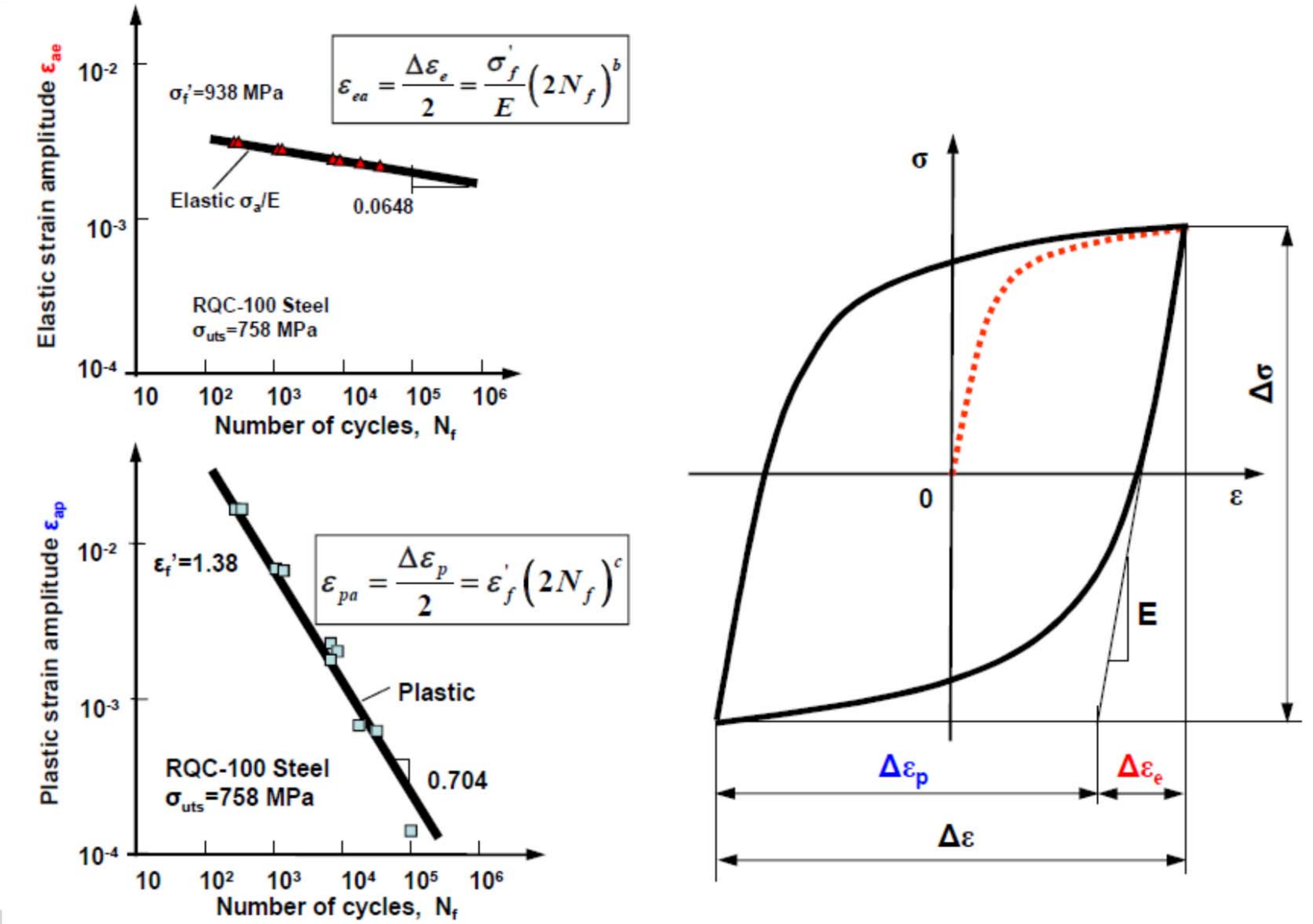
Cyclic Stress-Strain Behavior



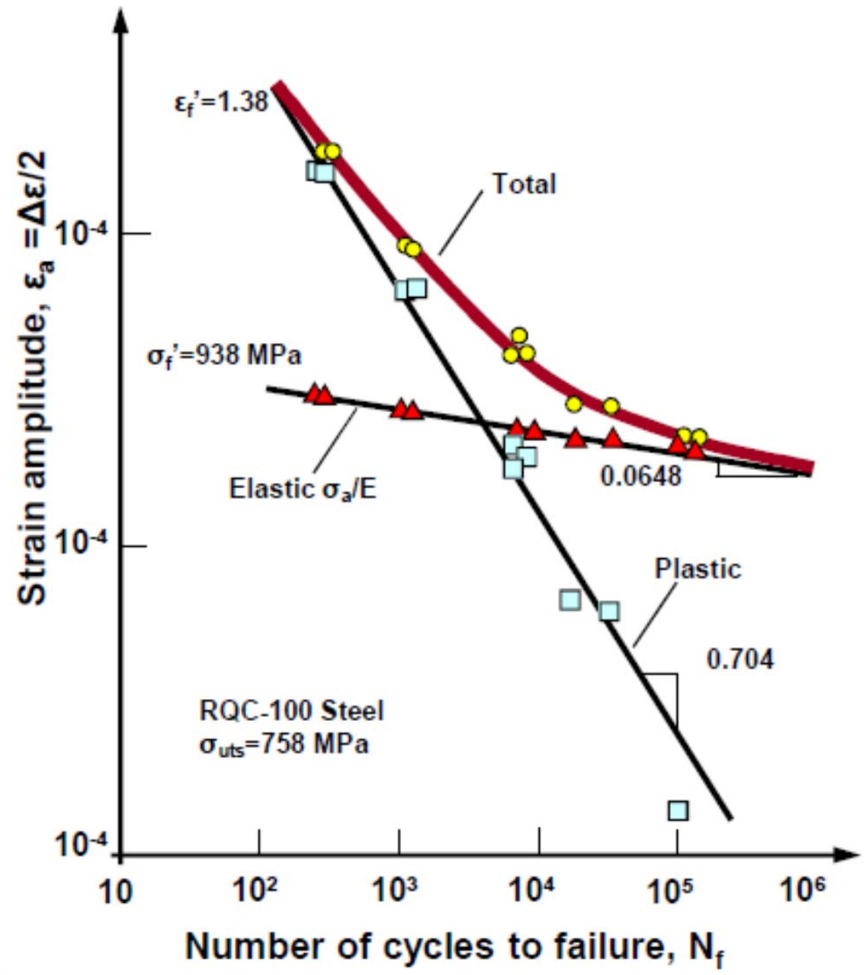
Cyclic vs. Monotonic



Fatigue Strain-Life Curve



Fatigue Strain-Life Curve



- Coffin & Manson Equation

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\sigma_f^{'}}{E}\left(2N_f\right)^b + \varepsilon_f^{'}\left(2N_f\right)^c$$

Fatigue Strain-Life Properties

Table 14.1 Cyclic Stress–Strain and Strain–Life Constants for Selected Engineering Metals.[1]

		Tensile Properties				Cyclic σ-ε Curve			Strain–Life Curve			
Material	Source	σ_o	σ_u	$\tilde{\sigma}_{fB}$	% RA	E	H'	n'	σ'_f	b	ε'_f	c
(a) Steels												
SAE 1015	(8)	228	415	726	68	207,000	1349	0.282	1020	−0.138	0.439	−0.513
(normalized)		(33.0)	(60.2)	(105)		(30,000)	(196)		(148)			
Man-Ten[2]	(7)	322	557	990	67	203,000	1096	0.187	1089	−0.115	0.912	−0.606
(hot rolled)		(46.7)	(80.8)	(144)		(29,500)	(159)		(158)			
RQC-100	(2)	683	758	1186	64	200,000	903	0.0905	938	−0.0648	1.38	−0.704
(roller Q & T)		(99.0)	(110)	(172)		(29,000)	(131)		(136)			
SAE 1045	(6)	382	621	985	51	202,000	1258	0.208	948	−0.092	0.260	−0.445
(HR & norm.)		(55.4)	(90.1)	(143)		(29,400)	(182)		(137)			
SAE 4142	(1)	1619	2450	2580	6	200,000	2810	0.040	2550	−0.0778	0.0032	−0.436
(As Q, 670 HB)		(235)	(355)	(375)		(29,000)	(407)		(370)			
SAE 4142	(1)	1688	2240	2650	27	207,000	4140	0.126	3410	−0.121	0.0732	−0.805
(Q & T, 560 HB)		(245)	(325)	(385)		(30,000)	(600)		(494)			
SAE 4142	(1)	1584	1757	1998	42	207,000	2080	0.093	1937	−0.0762	0.706	−0.869
(Q & T, 450 HB)		(230)	(255)	(290)		(30,000)	(302)		(281)			
SAE 4142	(1)	1378	1413	1826	48	207,000	2210	0.133	2140	−0.0944	0.637	−0.761
(Q & T, 380 HB)		(200)	(205)	(265)		(30,000)	(321)		(311)			
AISI 4340[2]	(3)	1103	1172	1634	56	207,000	1655	0.131	1758	−0.0977	2.12	−0.774
(Aircraft Qual.)		(160)	(170)	(237)		(30,000)	(240)		(255)			
AISI 4340	(1)	1371	1468	1557	38	200,000	1910	0.123	1879	−0.0859	0.640	−0.636
(409 HB)		(199)	(213)	(226)		(29,000)	(277)		(273)			
Ausformed H-11	(1)	2030	2580	3170	33	207,000	3475	0.059	3810	−0.0928	0.0743	−0.7144
(660 HB)		(295)	(375)	(460)		(30,000)	(504)		(553)			

[Dowling 7

Fatigue Strain-Life Properties

Table 14.1 Cyclic Stress–Strain and Strain–Life Constants for Selected Engineering Metals.[1]

Material	Source	Tensile Properties				Cyclic σ-ε Curve			Strain–Life Curve			
		σ_o	σ_u	$\tilde{\sigma}_{fB}$	% RA	E	H'	n'	σ'_f	b	ε'_f	c
AISI 4340[2] (Aircraft Qual.)	(3)	1103 (160)	1172 (170)	1634 (237)	56	207,000 (30,000)	1655 (240)	0.131	1758 (255)	−0.0977	2.12	−0.774
AISI 4340 (409 HB)	(1)	1371 (199)	1468 (213)	1557 (226)	38	200,000 (29,000)	1910 (277)	0.123	1879 (273)	−0.0859	0.640	−0.636
Ausformed H-11 (660 HB)	(1)	2030 (295)	2580 (375)	3170 (460)	33	207,000 (30,000)	3475 (504)	0.059	3810 (553)	−0.0928	0.0743	−0.7144
(b) Other Metals												
2024-T351 Al	(1)	379 (55.0)	469 (68.0)	558 (81.0)	25	73,100 (10,600)	662 (96.0)	0.070	927 (134)	−0.113	0.409	−0.713
2024-T4 Al[3] (Prestrained)	(4)	303 (44.0)	476 (69.0)	631 (91.5)	35	73,100 (10,600)	738 (107)	0.080	1294 (188)	−0.142	0.327	−0.645
7075-T6 Al	(5)	469 (68.0)	578 (84)	744 (108)	33	71,000 (10,300)	977 (142)	0.106	1466 (213)	−0.143	0.262	−0.619
Ti-6Al-4V (soln. tr. & age)	(1)	1185 (172)	1233 (179)	1717 (249)	41	117,000 (17,000)	1772 (257)	0.106	2030 (295)	−0.104	0.841	−0.688
Inconel X (Ni base, annl.)	(1)	703 (102)	1213 (176)	1309 (190)	20	214,000 (31,000)	1855 (269)	0.120	2255 (327)	−0.117	1.16	−0.749

Notes: [1]The tabulated values either have units of MPa (ksi), or they are dimensionless. [2]Test specimens prestrained, except at short lives, also periodically overstrained at long lives. [3]For nonprestrained tests, use same constants, except $\sigma'_f = 900(131)$ and $b = -0.102$.

Sources: Data in (1) [Conle 84]; (2) author's data on the ASTM Committee E9 material; (3) [Dowling 73]; (4) [Dowling 89] and [Topper 70]; (5) [Endo 69] and [Raske 72]; (6) [Leese 85]; (7) [Wetzel 77] pp. 41 and 66; (8) [Keshavan 67] and [Smith 70].

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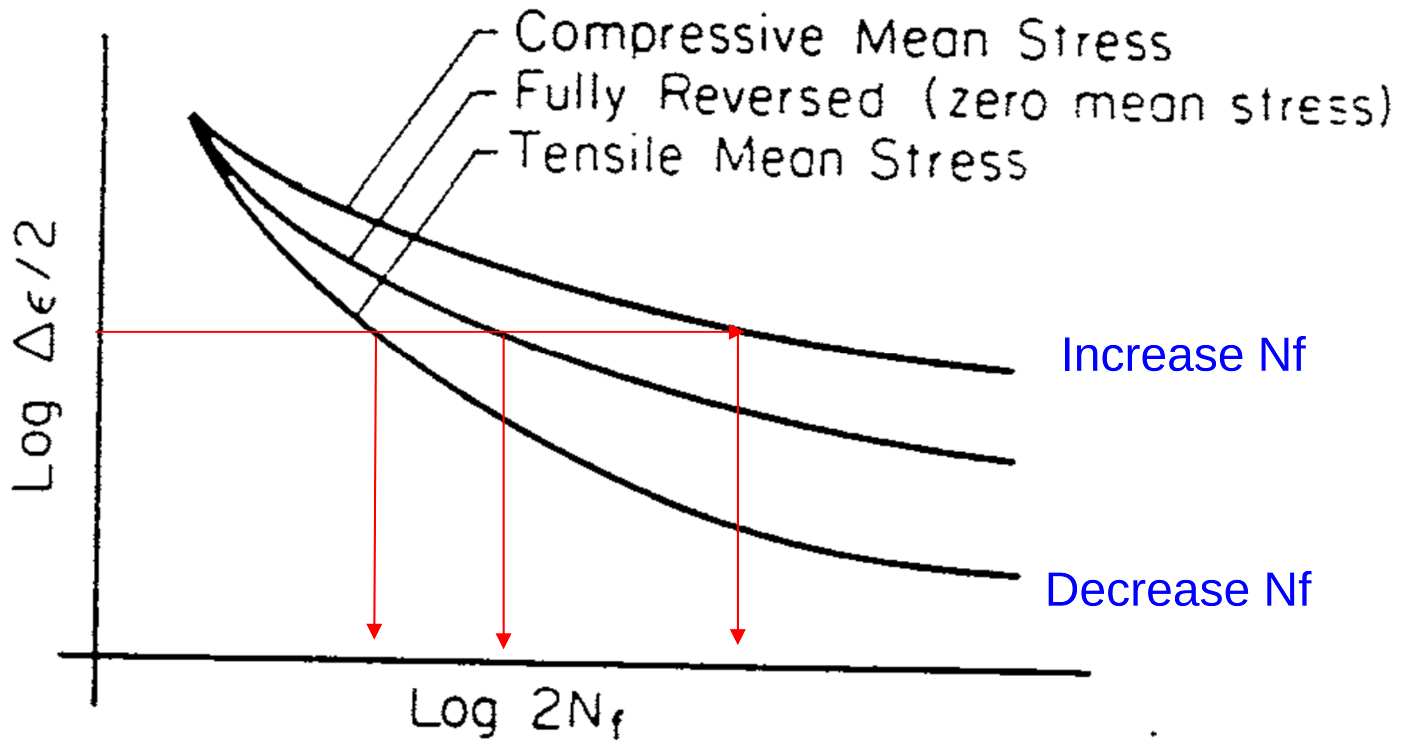
Mean Stress Effect



Mean stress effects are predominantly at longer lives

Stress Relaxation

At hight stress amplitude

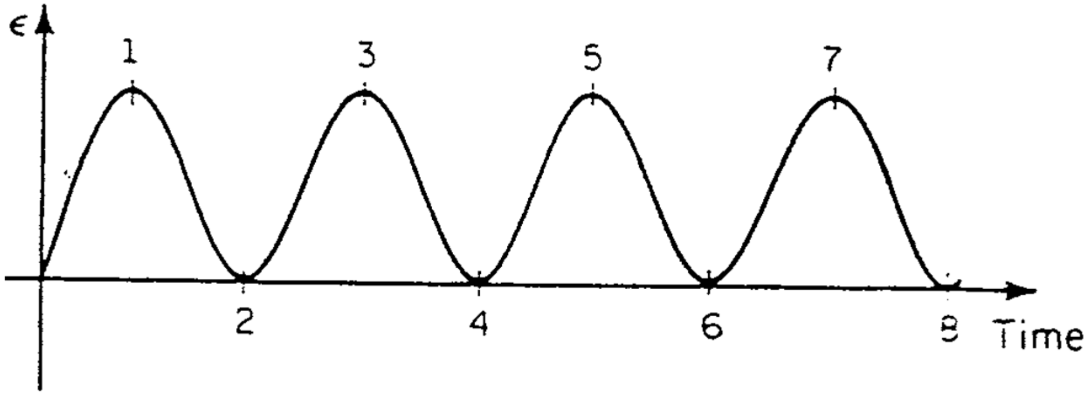
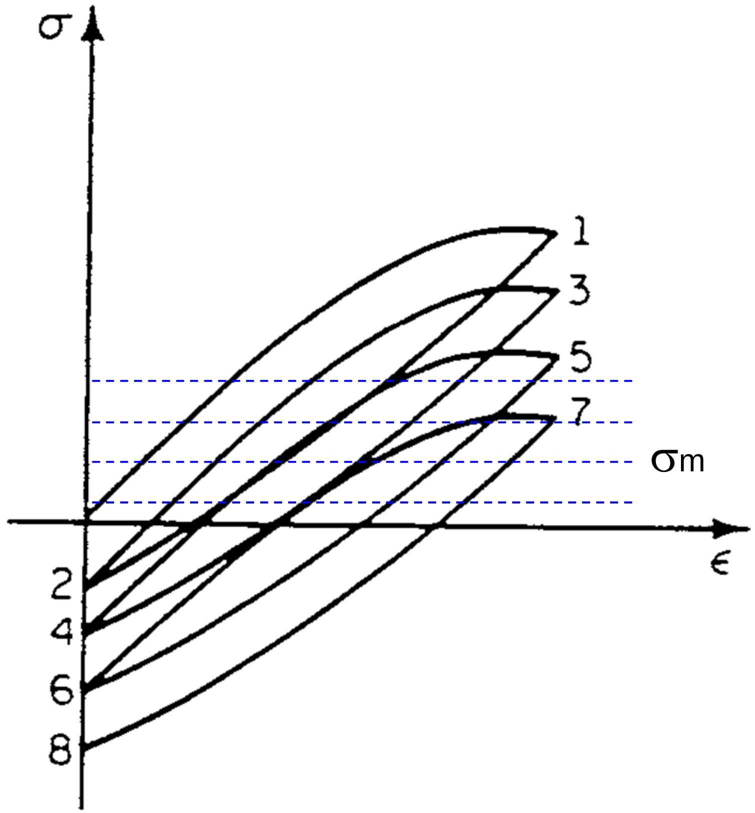
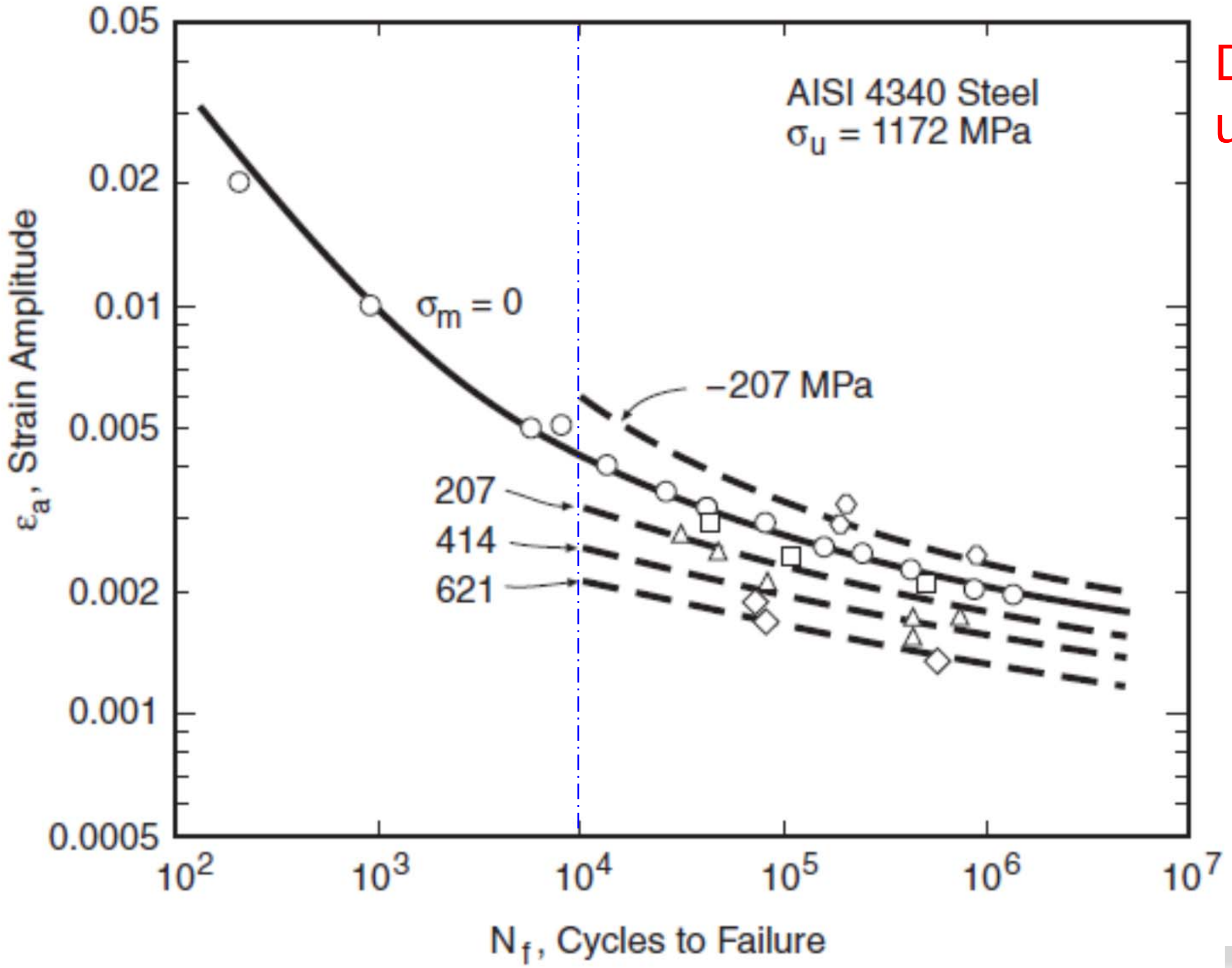


Figure 2.22 Mean stress relaxation.



Mean stress effects can be neglected at short lives

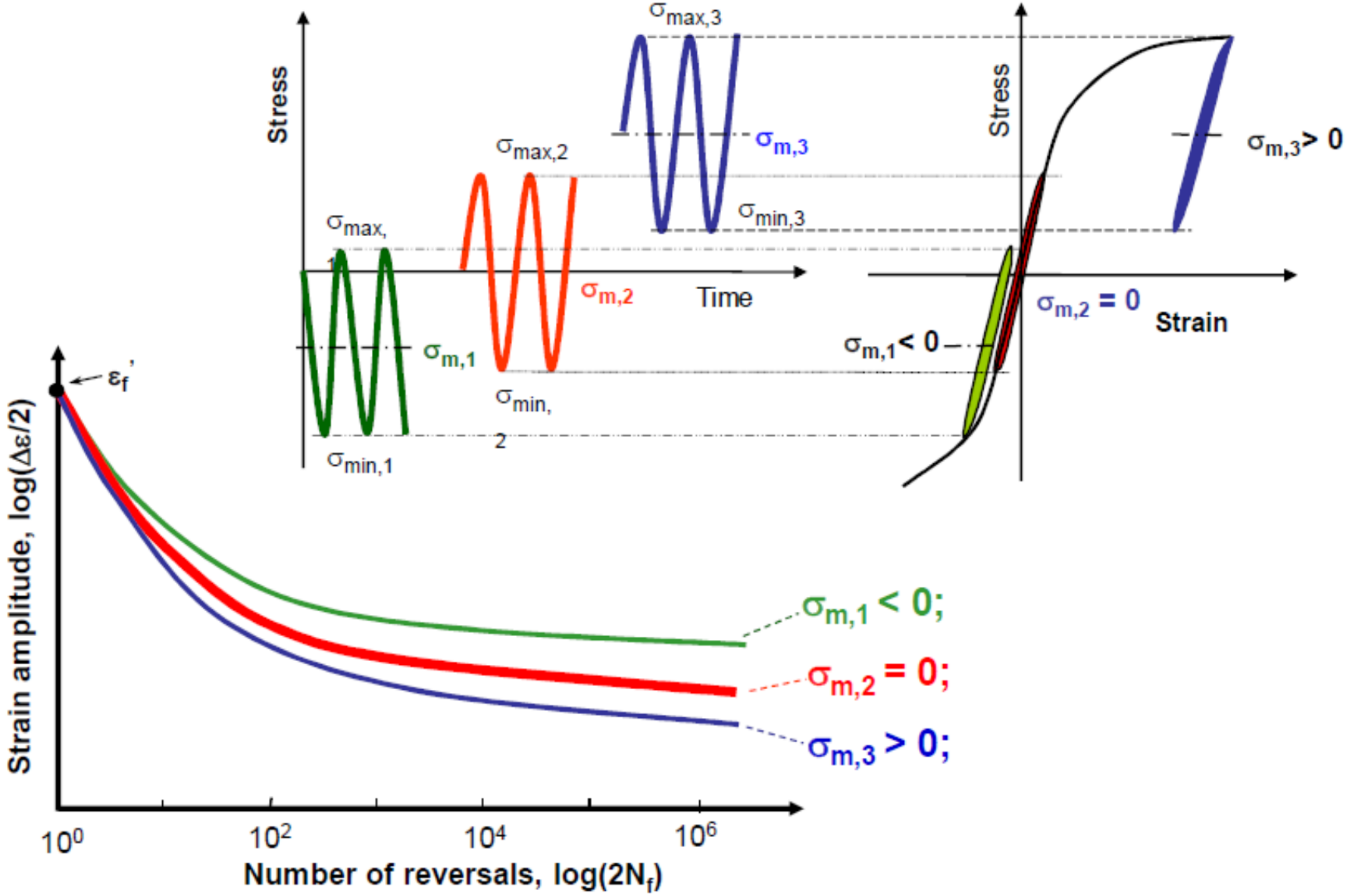
Mean Stress Effect



Dashed curves obtained using Morrow's equation

[Dowling 73].)

Mean Stress Effect



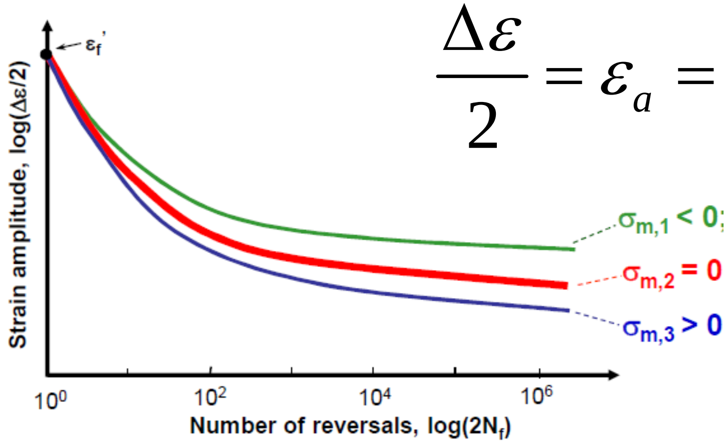
Mean Stress Effect

Morrow

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\sigma_f' - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon_f'\left(2N_f\right)^c$$

Manson-Halford

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\sigma_f' - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon_f'\left(\frac{\sigma_f' - \sigma_m}{\sigma_f'}\right)^{c/b}\left(2N_f\right)^c$$

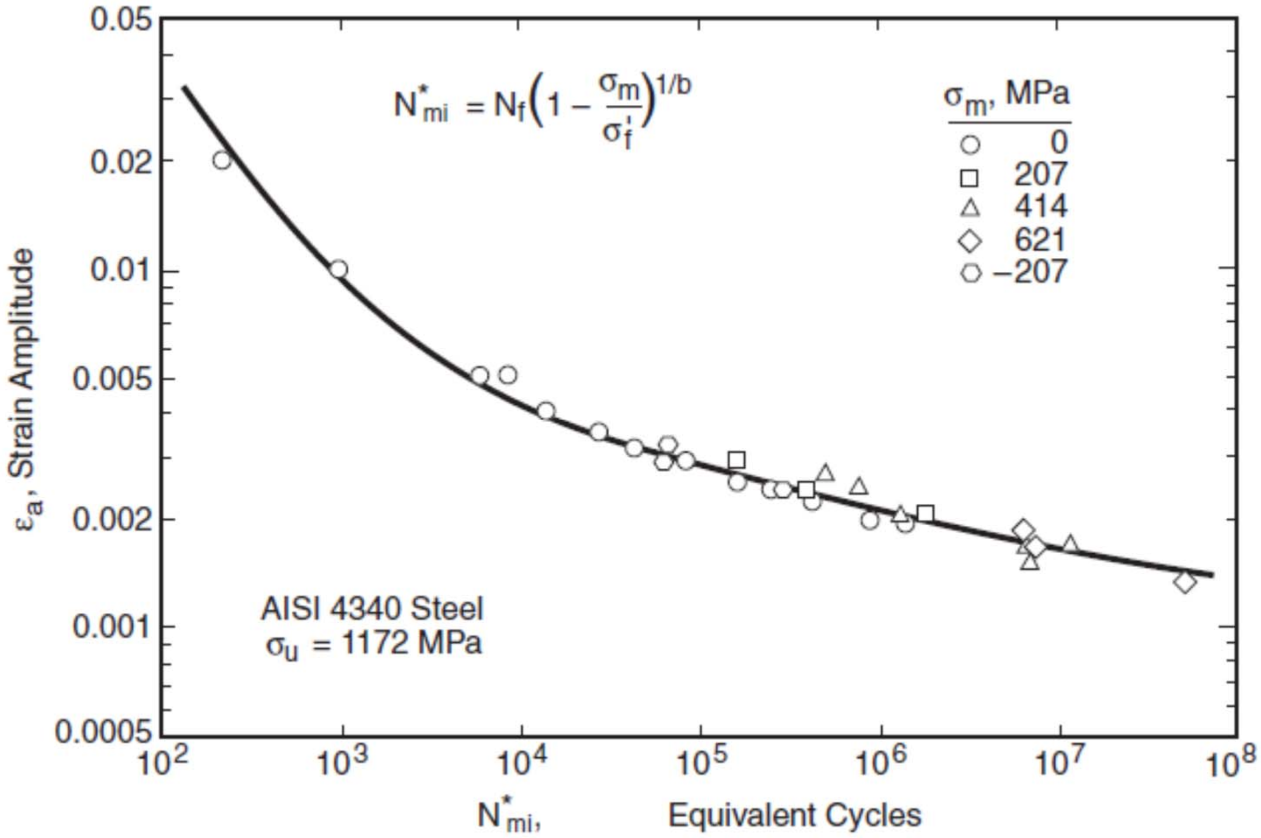


Smith-Watson-Topper

$$\sigma_{max}\frac{\Delta\varepsilon}{2} = \frac{\left(\sigma_f'\right)^2}{E}\left(2N_f\right)^{2b} + \sigma_f'\varepsilon_f'\left(2N_f\right)^{c+b}$$

Mean Stress Effect

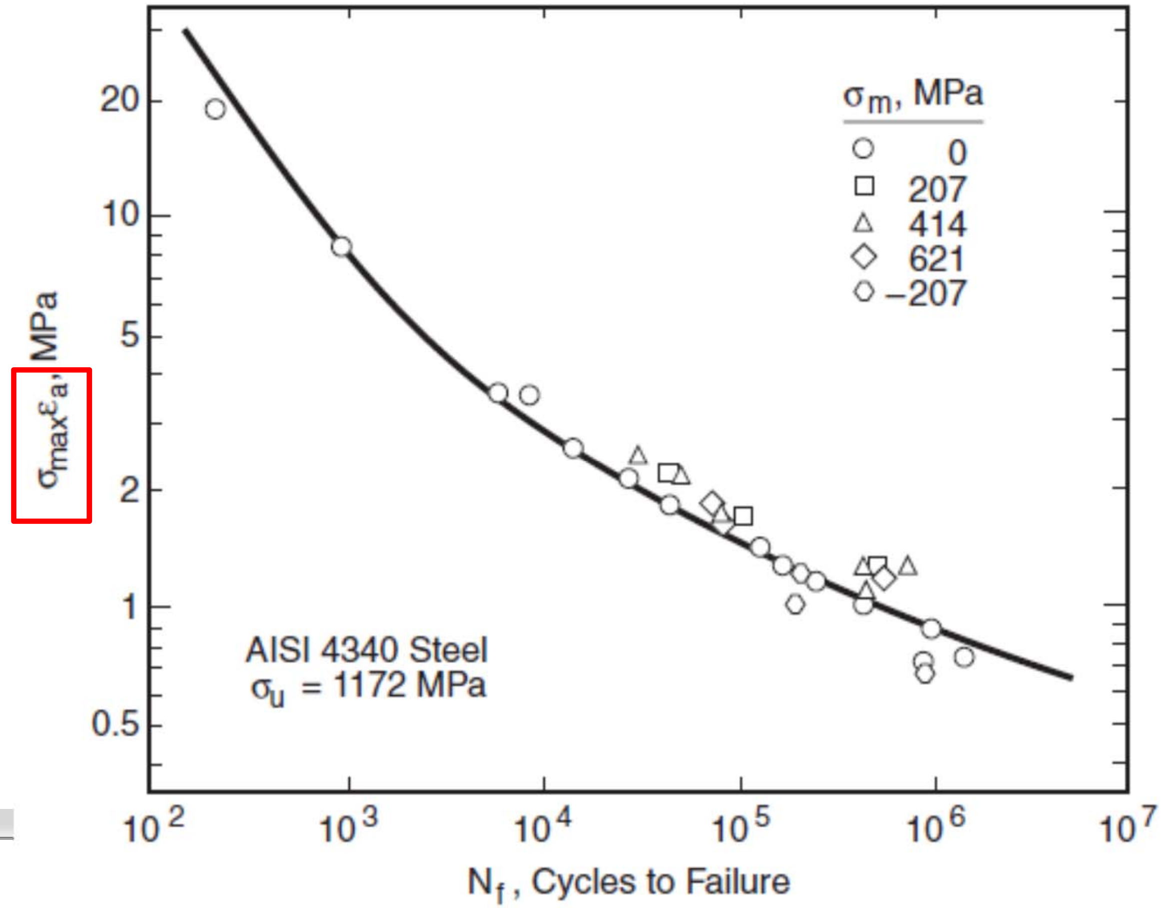
$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\sigma_f' - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon_f'\left(\frac{\sigma_f' - \sigma_m}{\sigma_f'}\right)^{c/b}\left(2N_f\right)^c$$



[Dowling 73].

Mean Stress Effect

$$\sigma_{max}\frac{\Delta\varepsilon}{2}=\frac{\left(\sigma_f^{'}\right)^2}{E}\left(2N_f\right)^{2b}+\sigma_f^{'}\varepsilon_f^{'}\left(2N_f\right)^{c+b}$$



[Dowling 73].)

Deformation Plasticity Theory

Stress-Strain relations

$$\varepsilon_x = \varepsilon_{ex} + \varepsilon_{px}, \qquad \varepsilon_y = \varepsilon_{ey} + \varepsilon_{py}, \qquad \varepsilon_z = \varepsilon_{ez} + \varepsilon_{pz}$$

$$\gamma_{xy} = \gamma_{exy} + \gamma_{pxy}, \qquad \gamma_{yz} = \gamma_{eyz} + \gamma_{pyz}, \qquad \gamma_{zx} = \gamma_{ezx} + \gamma_{pzx}$$

Elastic strains

$$\varepsilon_{ex} = \frac{1}{E}\left[\sigma_x - \nu\left(\sigma_y + \sigma_z\right)\right]$$

$$\varepsilon_{ey} = \frac{1}{E}\left[\sigma_y - \nu\left(\sigma_x + \sigma_z\right)\right]$$

$$\varepsilon_{ez} = \frac{1}{E}\left[\sigma_z - \nu\left(\sigma_x + \sigma_y\right)\right]$$

$$\gamma_{exy} = \frac{\tau_{xy}}{G}, \qquad \gamma_{eyz} = \frac{\tau_{yz}}{G}, \qquad \gamma_{ezx} = \frac{\tau_{zx}}{G}$$

Plastic Strains

$$\varepsilon_{px} = \frac{1}{E_p}\left[\sigma_x - 0.5\left(\sigma_y + \sigma_z\right)\right]$$

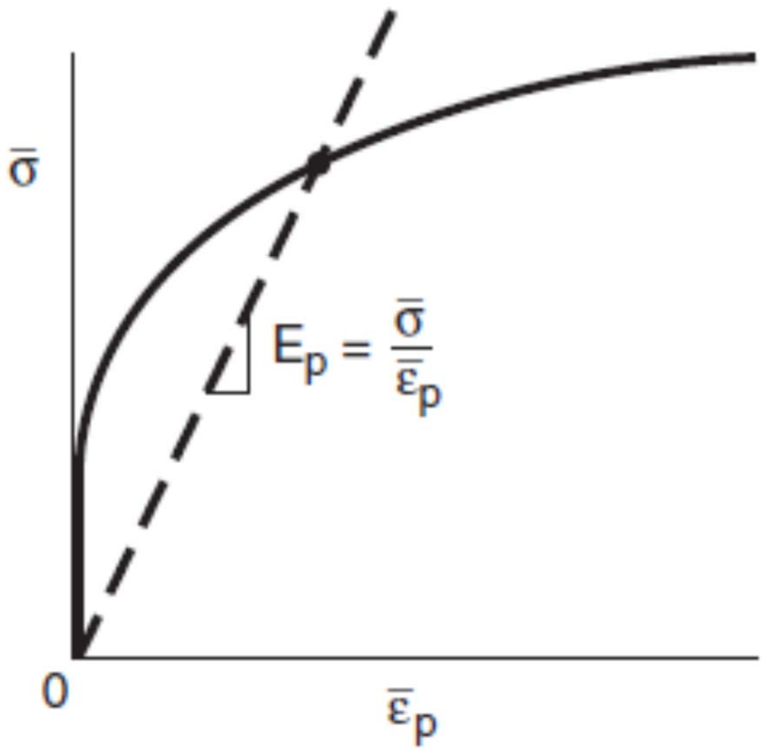
$$\varepsilon_{py} = \frac{1}{E_p}\left[\sigma_y - 0.5\left(\sigma_x + \sigma_z\right)\right]$$

$$\varepsilon_{pz} = \frac{1}{E_p}\left[\sigma_z - 0.5\left(\sigma_x + \sigma_y\right)\right]$$

$$\gamma_{pxy} = \frac{3}{E_p}\tau_{xy}, \qquad \gamma_{pyz} = \frac{3}{E_p}\tau_{yz}, \qquad \gamma_{pzx} = \frac{3}{E_p}\tau_{zx}$$

Deformation Plasticity Theory

Plastic Modulus



Effective total strain

$$\bar{\varepsilon} = \frac{\bar{\sigma}}{E} + \bar{\varepsilon}_p$$

Deformation Plasticity Theory

Effective Stress

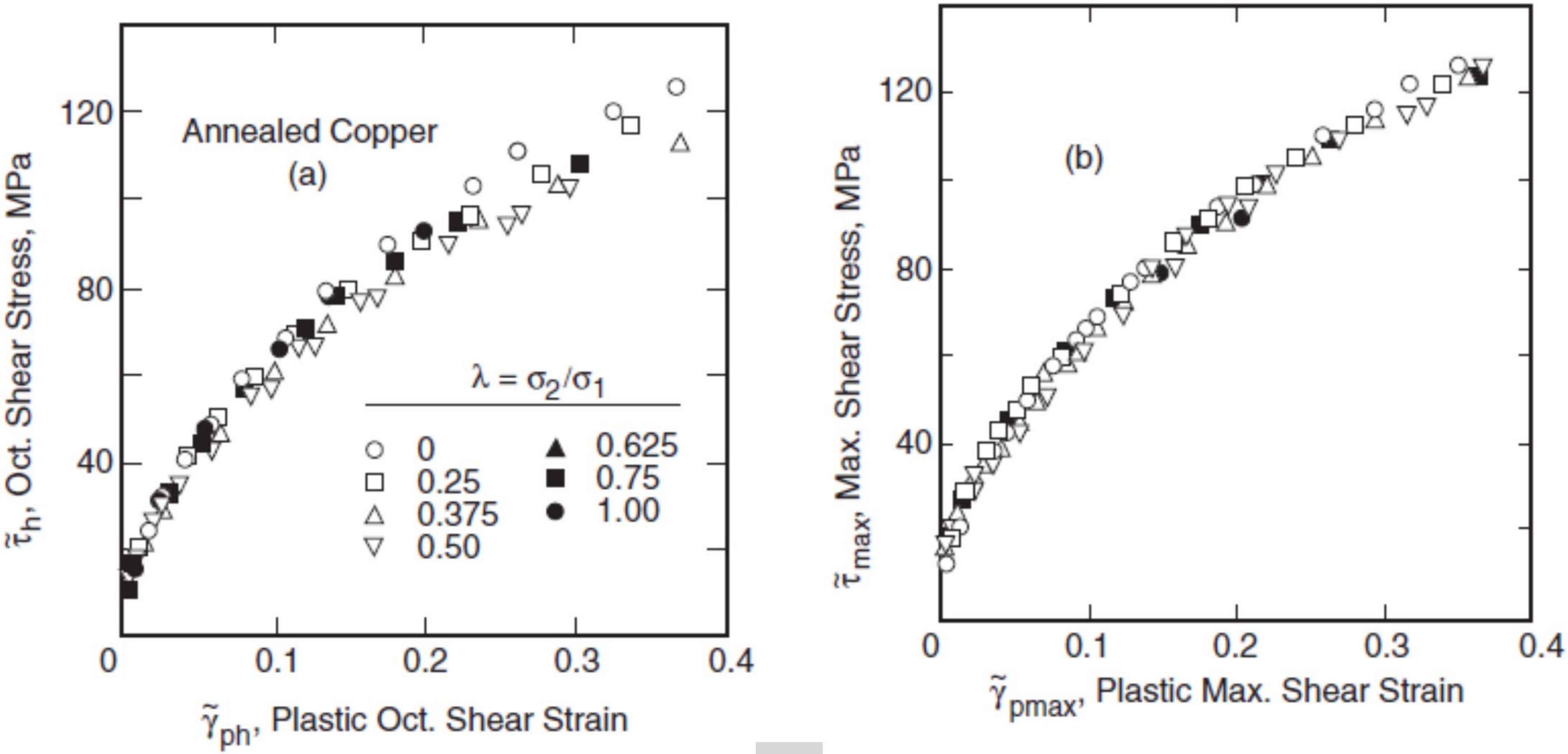
$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

Effective Plastic Strain

$$\bar{\varepsilon}_p = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_{p1} - \varepsilon_{p2})^2 + (\varepsilon_{p2} - \varepsilon_{p3})^2 + (\varepsilon_{p3} - \varepsilon_{p1})^2}$$

(Adapted from [Davis

Deformation Plasticity Theory



(Adapted from [Davis

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Modifying Factors

- Hostile chemical enviroments
- Temperature
- At short lives e-N curves are not highly sensitive to:
    - Surface finish
    - Residual stress
    - Small crack growth is importante
- Size Effects (experimental data limited)