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2.002 MECHANICS AND MATERIALS II

Spring, 2004

Creep and Creep Fracture: Part III
Creep Fracture

Mechanisms of Creep Fracture

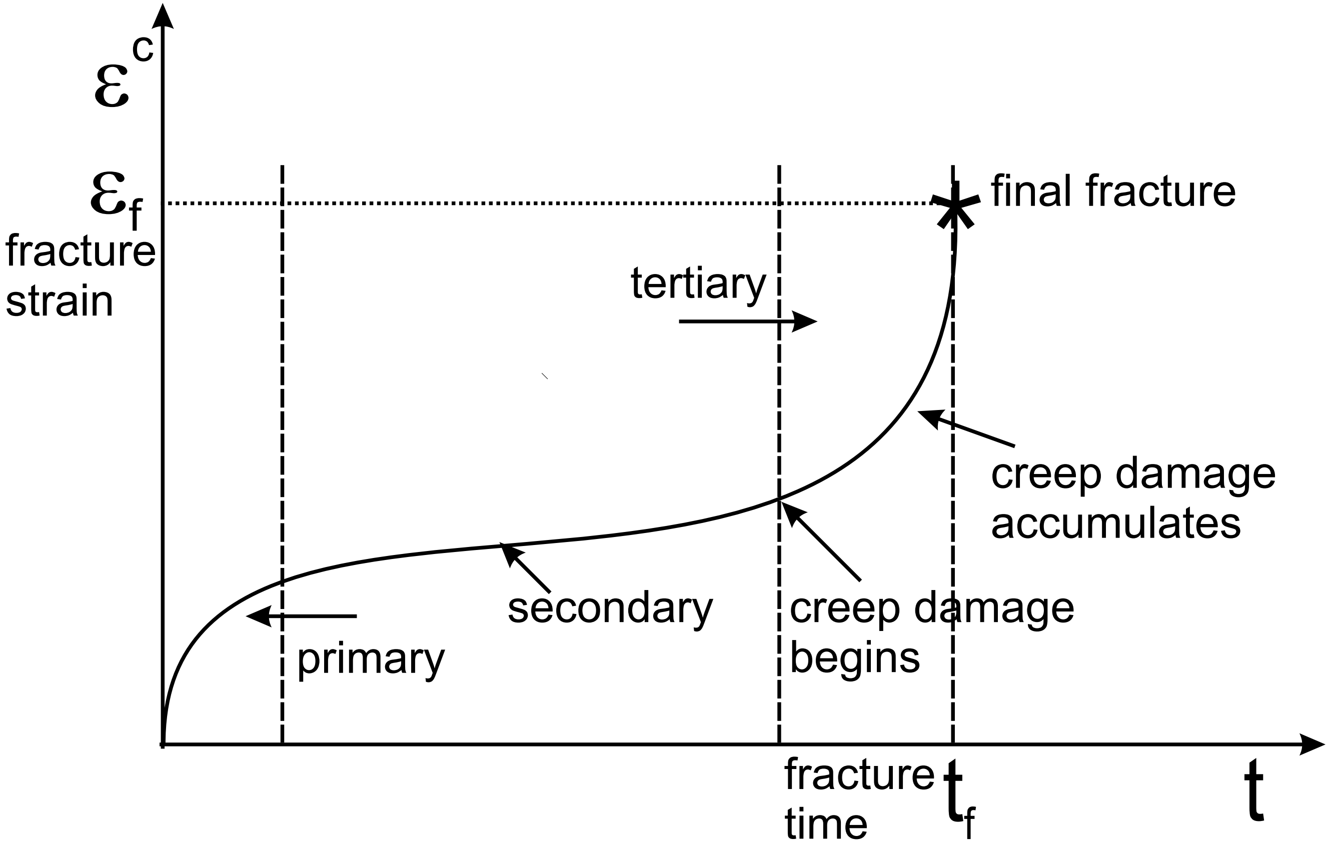

Figure 1: Creep strain-time curve for constant stress at constant temperature

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Figure 2: The upper row refers to low temperatures ($\leq 0.3\ T_M$) where plastic flow does not depend strongly on temperature or time; the lower row refers to the temperature range ($\geq 0.3\ T_M$)in which materials creep.

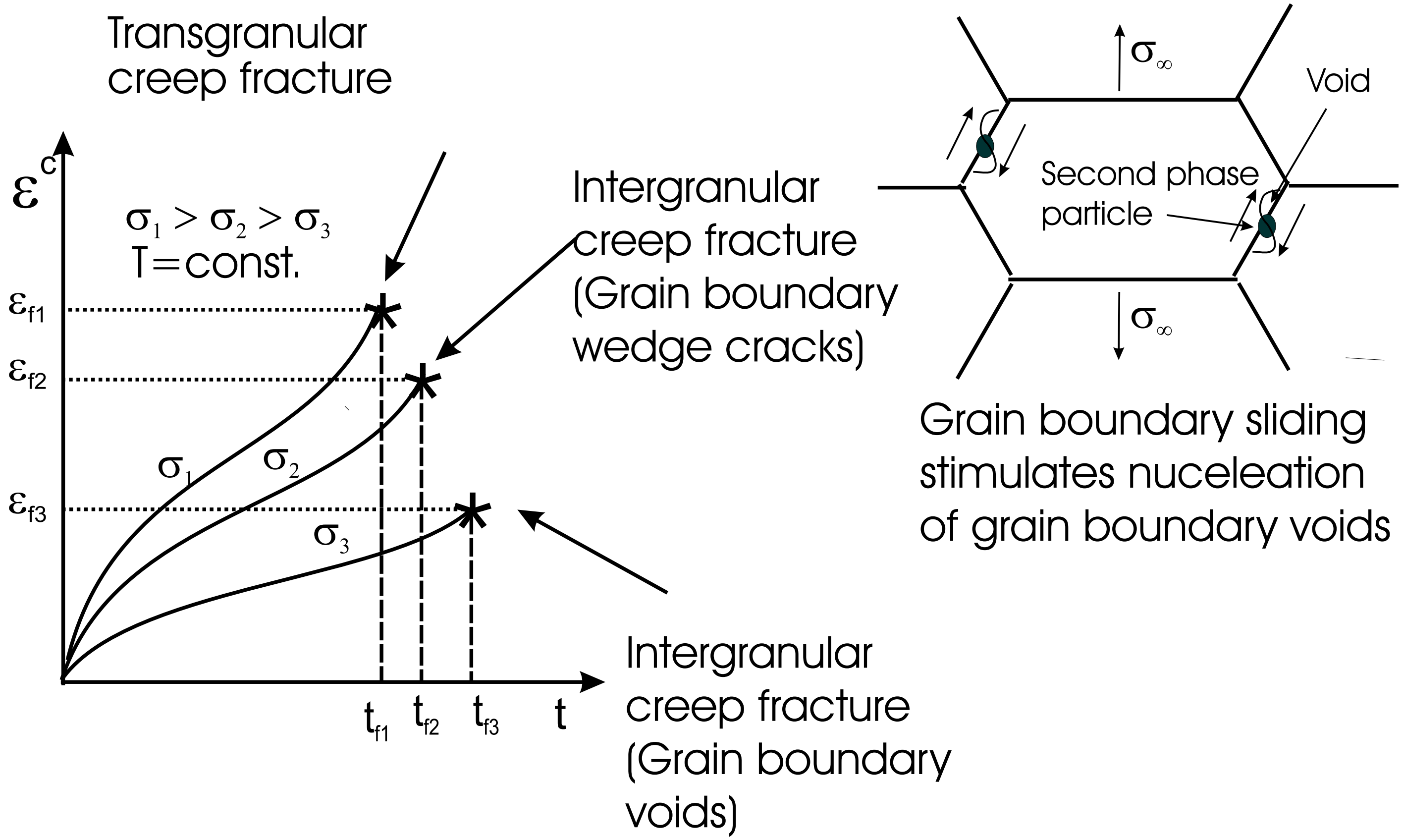

Figure 3: Schematic of creep fracture mechanisms

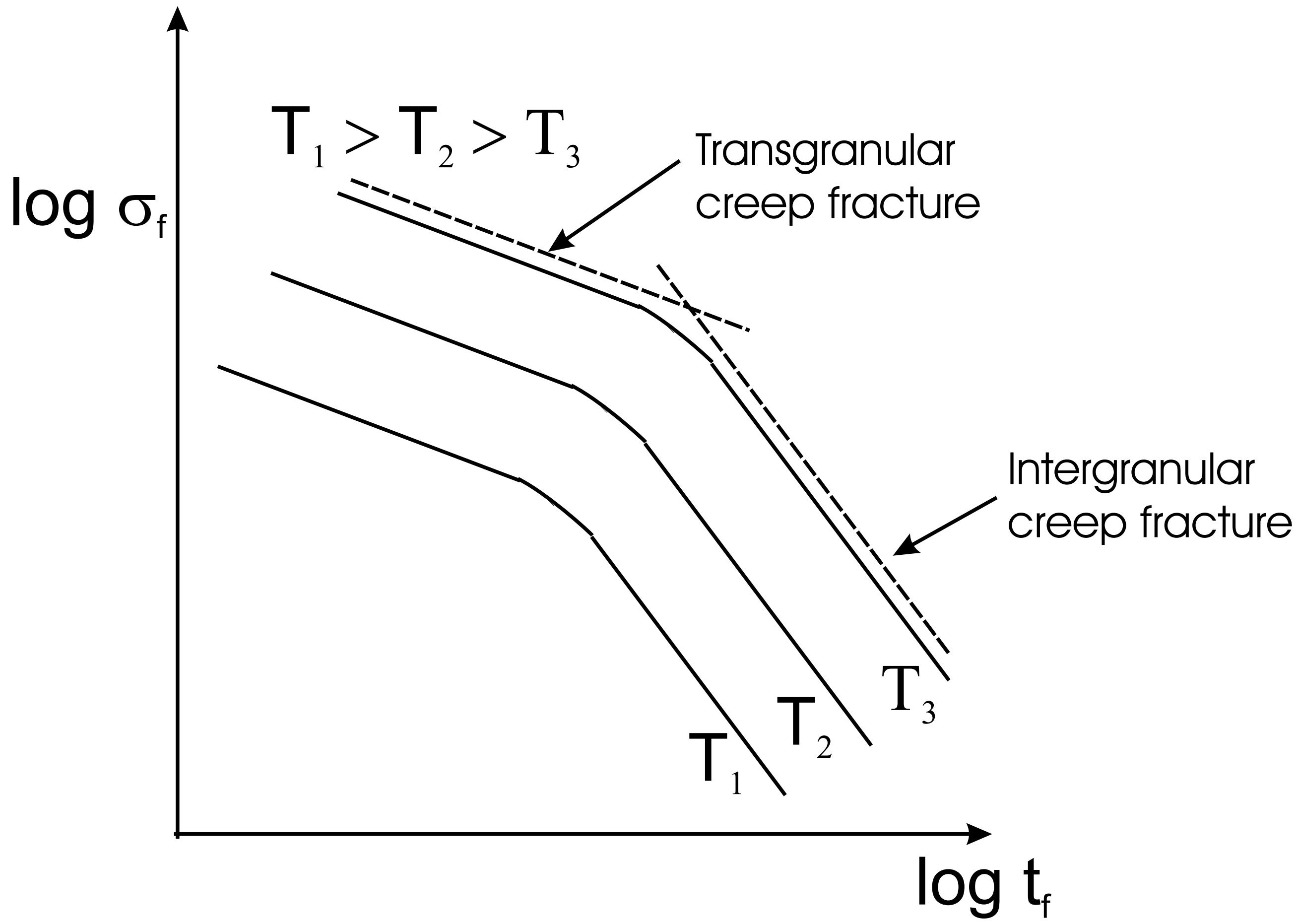

Figure 4: Schematic of uniaxial stress versus time to fracture data

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Figure 5: Map of isothermal fracture data for Nimonic-80A

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Figure 6: Map of isothermal fracture data for 304 stainless steel

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Figure 7: Map of isothermal fracture data for 316 stainless steel

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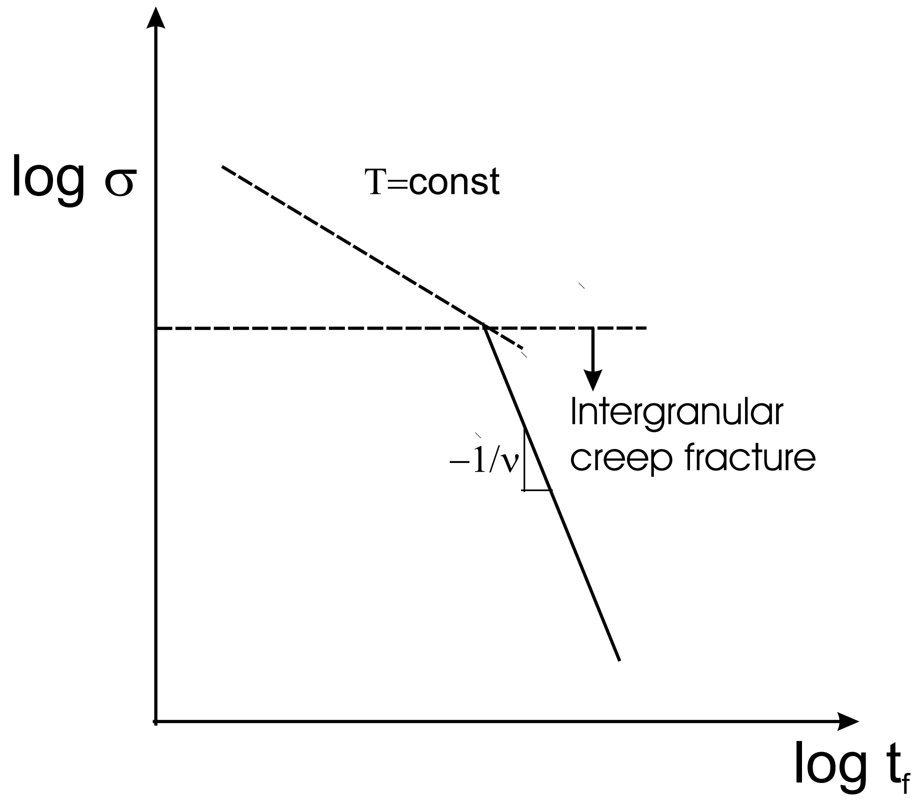
Figure 8: Micrographs of copper plates illustrating the continuous distribution of creep damage in plates containing notches and subjected to far-field uniaxial tension. Note that it is predominantly the grain boundaries perpendicular to the applied stress that are preferentially damaged.

Creep Fracture

1. Creep Rupture Diagram



$$
\begin{aligned}
log\sigma &= log\tilde{C} - (1/\nu)logt_f \\
t_f^{1/\nu} &= \frac{\tilde{C}}{\sigma} \Rightarrow t_f = \frac{C}{\sigma^\nu}
\end{aligned}
$$

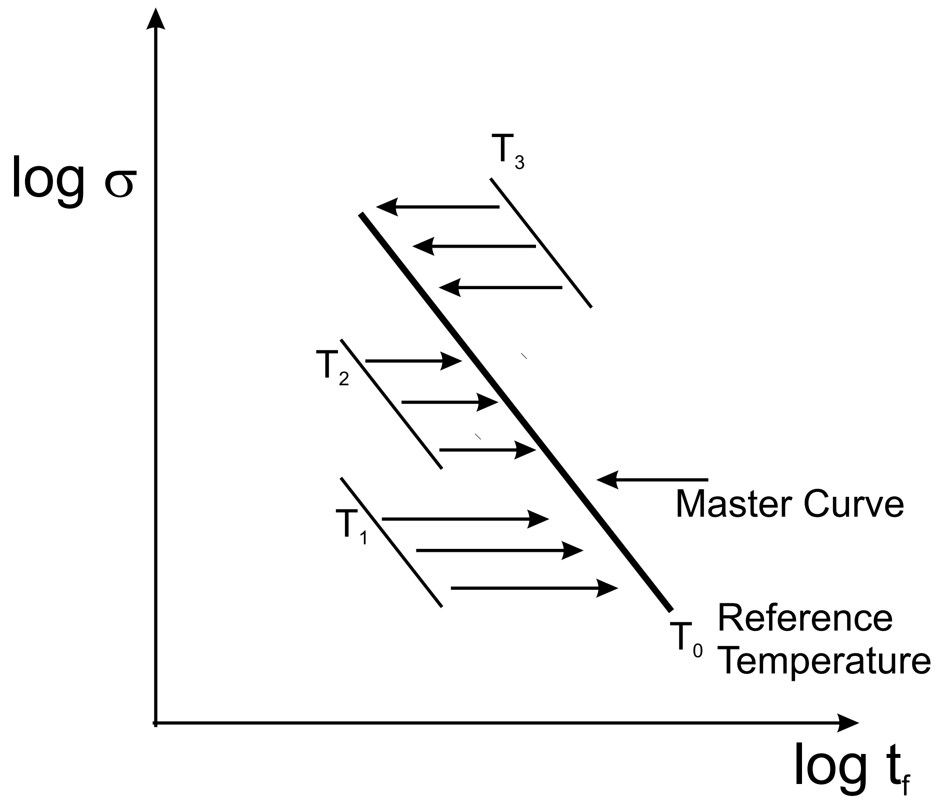
- Times to failure are normally presented as creep rupture diagrams. Their application is obvious. If you know the stress and temperature you can read off the life; for a given design life at a certain temperature, you can read off the stress.

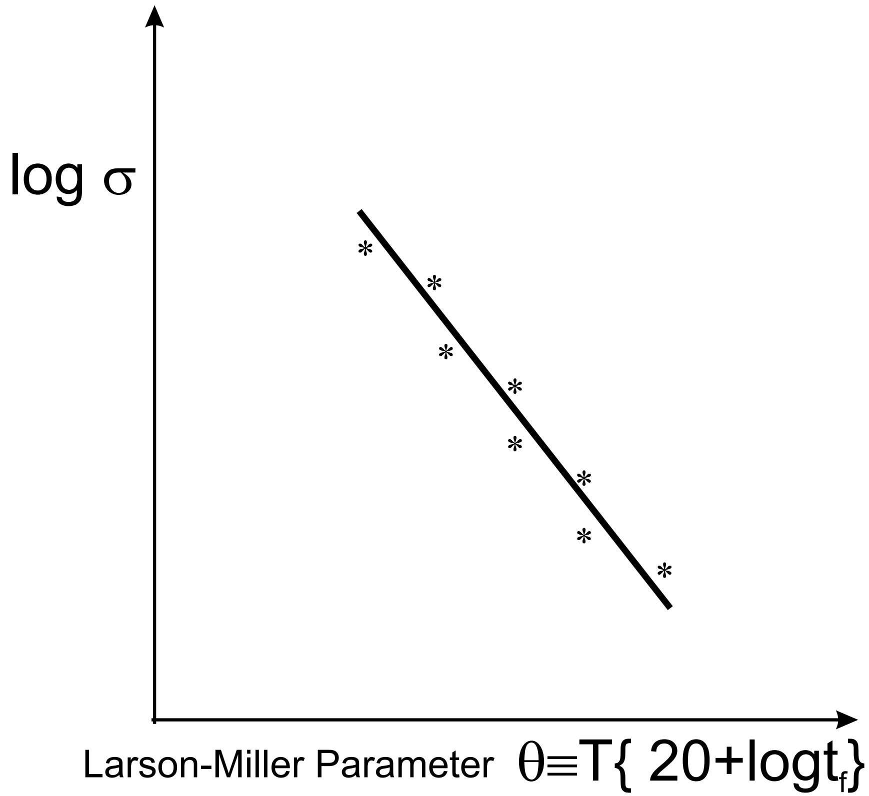
2. Monkman-Grant

$$
\begin{aligned}
t_f &= \frac{C}{\sigma^\nu} \\
\sigma &= s\left\{\frac{\dot{\epsilon}_{ss}^c}{\dot{\epsilon}_0}\right\}^{1/n} \\
\sigma^\nu &= \left(\frac{s^\nu}{\dot{\epsilon}_0^{\nu/n}}\right)\dot{\epsilon}_{ss}^{\nu/n} \\
t_f(\dot{\epsilon}_{ss}^c)^{\tilde{\nu}} &= \tilde{C} \quad \text{(Monkman and Grant)}
\end{aligned}
$$

- Typically, $\tilde{\nu} \approx 1$ and $\tilde{C} \approx 0.1 \Rightarrow$ the creep strain to fracture $\approx 10\,\%$

3. Time-Temperature Equivalence

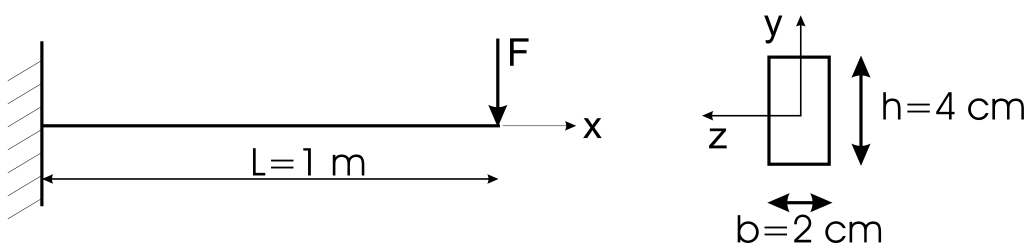




- Data is given in terms of σ in psi, t_f in hours and T in degrees Rankine $(460 +^0 F)$.

Example Problem on Creep

- A support beam made of $18Cr - 8Ni$ stainless steel is to be used in a chemical reaction chamber operating at 600^0C. The beam geometry and loading are idealized as shown below.



- The performance requirements are that

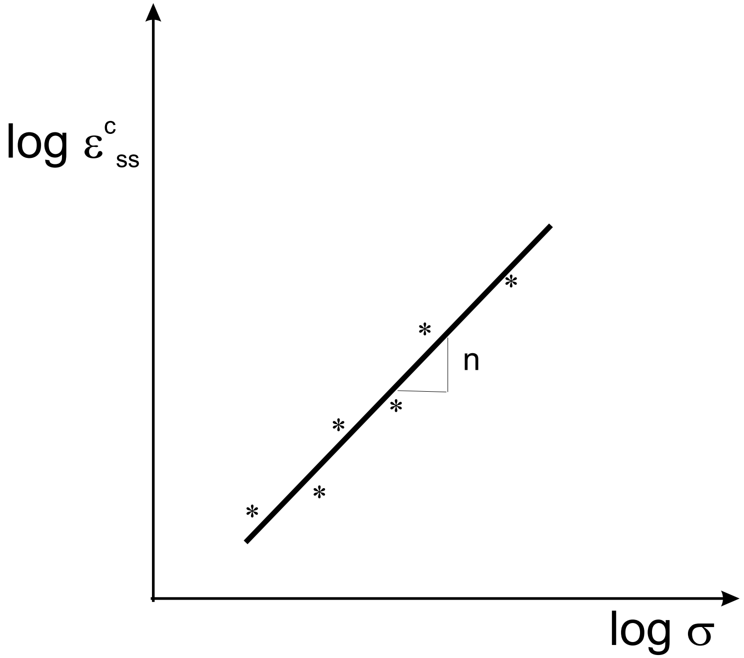
  1. The beam is to carry a constant load $F = 600\,N$.

2. No macro-crack formation due to creep fracture in 25 years.

3. Tip-deflection not to exceed 4 cm in 25 years.

- Determine if the beam meets the performance specifications. If either of the failure criteria are not met, then what is the maximum value of F that the beam can carry and not fail?

Data for 304 Stainless Steel



$$\dot{\epsilon}^c_{ss} = B\sigma^n; B = 1.095 \times 10^{-18}, n = 4.5$$

$$\Rightarrow \dot{\epsilon} = \dot{\epsilon}_0 \left\{ \frac{|\sigma|}{s} \right\}^n ; \dot{\epsilon}_0 = 1 \times 10^{-9} sec^{-1}, s = 98MPa, n = 4.5$$

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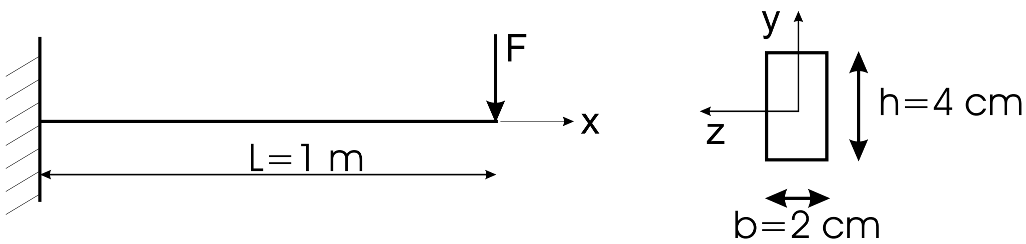
"Master Rupture Curve for 18-8 Stainless Steel."

Solution:



$$\begin{aligned} M(x) &= -F(L-x) \qquad 0 \leq x \leq L \\ \sigma(x,y) &= -\frac{M(x)}{I_n}|y|^{1/n}\mathrm{sgn}(y) \\ I_n &= \int_A |y|^{1+1/n}\, dA \end{aligned} \tag{1}$$

For a rectangular beam

$$
\begin{aligned}
I_n &= \frac{n}{2+4n} b h^2 \left\{ \frac{h}{2} \right\}^{1/n} \qquad (2) \\
\frac{\partial^2 \dot{v}}{\partial x^2} &= \dot{\epsilon}_0 \left\{ \frac{|M|}{s I_n} \right\}^n \text{sgn}(M)
\end{aligned}
$$

BCs: $\dot{v} = 0$ at $x = 0$, and $\frac{\partial \dot{v}}{\partial x} = 0$ at $x = 0$

$$
\begin{aligned}
\dot{v} &= -\dot{\epsilon}_0 \left\{ \frac{|F|}{s I_n} \right\}^n \frac{1}{n+1} \left[\frac{(L-x)^{n+2}}{n+2} + L^{n+1} x - \frac{L^{n+2}}{n+2} \right] \\
\dot{\delta} &= |\dot{v}(x = L)| = \dot{\epsilon}_0 \left\{ \frac{|F|}{s I_n} \right\}^n \frac{L^{n+2}}{n+2} \qquad (3)
\end{aligned}
$$

Check for Macro-crack Formation

From (1) and (2)

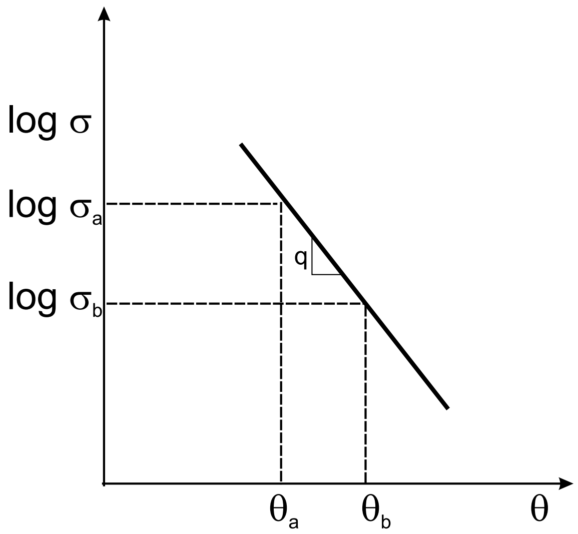
$$\sigma(x,y) = -\frac{M(x)}{\left\{\frac{n}{2+4n}bh^2\right\}}\left|\frac{2y}{h}\right|^{1/n}\operatorname{sgn}(y)$$

Since $M(x) = -F(L-x)$, maximum moment is at $x = 0$, i.e., $M_{max} = -FL$, and maximum tensile stress occurs at $y = h/2$, we get

$$\sigma_{max} = \frac{FL}{\left\{\frac{n}{2+4n}bh^2\right\}} = \frac{600\,N \times 1\,m}{\left\{\frac{4.5}{2+4\times 4.5} \times 0.02 \times 0.04^2\,m^3\right\}}$$

$\sigma_{max} = 83.33\,MPa$, and since $1\,MPa = 145\,psi$, we get $\sigma_{max} = 12,083\,psi$. The temperature is $600^0C = 1112^0F = 1572^0R$

From Larson-Miller master curve for 18-8 stainless steel,



$$log\sigma = logp - q\theta$$ p and q are constants

Solve for q:

$$q = \frac{log(\sigma_a/\sigma_b)}{\theta_b - \theta_a} \;\; ; \;\; logp = log\sigma_a + q\theta_a$$

For $\sigma_a = 10,000\,psi\,,\;\; \theta_a = 41,000$;
for $\sigma_b = 2,000\,psi\,,\;\; \theta_b = 50,000$
Therefore, $q = \frac{log(5)}{9000} = 7.77 \times 10^{-5}$
Solve for p: $logp = log10,000 + (7.77 \times 10^{-5}) * 41,000 =$
7.1842
$\Rightarrow p = 1.53 \times 10^7$
Now, with $\theta_{LM} = T(20 + \log(t_f))$,

$$log\sigma = logp - qT(20 + logt_f)$$

$$\Rightarrow \log\left(\frac{p}{\sigma}\right)^{1/(qT)} = \log(10^{20}t_f)$$

or

$$t_f = 10^{-20}(p/\sigma)^{1/(qT)}$$

where t_f is the rupture time in **hours**, T is the temperature in **degrees Rankine** and σ is the stress in **psi**.

$$t_f = 10^{-20}\left\{\frac{1.53\times 10^7}{12,083}\right\}^{\frac{1}{7.77\times 10^{-5}\times 1572}}$$

$$= 10^{-20}\left\{1.2662\times 10^3\right\}^{8.187} = 2.513\times 10^5\, hours$$

Since $1\, year = 365\times 24 = 8760\, hours$,

$$t_f = 28.69\, years$$

Therefore, a macro-crack will form on the tensile side of the beam after approximately 28 years. The beam is ∼safe for 25 years.

Check for Deflection

$$\dot{\delta} = \dot{\epsilon}_0 \left\{ \frac{|F|}{sI_n} \right\}^n \frac{L^{n+2}}{n+2}$$

$$I_n = \frac{n}{2+4n} bh^2 \left\{ \frac{h}{2} \right\}^{1/n}$$

For $b = 0.02\,m$, $h = 0.04\,m$, $n = 4.5$, $I_n = 3.0184 \times 10^{-6}\,m^{[3+(1/4.5)]}$, $F = 600\,N$, $\dot{\epsilon}_0 = 10^{-9}\,sec^{-1}$, and $s = 98 \times 10^6\,N/m^2$

$$\dot{\delta} = \frac{10^{-9}}{sec} \left\{ \frac{600N}{(98 \times 10^6 \frac{N}{m^2})\,(3.0184 \times 10^{-6} m^{[3+(1/4.5)]})} \right\}^{4.5} \left\{ \frac{(1m)^{[2+4.5]}}{6.5} \right\}$$

$$\dot{\delta} = 3.7 \times 10^{-9}\,m/s \Rightarrow \delta = (3.7 \times 10^{-9} m/s) \times t$$

$t = 25\,years = 25y \times 365da/y \times 24h/da \times 3600sec/h = 7.884 \times 10^8\,sec$

Therefore,

$$\delta = (3.7 \times 10^{-9}) m/s \times (7.884 \times 10^{8}) s = 2.951\, m$$

Too much deflection!
A deflection of 4 cm would occur after only

$$t = \frac{0.04 m}{3.7 \times 10^{-9} m/s} = 1.08 \times 10^{7}\, sec = 3000\, hours$$

The load has to be decreased substantially. For a total deflection of $4 \times 10^{-2}\, m$ in 25 $years$

$$\dot{\delta} = \frac{4 \times 10^{-2} m}{25 y \times 365 da/y \times 24 h/da \times 3600 s/h} = 5.0 \times 10^{-11}\, m/s$$

From

$$F = \left[\frac{(\dot{\delta}/\dot{\epsilon}_0)}{\left(\frac{L^{n+2}}{n+2}\right)} \right]^{1/n} sI_n = 231\,N = 52\,lbf$$

Alternatively, the ratio of the deflections is the ratio of the deflection rates, which in turn are proportional to the load ratio, raised to the power $n = 4.5$;

$$\left(\frac{|F|}{600\,N}\right)^{4.5} = \frac{.04m/25y}{2.951m/25y}$$

$$\Rightarrow |F| = 600\,N \times \left(\frac{.04}{2.951}\right)^{\frac{1}{4.5}} = 600\,N \times (.01355)^{.2222} = 231\,N.$$