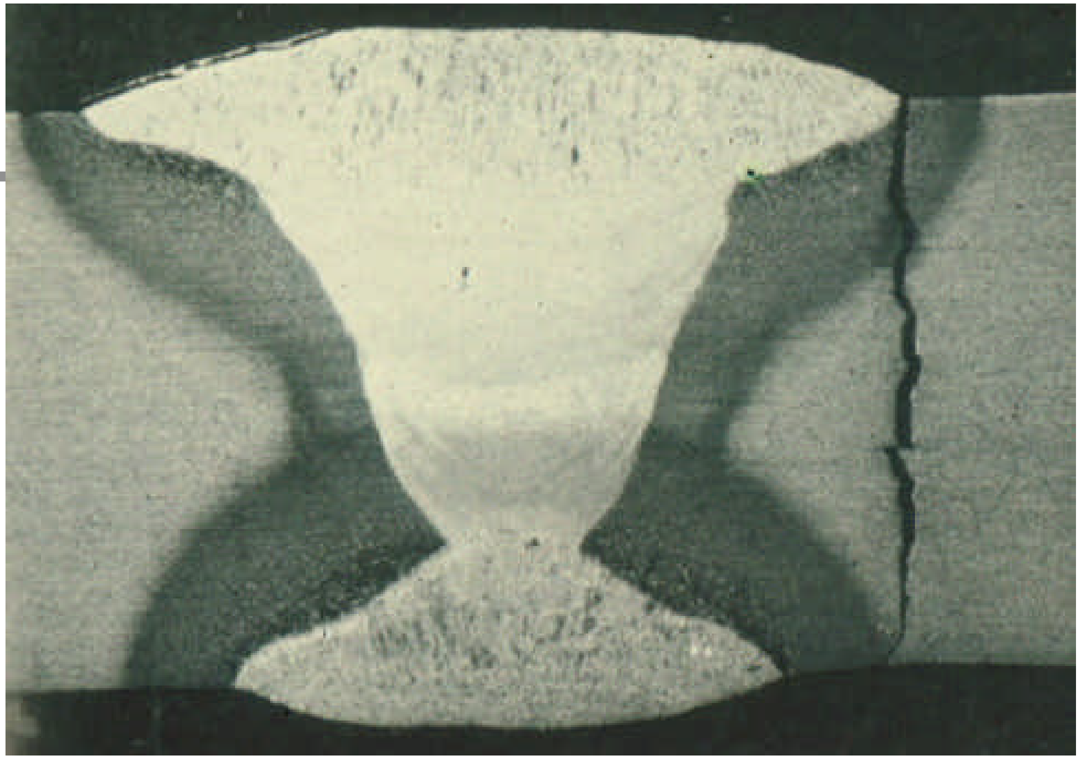
V Predicted Weldment Fatigue Behavior



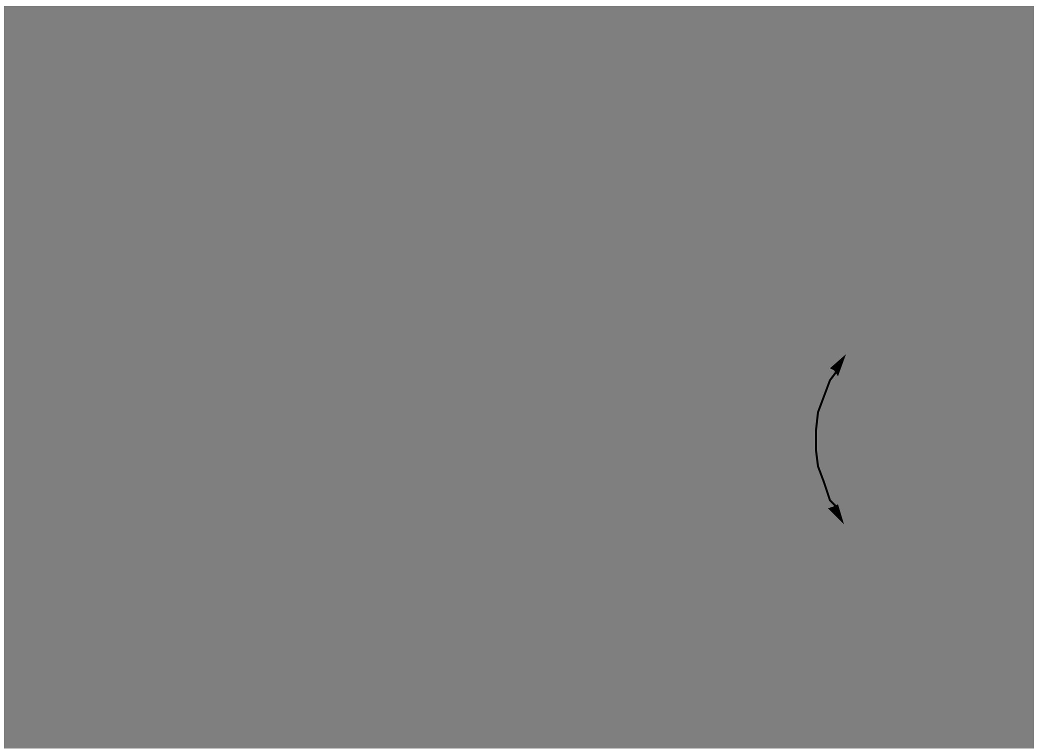
Outline

- Heavy and Light Industry weldments
- The IP model
- Some predictions of the IP model

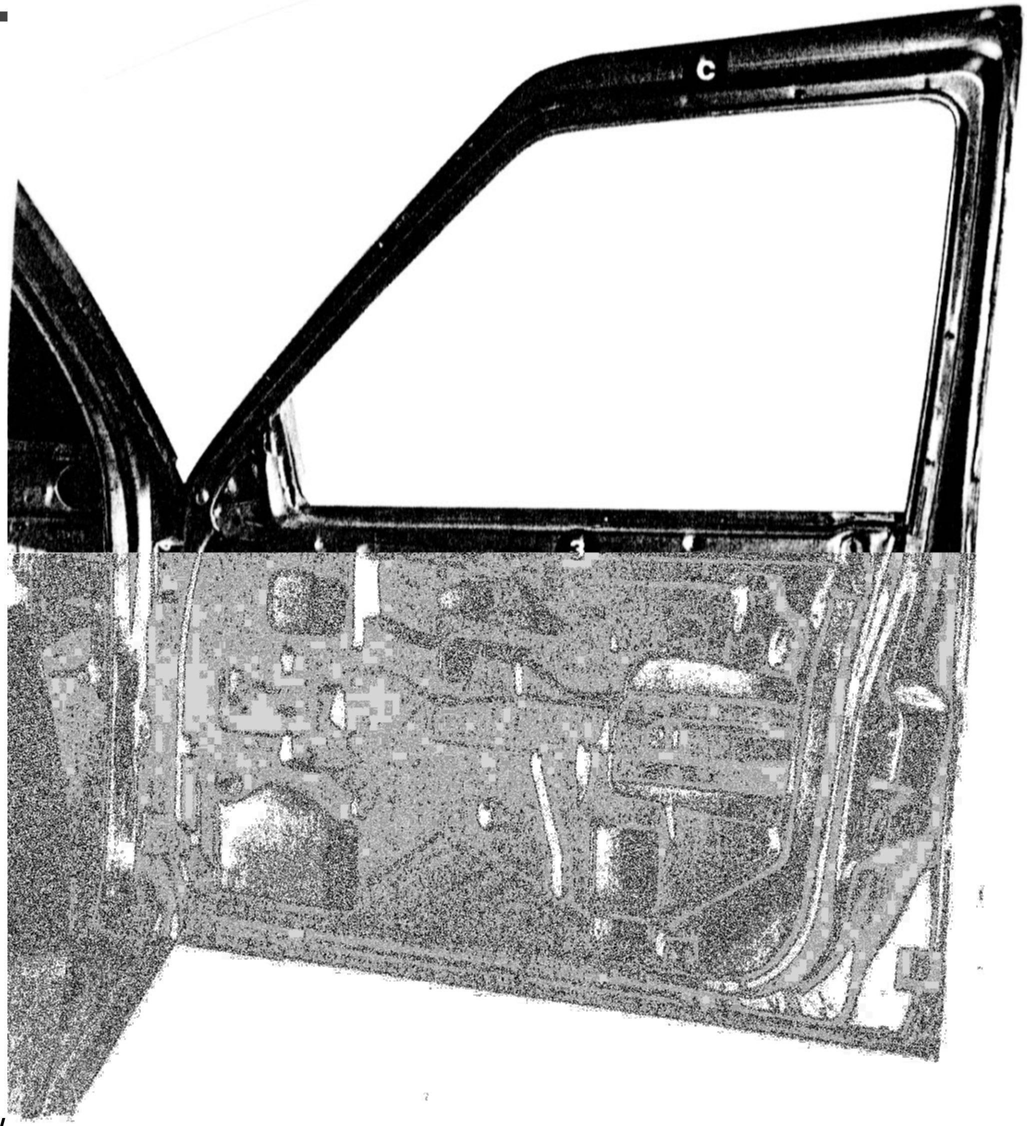
Heavy industry

Heavy industry

Complex weldment

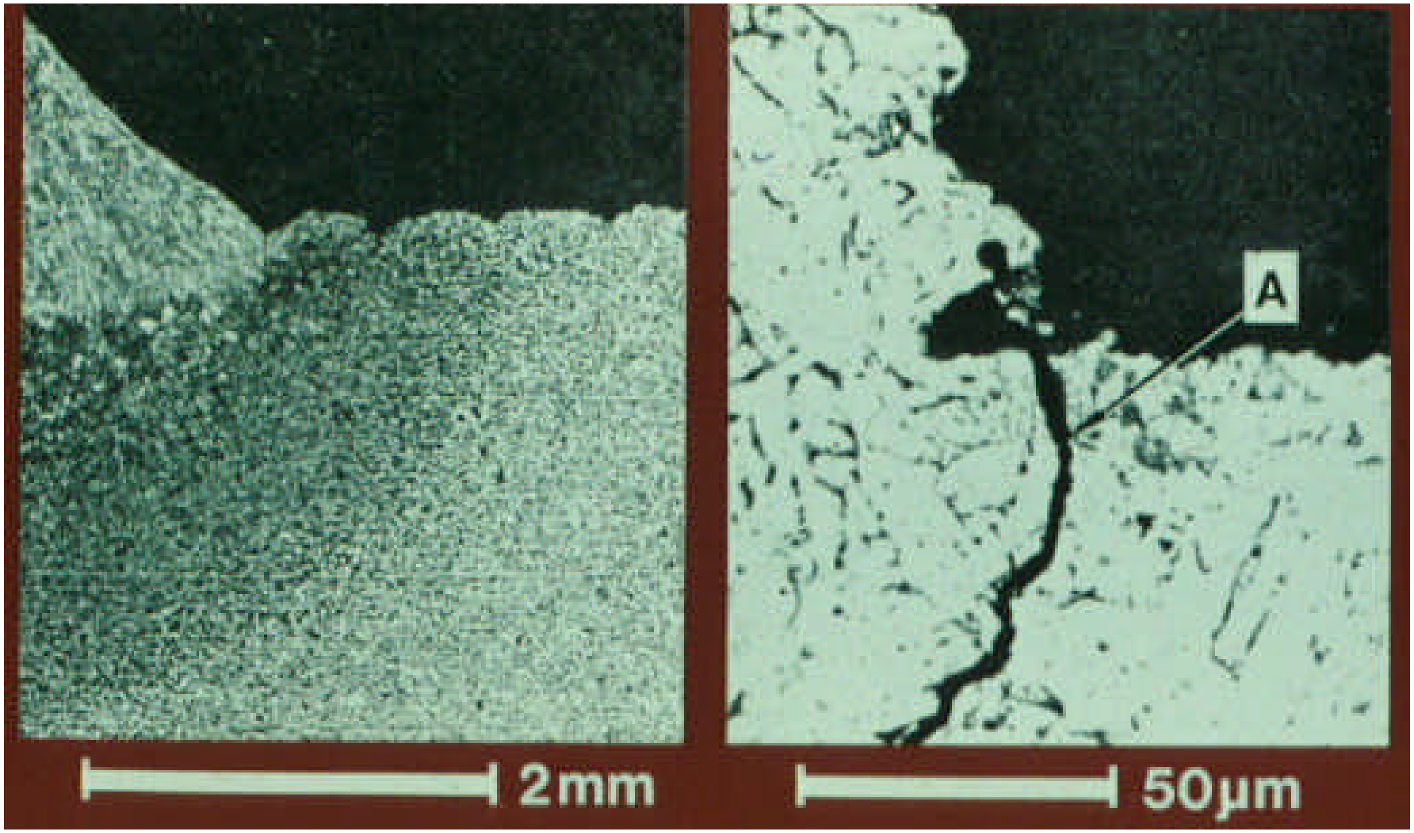


Light Industry



There are about 4000 to 6000 spot welds in the average automobile. For the most part these are executed by welding robots.

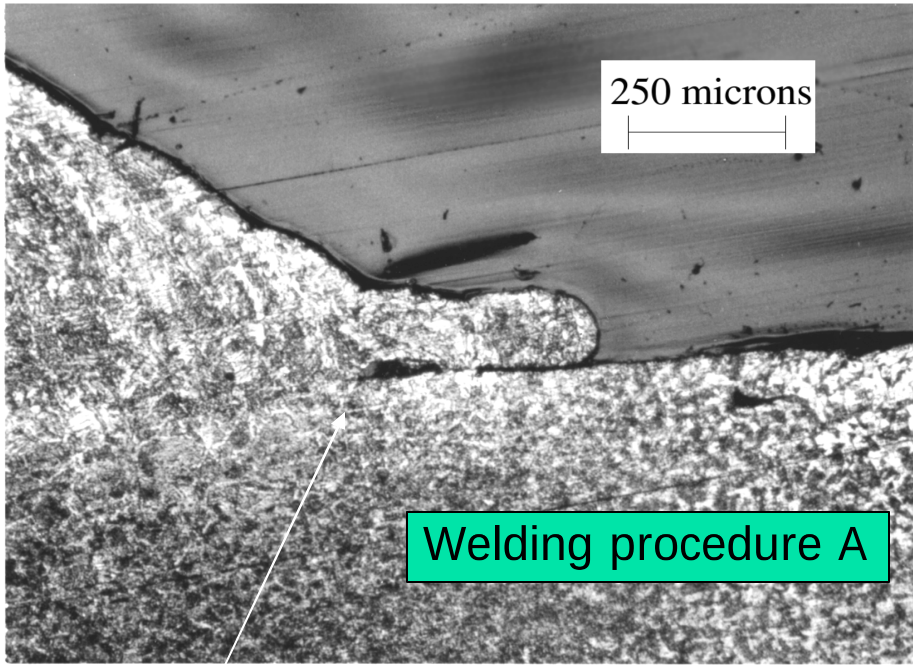
Weld quality



The civil engineering view: Ever-present small flaws virtually eliminate fatigue crack initiation life N_I of weldments.

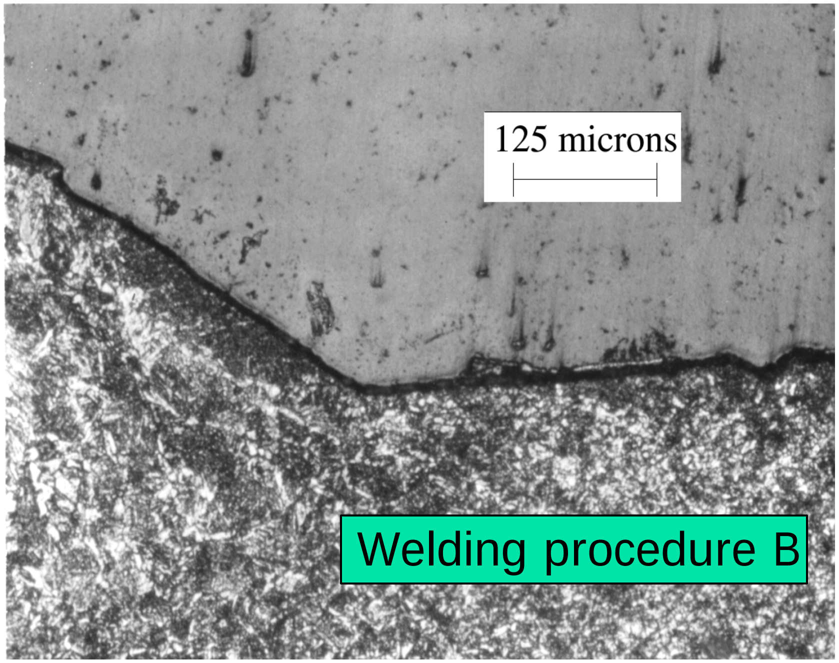
Weld quality and welding procedure

"Nominal"



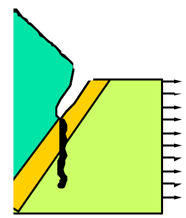
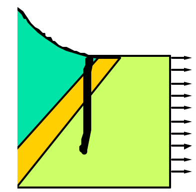
Cold laps virtually eliminate the fatigue crack initiation life (N_I)

"Ideal"



Such weldments may have an appreciable fatigue crack initiation life (N_I)

Two rather different paradigms

Symbol		
Application	<u>Civil Eng.</u> "Heavy Industry" "Nominal" One-of-a-kind Very high reliability	<u>Mechanical Eng.</u> "Light Industry" "Ideal" Mass production Moderate reliability
Weld Quality	Low: Flaws < 0.1-in	High: Flaws > 0.01-in
Weldment size	Big > 1-in	Small < 1/2-in
Weldment Complexity	High (redundant)	Low (simple)

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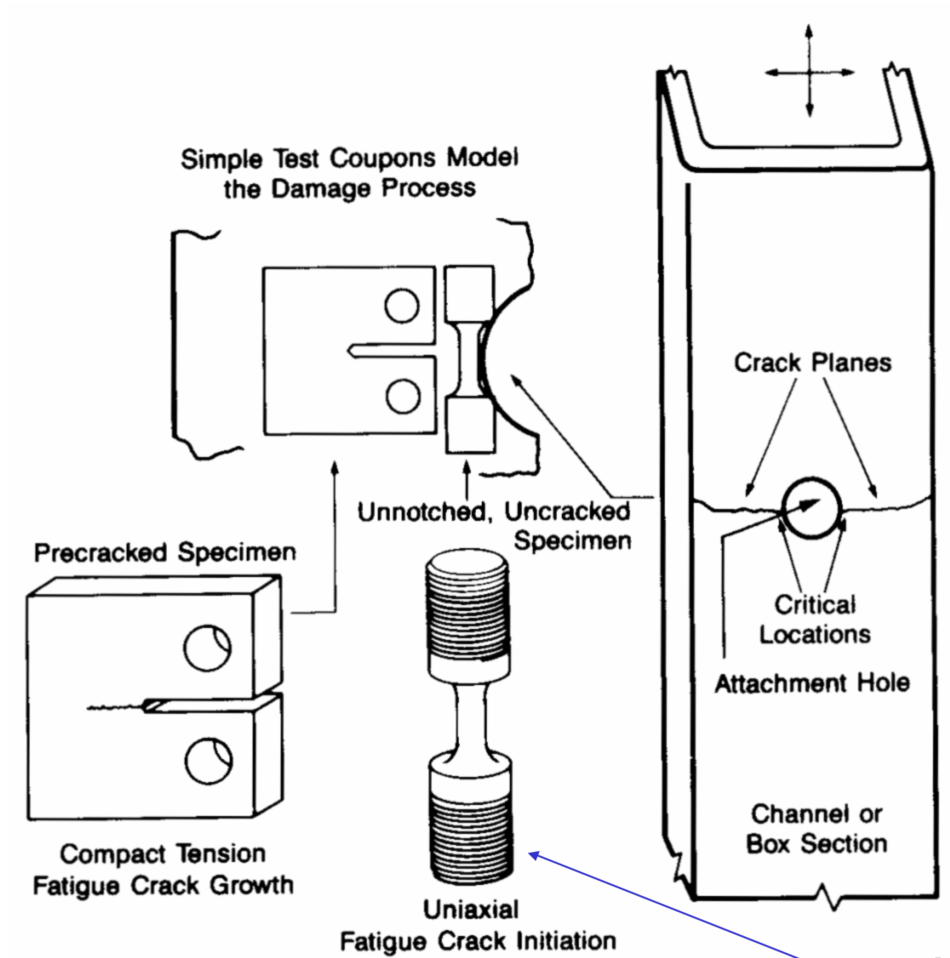
Fatigue of a component



The fatigue life of an engineering component consists of two main life periods:

Initiation or nucleation of a fatigue crack (NI)

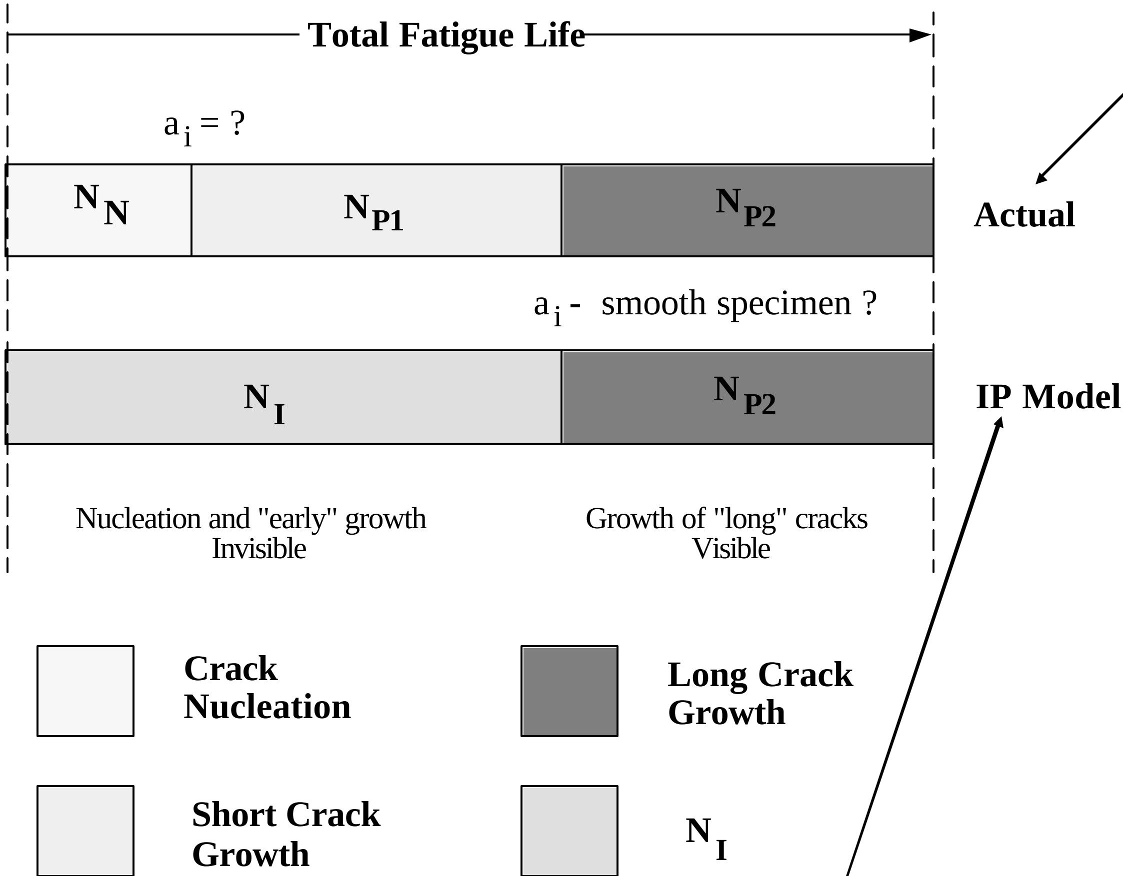
And

Its growth to failure (NP)

A smooth specimen

Initiation-Propagation (IP) Model

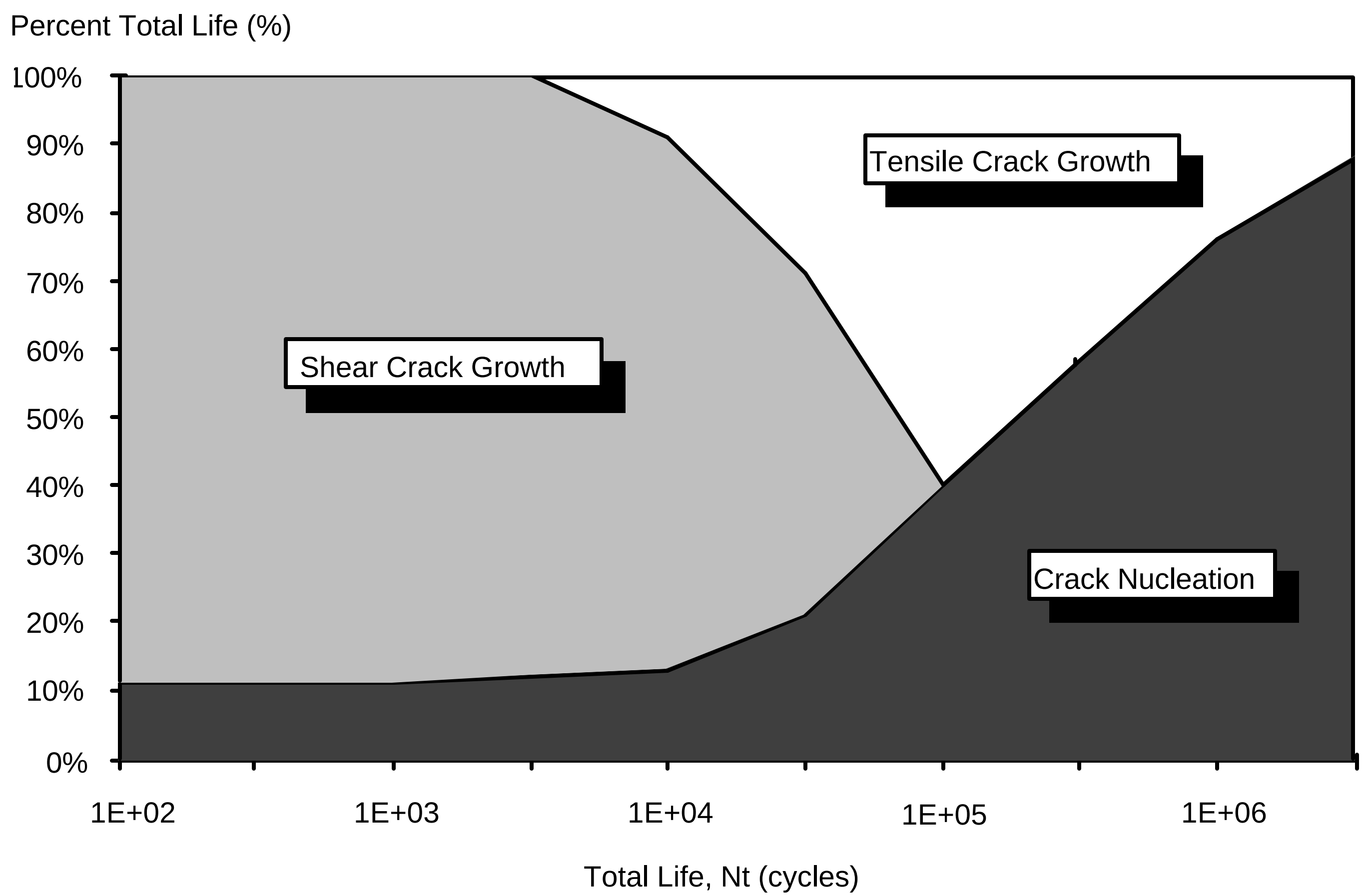
$$N_T = N_N + N_{P1} + N_{P2}$$



$$N_T = (N_N + N_{P1}) + N_{P2} = N_I + N_{P2}$$

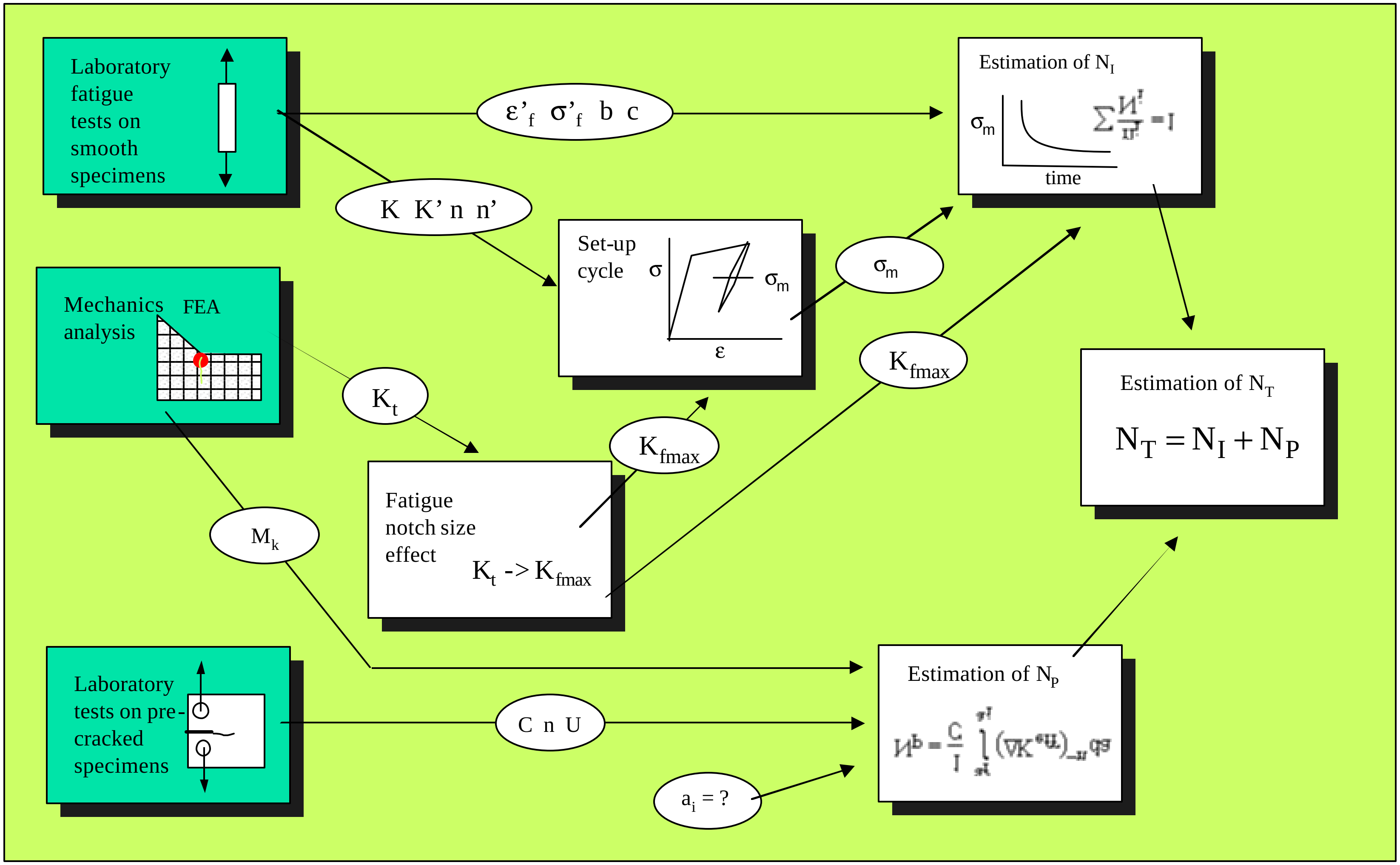
The total fatigue life of a component may be considered to be the sum of three periods: crack nucleation (N_N), short crack growth (N_{P1}) in which the crack closure phenomenon is a function of crack length, and long crack propagation (N_{P2}) in which the crack closure phenomenon is more or less independent of crack length

Relative importance of N_I and N_P



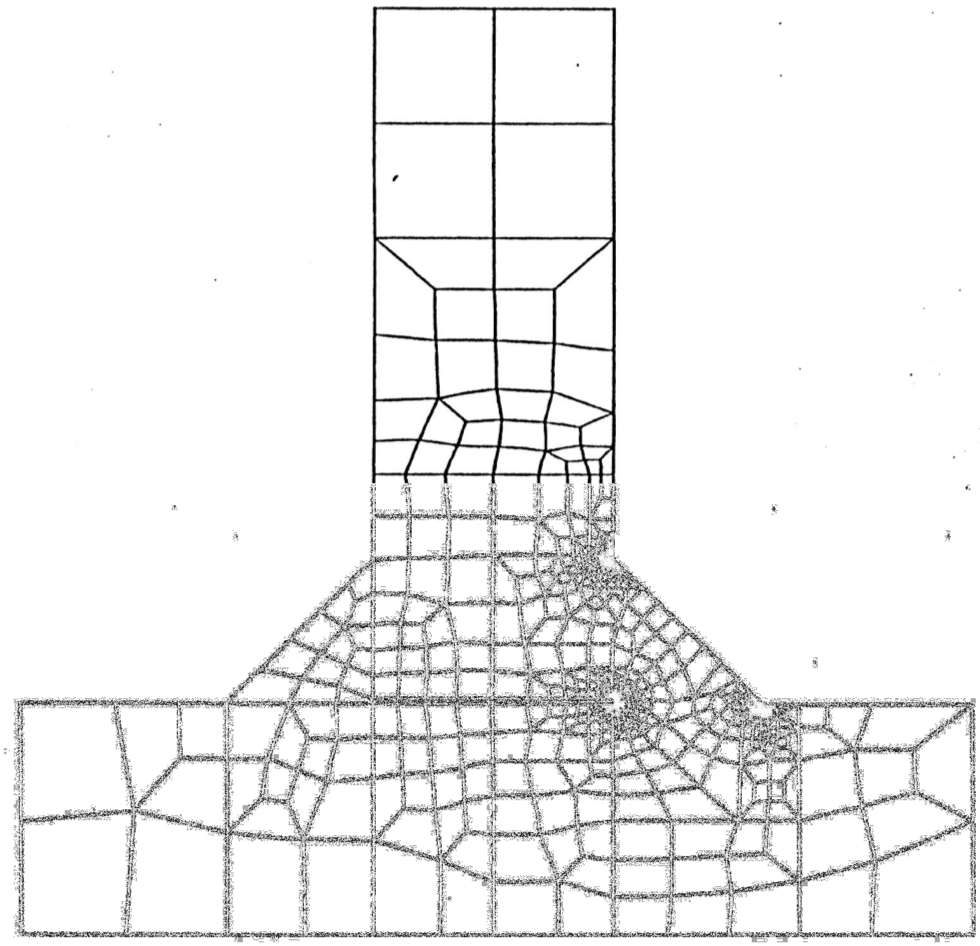
The relative importance of fatigue crack initiation and propagation (SAE 1045 steel after Socie)

IP Model details

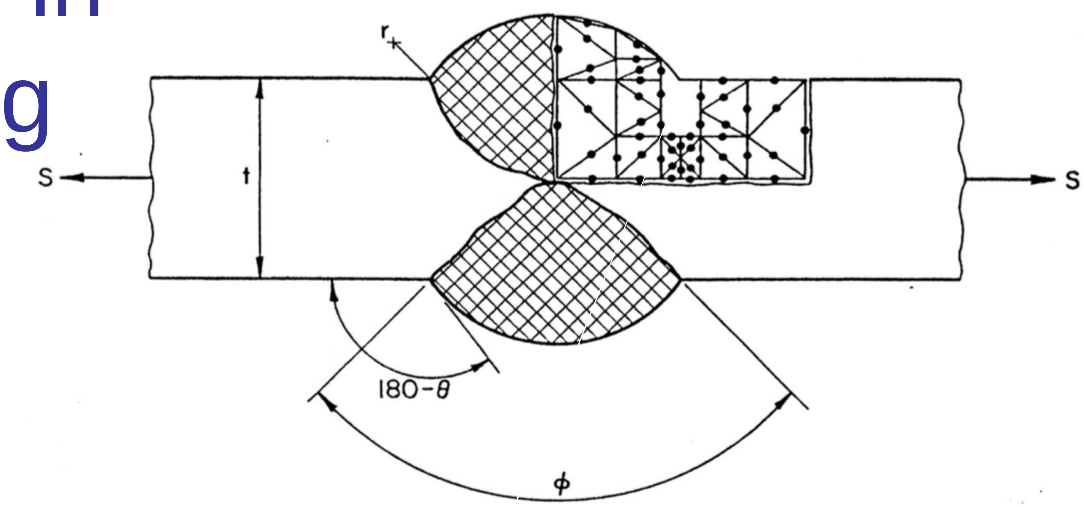


FEM determination of notch root stresses

Two weld toes,
on incomplete
joint penetration

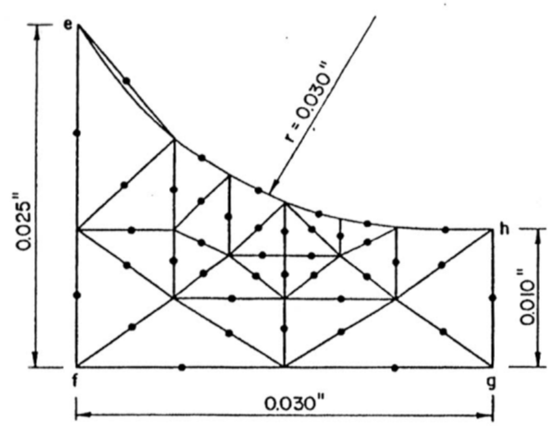


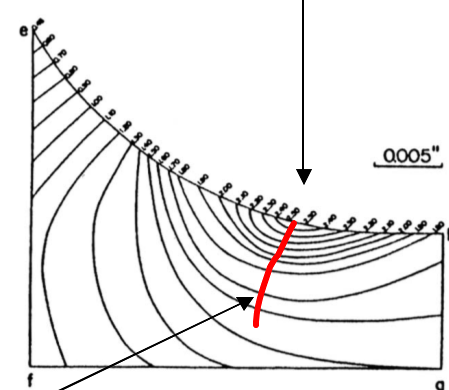
Determining K_t for use in calculating N_I



Highest stress region of weld toe is 20° away from the point of tangency

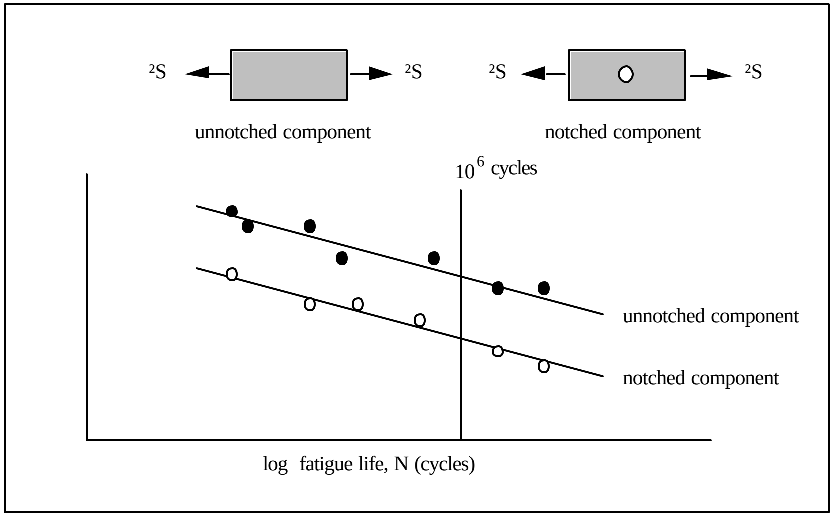
(Can also get stresses along crack path for N_P calculation from this analysis.)



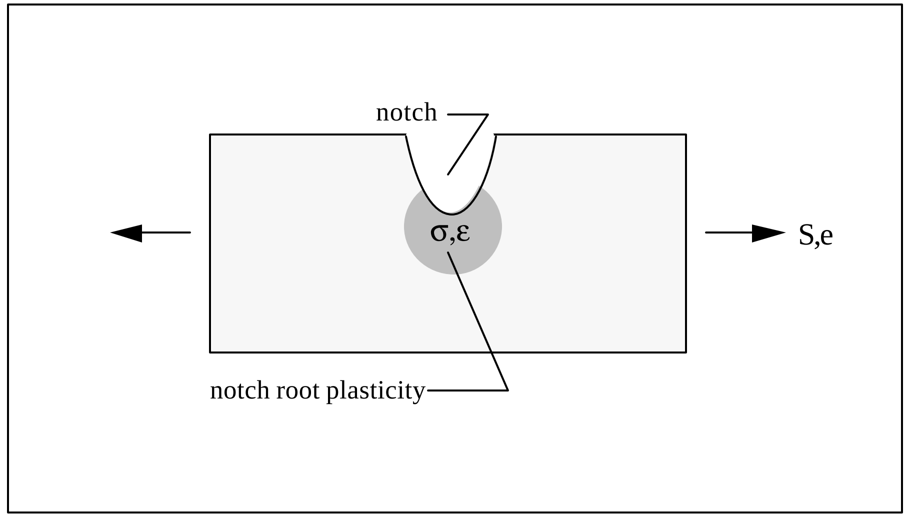


Estimation of notch-root conditions

Experimental determination of K_f



Analytical determination of K_t



The severity of a notch in fatigue, that is the magnitude of K_f can be measured... The effect of notch-size can be estimated using Peterson's equation.

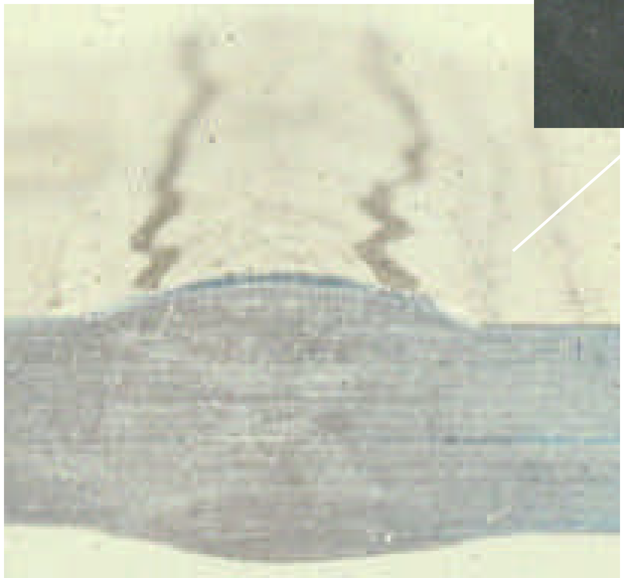
$$K_f = 1 + \frac{K_t - 1}{1 + \frac{a}{r}}$$

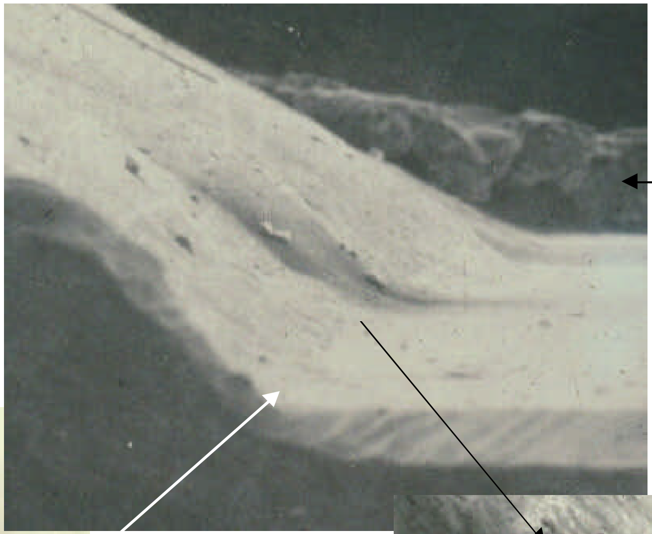
Alternatively, for generally elastic body, the local stress can be estimated analytically using Neuber's Rule.

$$\sigma\,\varepsilon = \frac{(K_t\,S)^2}{E}$$

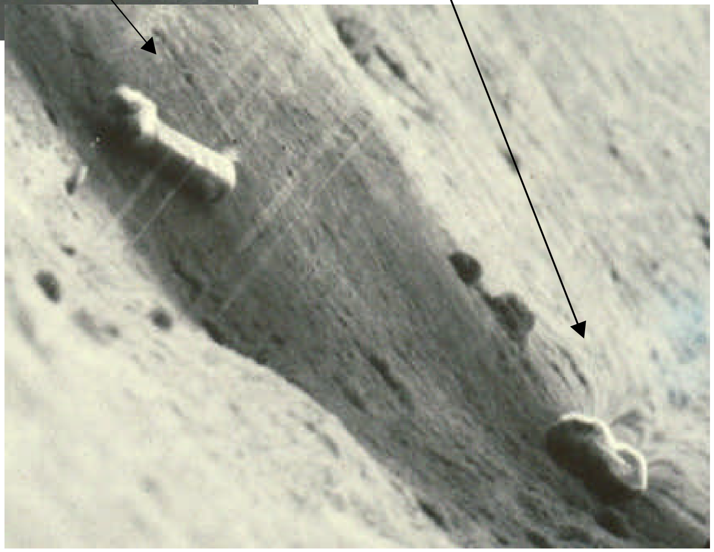
Perfect weldments: concept of the worst-case notch

0.5-in. plate thickness 5083 Al weldment





Looks pretty smooth with well defined radius, BUT!!!???



Perfect weldments: K_{fmax}

$$K_t = 1 + \alpha \sqrt{\frac{t}{r}}$$

Peterson's equation

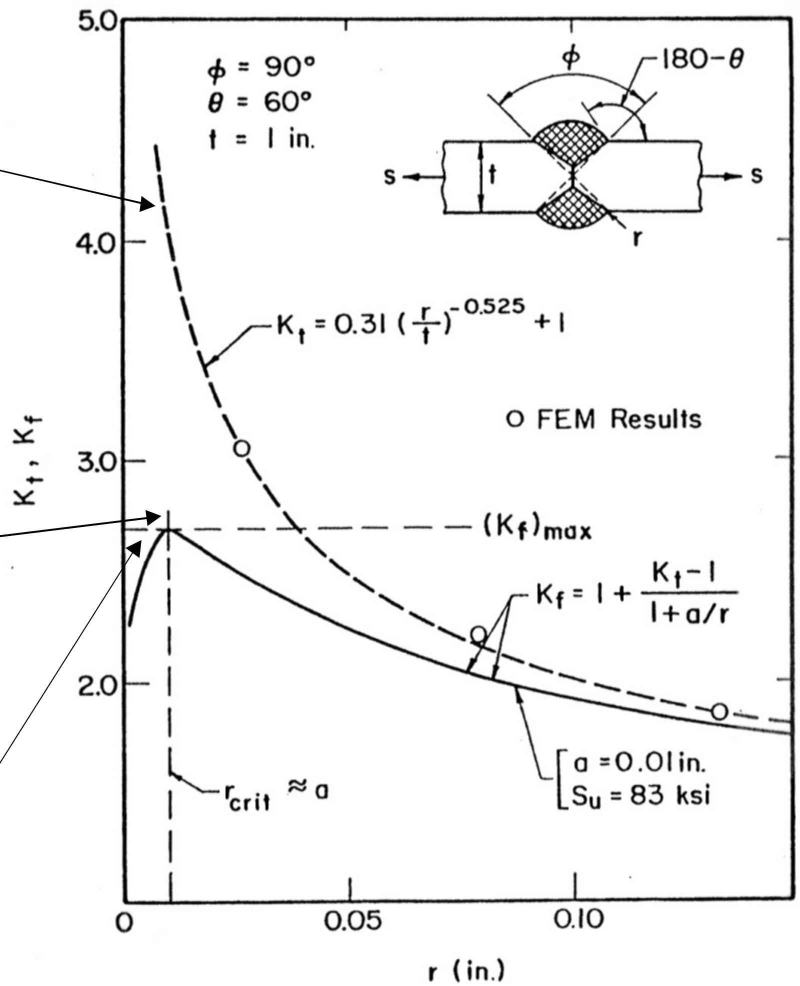
$$K_f = 1 + \frac{K_t - 1}{1 + \frac{a}{r}}$$

$$\frac{\partial K_f}{\partial r} = 0, \quad r_{crit} = a$$

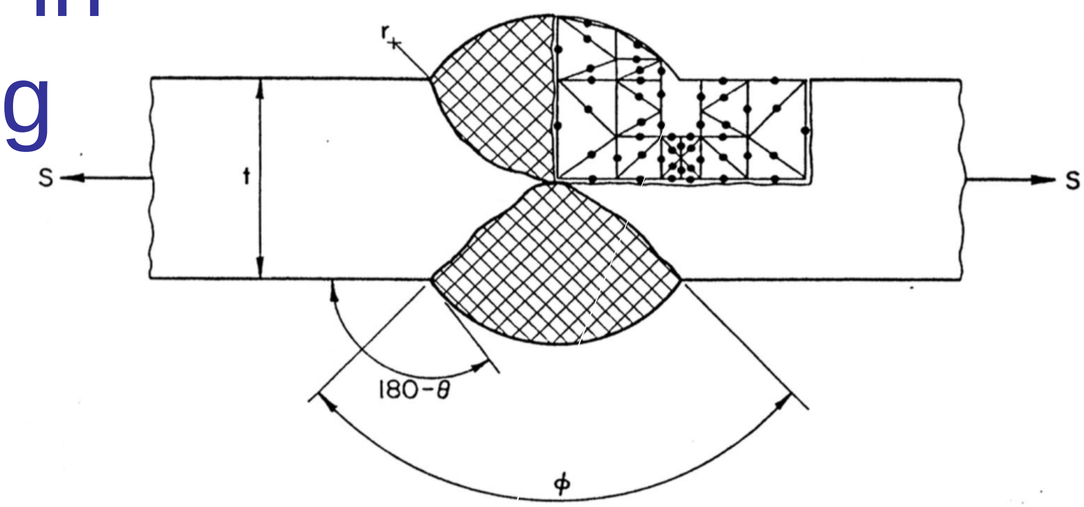
$$K_{f\,max} = 1 + \frac{1}{2} \alpha S_u \sqrt{\frac{t}{a}}$$

$$a(\text{in.}) \approx 0.001 \left(\frac{300}{S_u} \right)^2$$

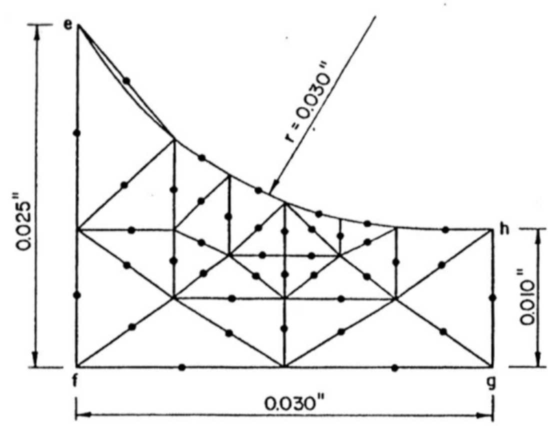
$$K_{f\,max} = 1 + 0.015\, \alpha\, S_u \sqrt{t}$$

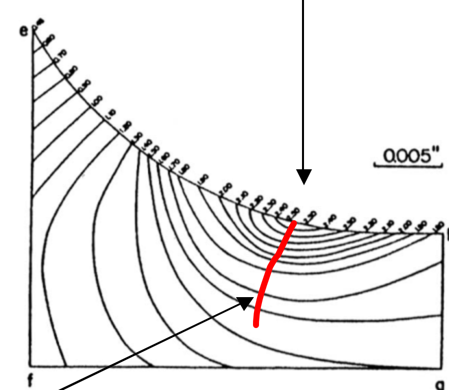


Determining K_t for use in calculating N_I



Highest stress region of weld toe is 20° away from the point of tangency

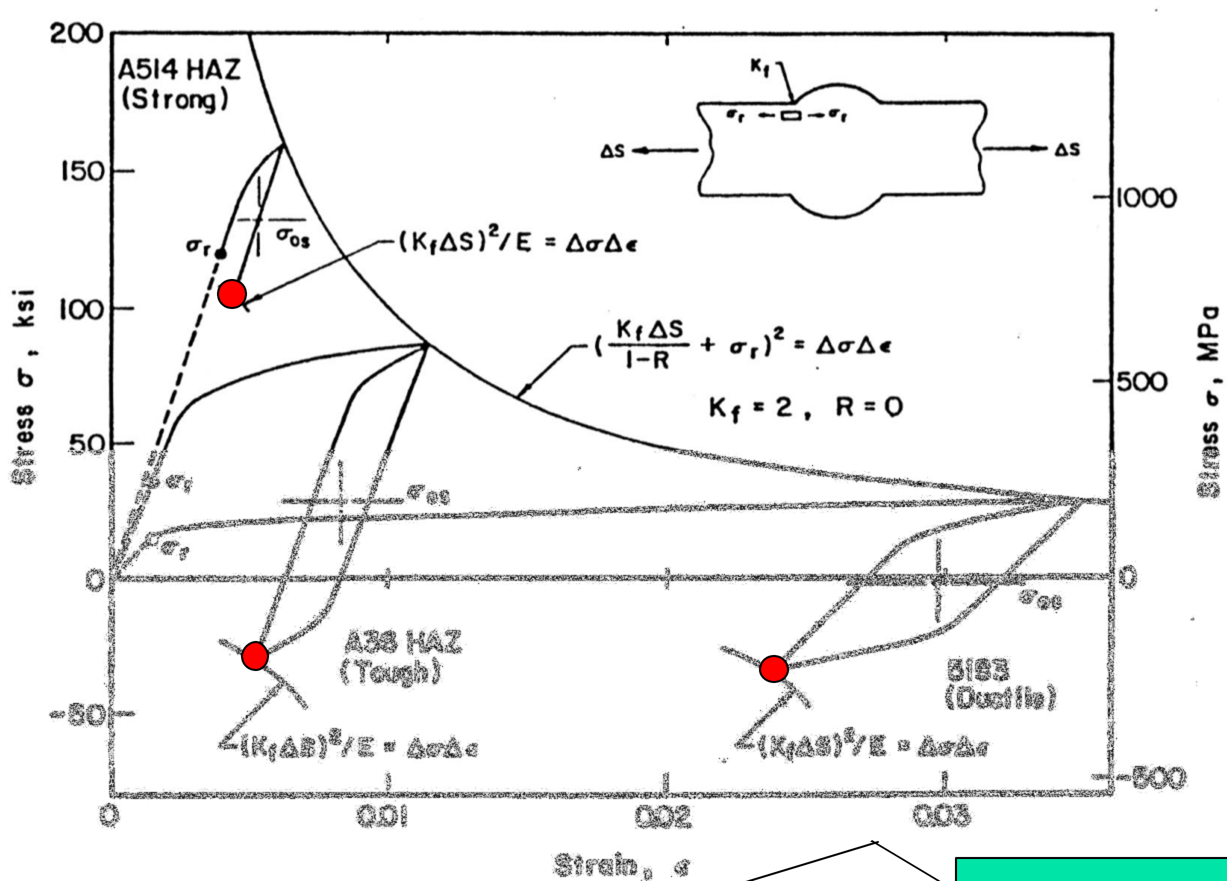




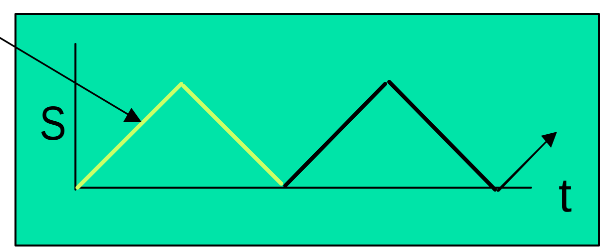
(Can also get stresses along crack path for N_P calculation from this analysis.)

Events during the first load application

- Notch-root residuals after set-up cycle

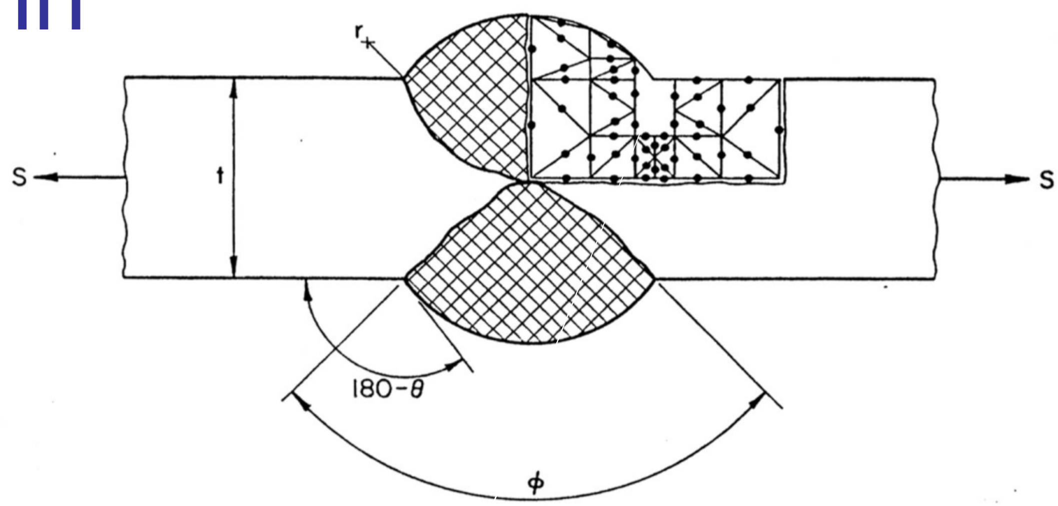


The difference between the monotonic (tensile)and cyclic σ–ε behavior causes the notch root mean stresses to be altered during the first load application!!!!



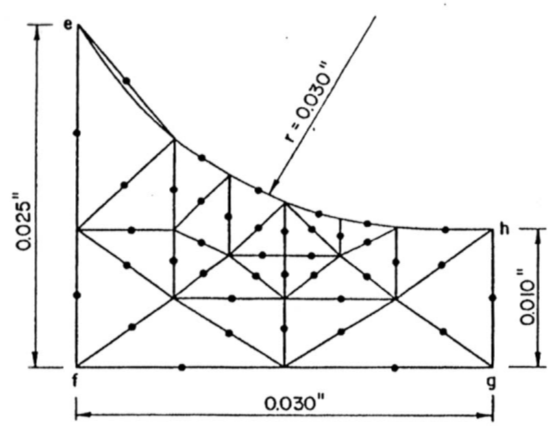
Set-up cycle analysis

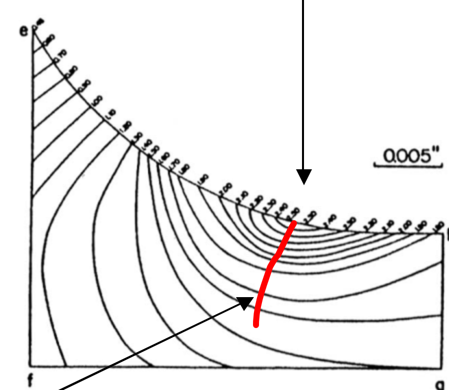
Determining ?K for use in calculating N_P



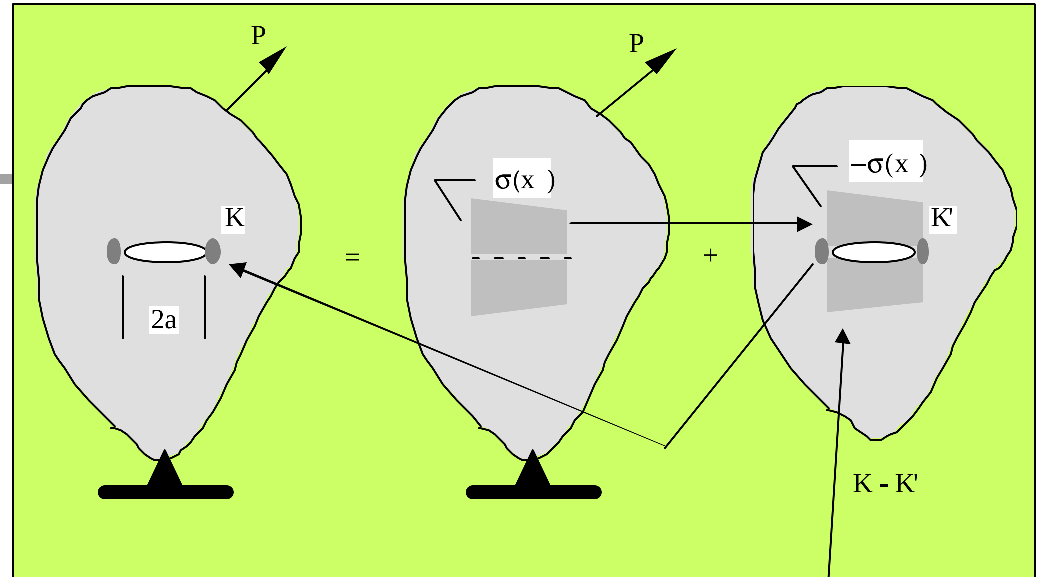
Highest stress region of weld toe is 20° away from the point of tangency

Get stresses along crack path for N_P calculation from this analysis.

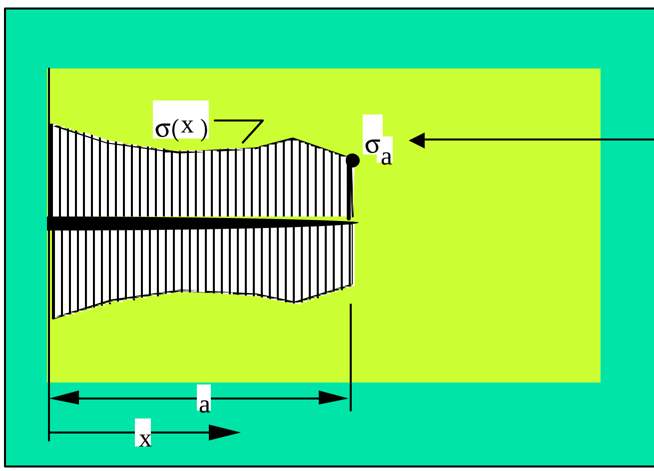




Determining ?K(a) for the calculation of N_P



Weight function approach



$$\Delta K(a) = Y(a)\,\Delta S\,\sqrt{\pi a}$$

$$Y(a) = \frac{1}{S}\left(1.12\,\sigma_a - \int_0^a f\left(\frac{x}{a}\right)\frac{d\sigma}{da}\,dx\right)$$

$$f\left(\frac{x}{a}\right) = 1.12\left(\frac{2}{\pi}\right)\sin^{-1}\left(\frac{x}{a}\right)$$

Estimating N_{P2}

a_i = ????
?K(a) = ?
U(a) = ???

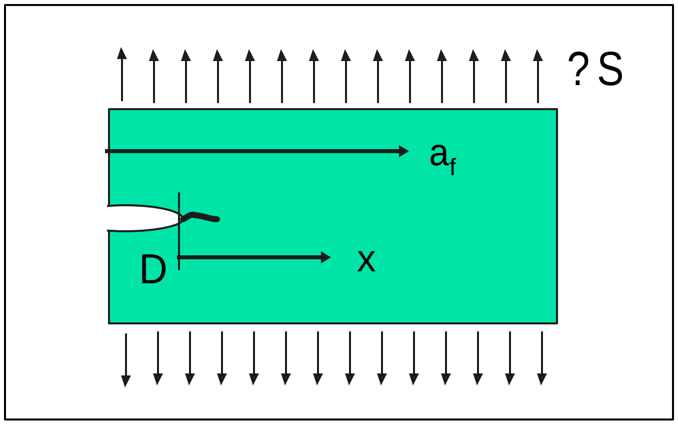
N_{P2} is estimated using crack growth data for long cracks and the Paris Power Law

$$N_{P2} = \int_{a_i}^{a_f} \frac{da}{C\, \Delta K_{eff}^{\,n}}$$

where:

a_i	=	initial crack length,
a_f	=	crack length at failure, and
C, n	=	material constants in the Paris Power Law.

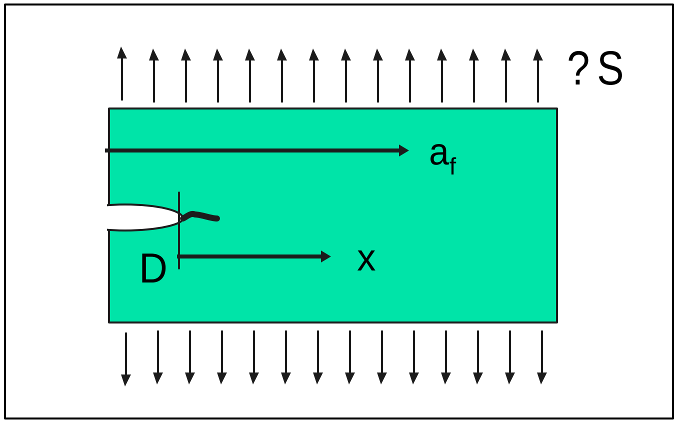
IP Model example: $a_f = ?$



You have noticed a fatigue crack of length (x) propagating from a sharp elliptical notch of depth (D) and notch root radius (r) in a semi-infinite body (component) subjected to a fluctuating remote stress which ranges from 0 to S_{max} = 10 ksi. The current temperature is 0 °F. What will the crack length be at fracture $a_f = (D + x_f)$?

Applied remote stress (S_{max}, ksi):	10
Applied remote stress range (?S, ksi)	10
Fracture toughness @ 68°F (K_{IC}, ksiv in):	70
Fracture toughness @ 0°F (K_{IC}, ksiv in):	45
Geometry correction factor for an edge crack (Y):	1.12
Linear-elastic fracture mechanics (LEFM):	$K_{IC} = YS_f (\pi a_f)^{1/2}$

IP Model example: N_P = ?



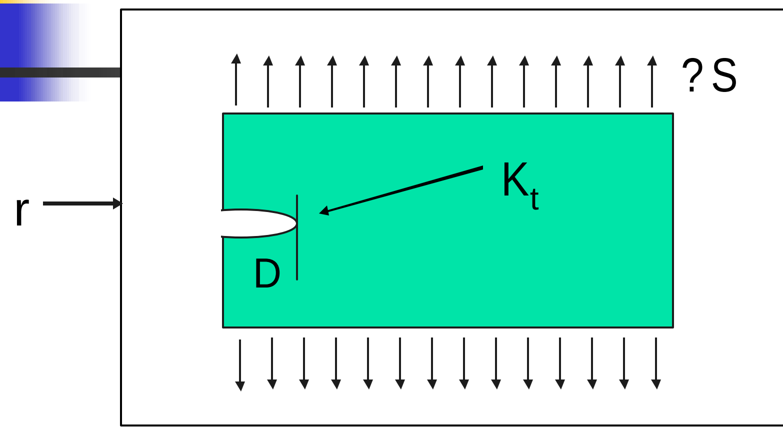
Calculate the number of cycles to propagate the fatigue crack from an initial length (x_i) of 0.01 in to the length at which it fractures (a_f), that is, estimate the fatigue crack propagation life (N_P). Assume for the moment that the notch is really a crack of depth D, i. e.: $a_i = D + x_i$ af = D + x_f.

Applied remote stress (S_{max}, ksi):	10
Applied remote stress range (? S, ksi)	10
Fatigue crack propagation coefficient (C, ksiv in)	1x10-9
Fatigue crack propagation exponent (n)	3
Notch depth (D, in)	0.1
Geometry correction factor for an edge crack (Y):	1.12

Fatigue crack propagation life:

$$N_P = \frac{1}{C\,(1-m/2)\,(Y\Delta S\sqrt{\pi})^m}\left(a_f^{\,1-\frac{m}{2}} - a_o^{\,1-\frac{m}{2}}\right)$$

IP Model example: N_I = ?



The fatigue crack initiation life (N_I) of the notched component can be calculated considering the elliptical notch to have a fatigue notch factor (K_f) which can be estimated using Peterson's equation which estimates size effect of the notch in fatigue from the elastic stress concentration factor (K_t).

$$N_I = \frac{1}{2}\left(\frac{\sigma_f^{'} - \sigma_m}{K_f \Delta S/2}\right)^{-1/b}$$

Notch depth (D, in.):	0.1
Notch root radius (r, in.):	0.01
Elastic stress concentration factor of an ellipse (K_t):	
Fatigue notch factor (K_f) - Peterson's Equation:	
Peterson's constant for this material (a, in.):	0.01
Applied remote stress range (? S, ksi):	10
Applied mean stress (Sm, ksi):	5
Notch root mean stress (σ_m, ksi):	S_m K_f
Fatigue strength coefficient (σ'_f, ksi):	110
Fatigue strength exponent (b):	-0.1

$$K_t = 1 + 2\sqrt{\frac{D}{r}}$$

$$K_f = 1 + \frac{K_t - 1}{1 + \frac{a}{r}}$$

IP Model example: N_T = ?

a_f (in.) = 5.14

K_t = 7.32

K_f = 4.16

N_I (cycles) = 1,051,000 62%

N_P (cycles) = 650,000 38%

$N_T = N_I + N_P$ (cycles) = 1,701,000 100%

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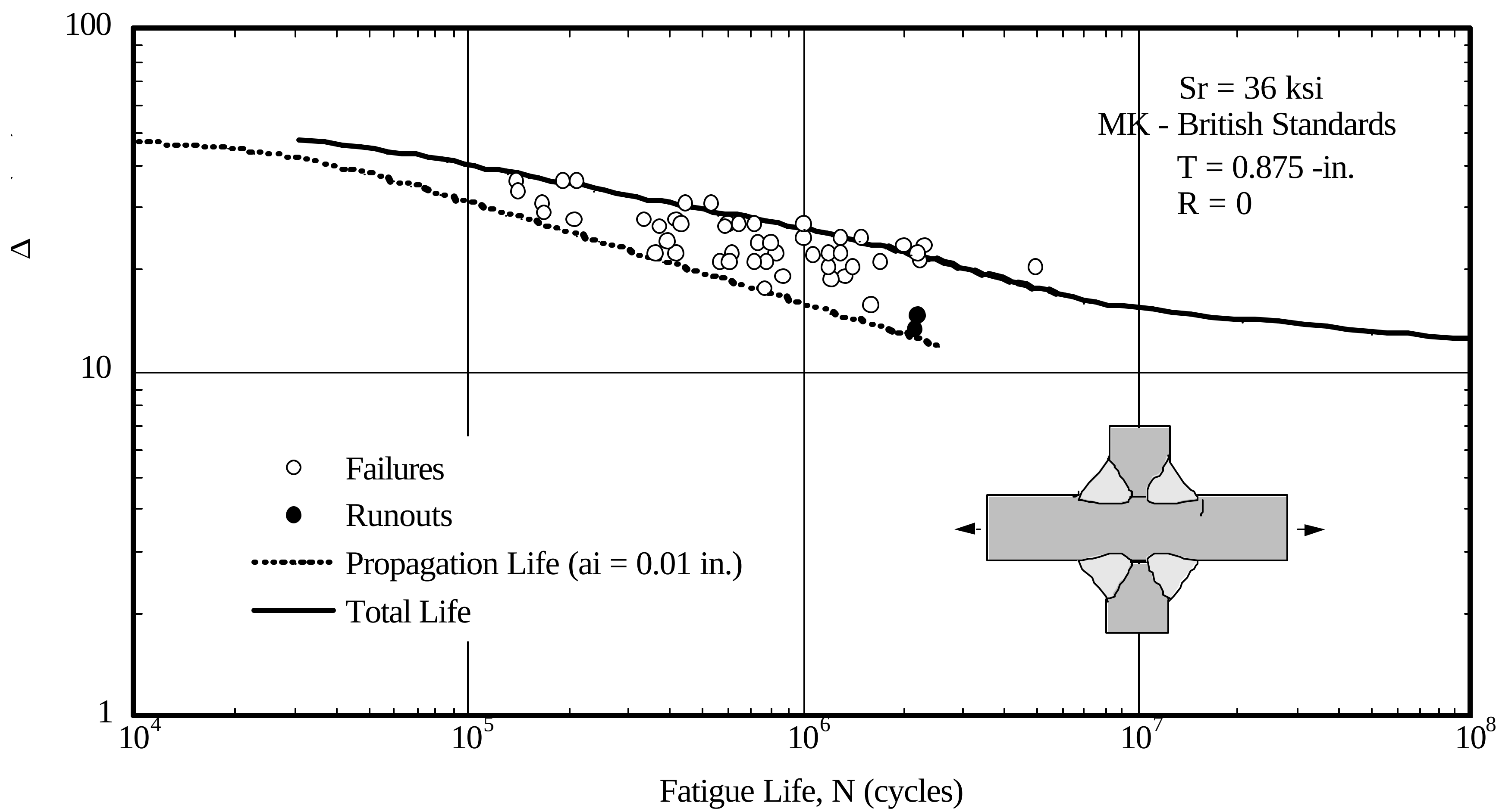
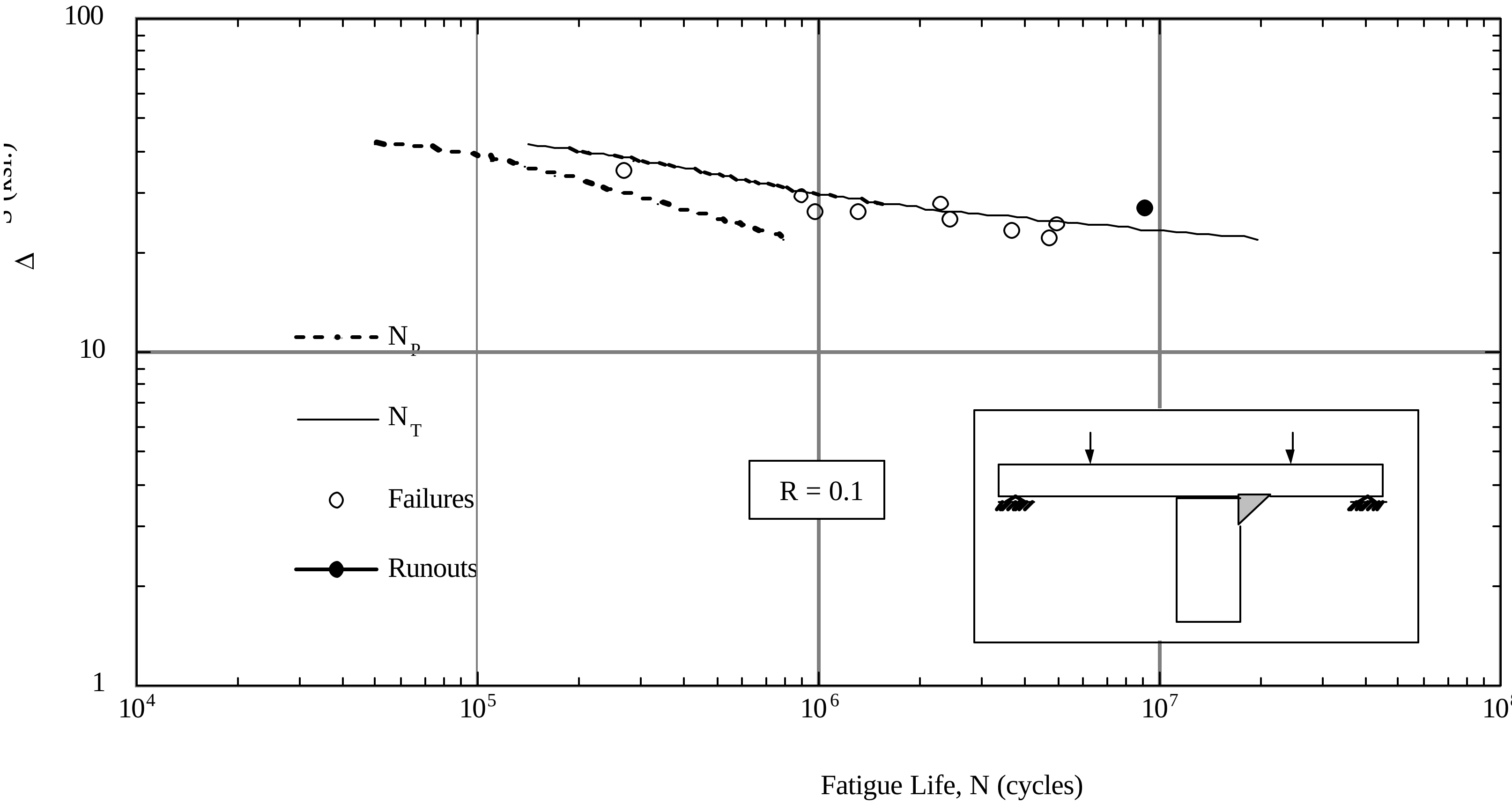
IP model results for a cruciform joint

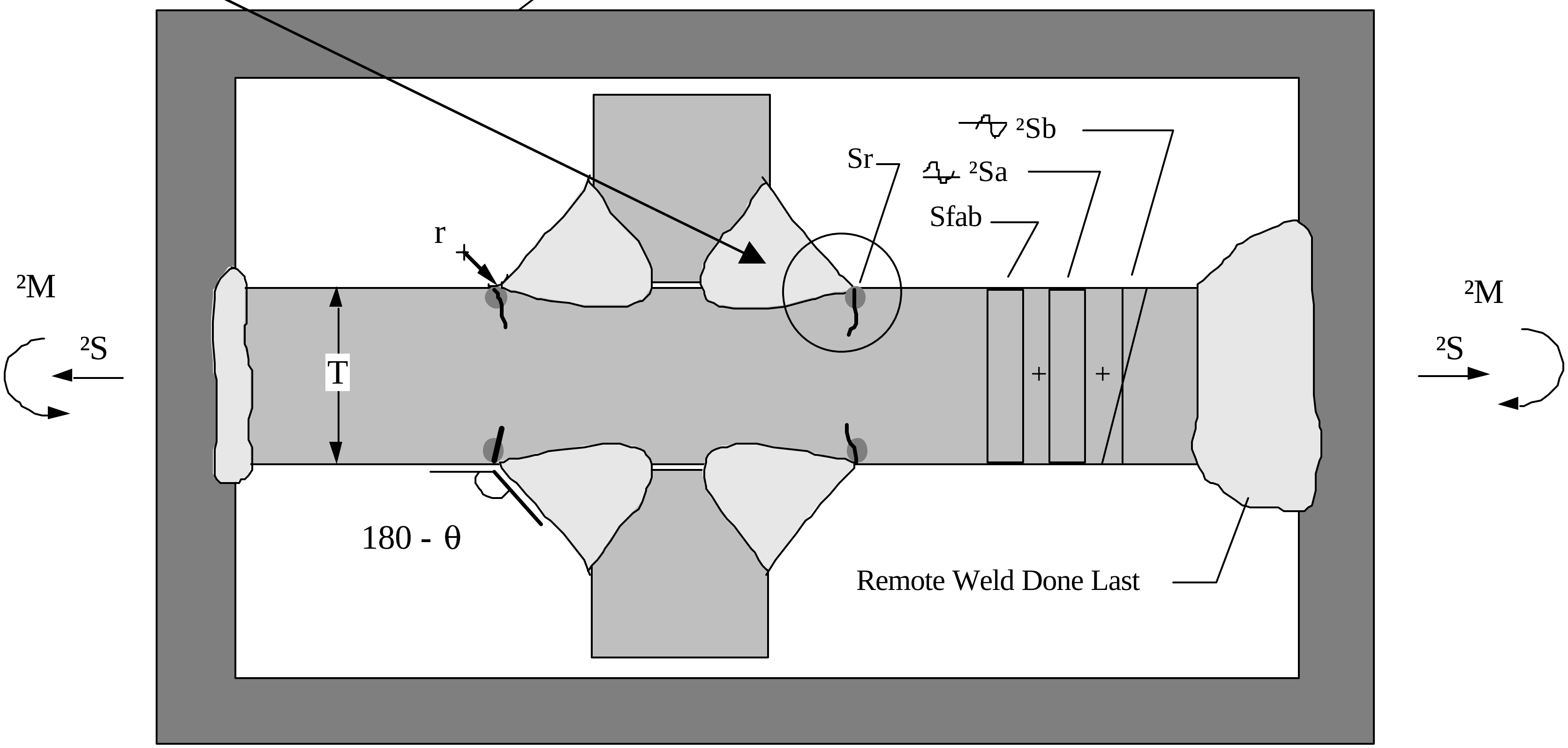


IP Model predictions and experimental results



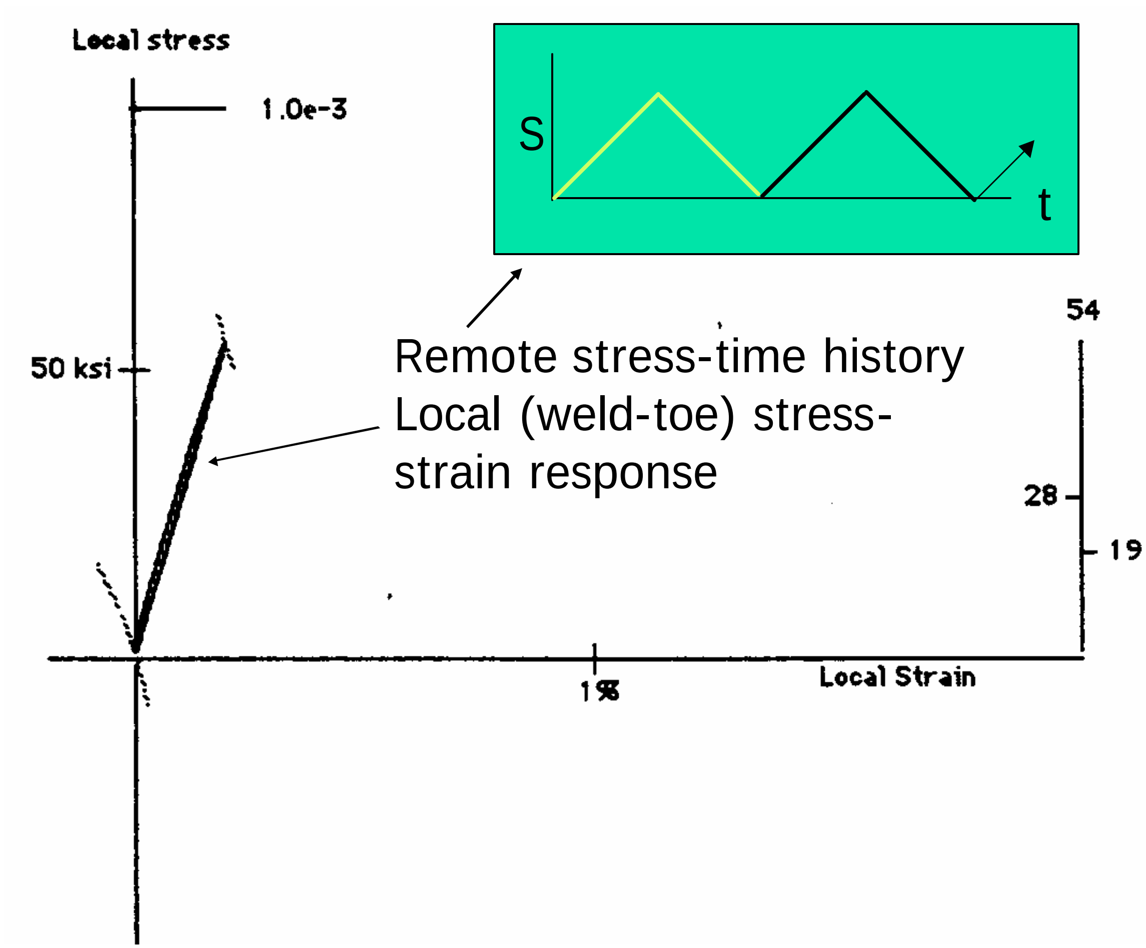
IP model predictions for a cruciform weldment

IP model predicts notch-root (local) stresses and strains



Mean stresses considered to be composed of applied mean (R ratio), fabrication residual stresses (S_{fab})and welding residual stresses (Sr).

Residual stress effects - 1/2-in



Mild steel Cruciform
?S = 25 ksi
Axial R = 0
Flank angle = 40°

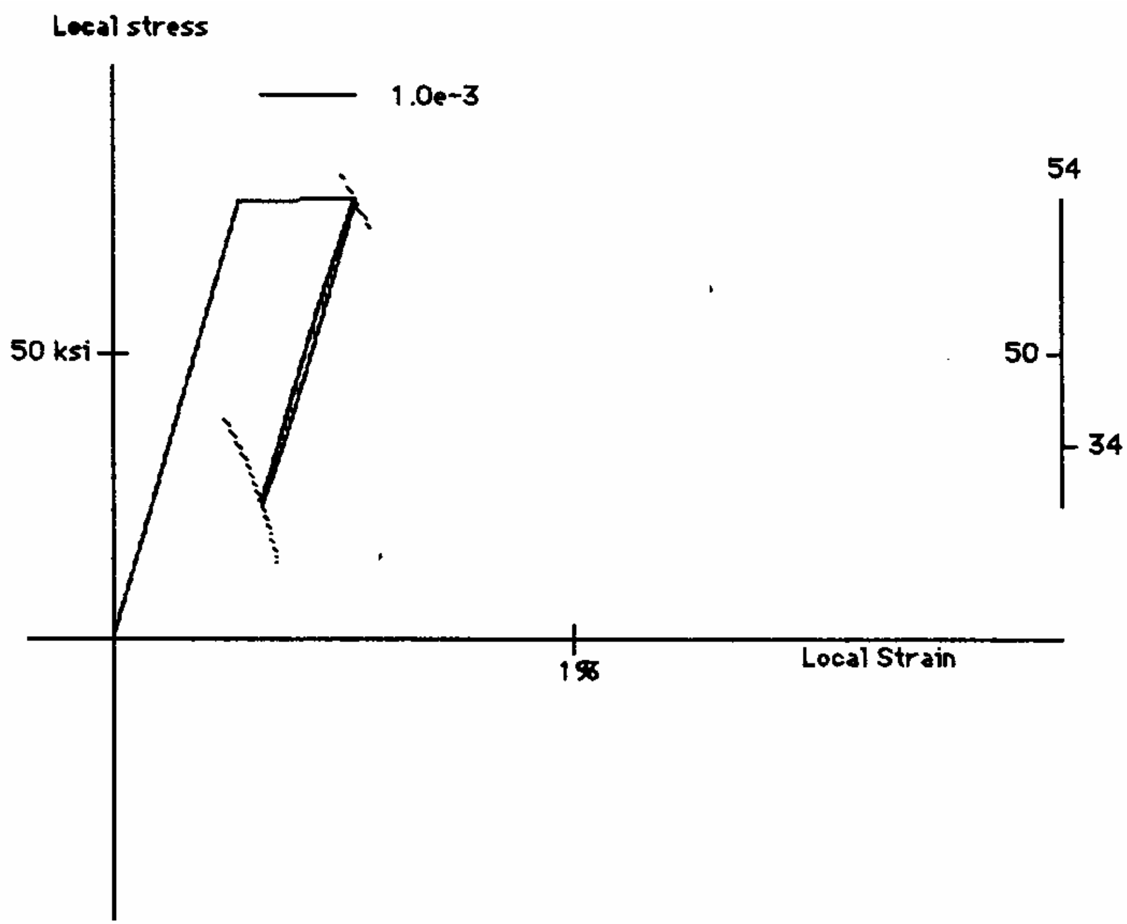
Thickness = 0.5-in.
K_{feff} = 2.2

RS.Weld = 0 ksi
RS.Fabric = 0 ksi

N_t = 17,170,000

N_i = 17,000,000
N_p = 170,000

Residual stress effects - 1/2-in



Mild steel Cruciform
? S = 25 ksi
Axial R = 0
Flank angle = 40°

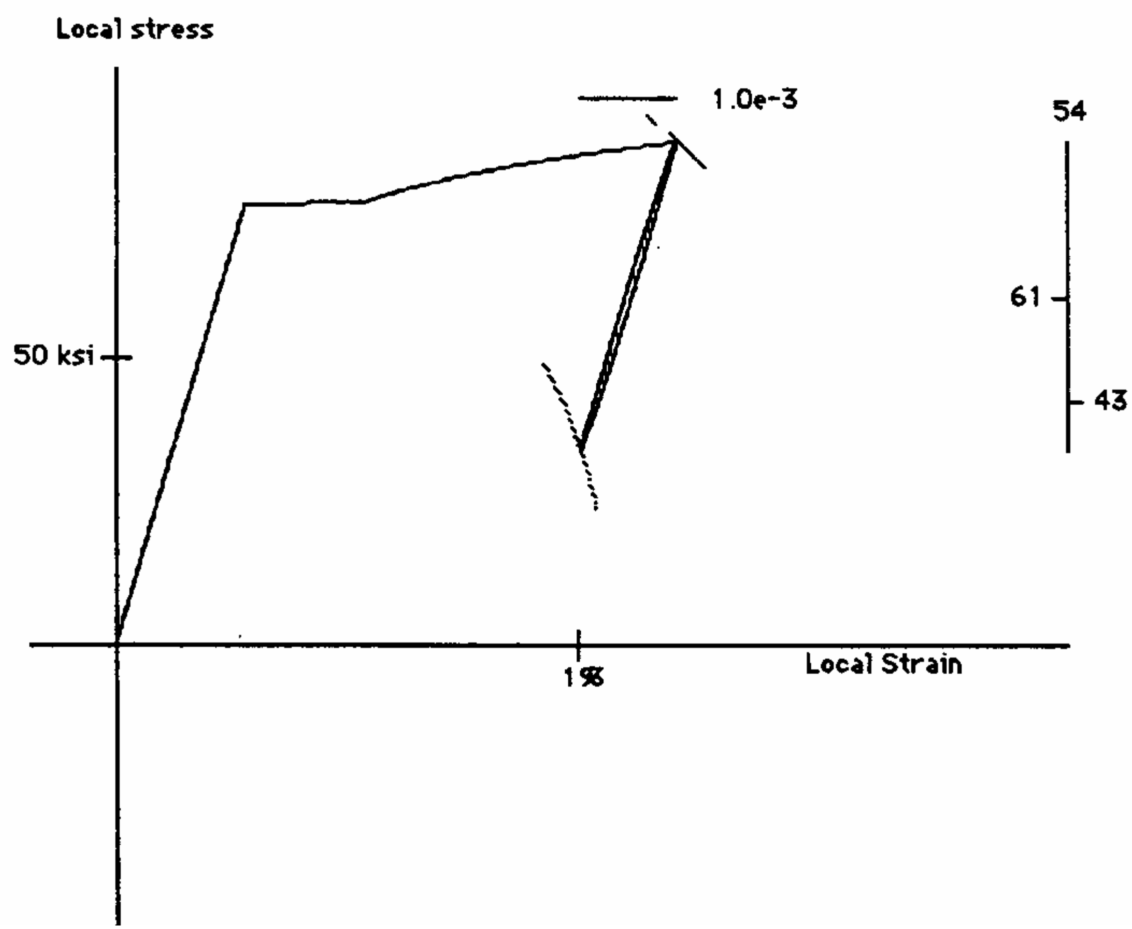
Thickness = 0.5-in.
K_{feff} = 2.2

RS.Weld = 36 ksi
RS.Fabric = 0 ksi

N_t = 2,400,000

N_i = 2,200,000
N_p = 170,000

Residual stress effects - 1/2-in



Mild steel Cruciform
? S = 25 ksi
Axial R = 0
Flank angle = 40°

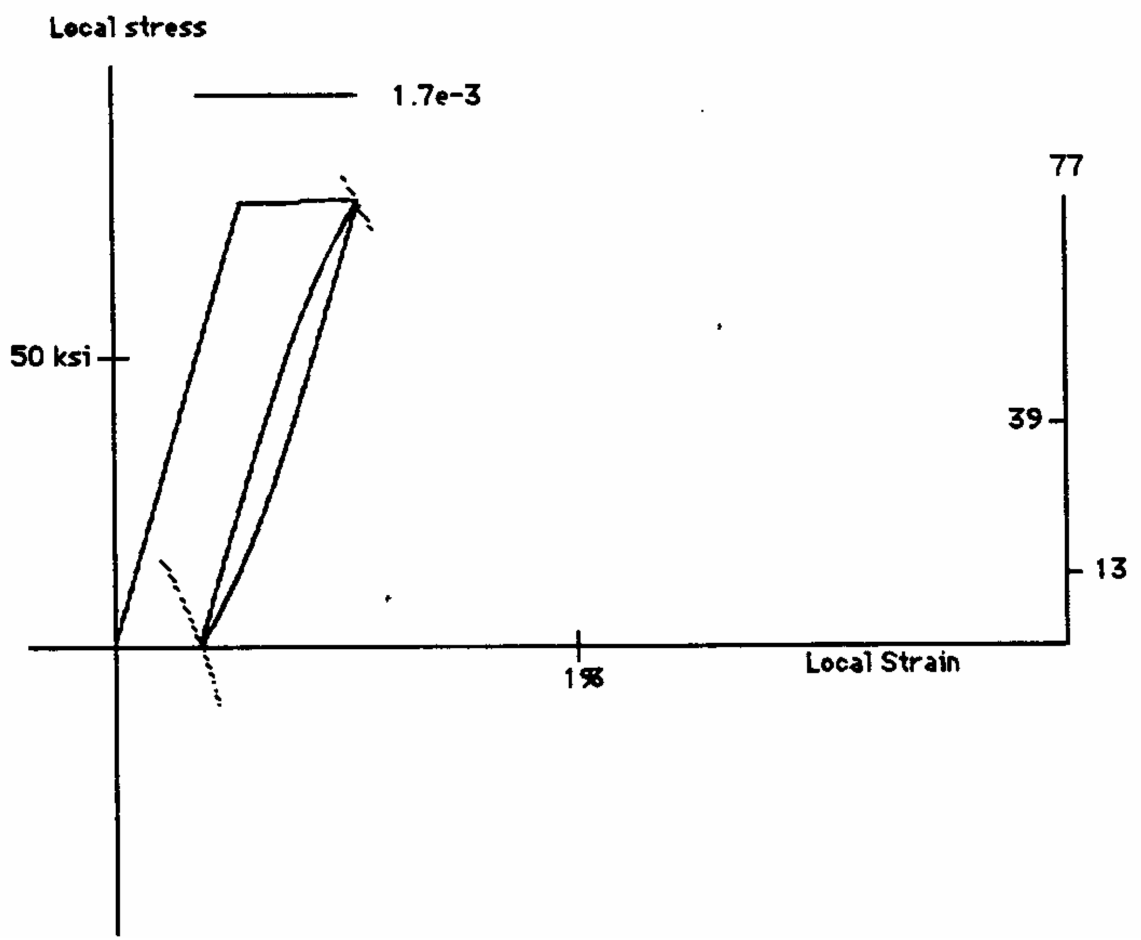
Thickness = 0.5-in.
K_{feff} = 2.2

RS.Weld = 36 ksi
RS.Fabric = 36 ksi

N_t = 980,000

N_i = 930,000
N_p = 500,000

Residual stress effects - 2-in



Mild steel Cruciform
2?S = 25 ksi
Axial R = 0
Flank angle = 40°

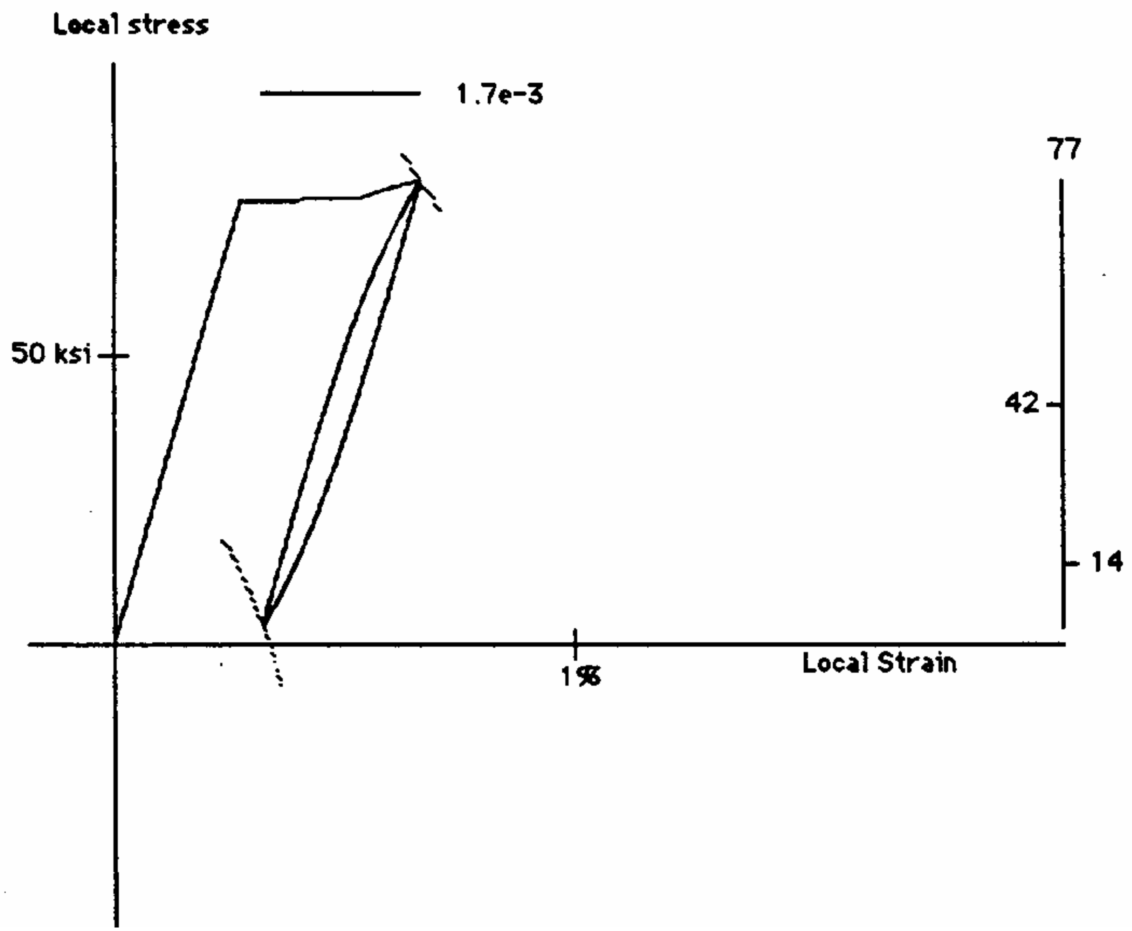
Thickness = 2.0-in.
K_{feff} = 3.42

RS.Weld = 0 ksi
RS.Fabric = 0 ksi

N_t = 360,000

N_i = 260,000
N_p = 100,000

Residual stress effects - 2-in



Mild steel Cruciform
?S = 25 ksi
Axial R = 0
Flank angle = 40°

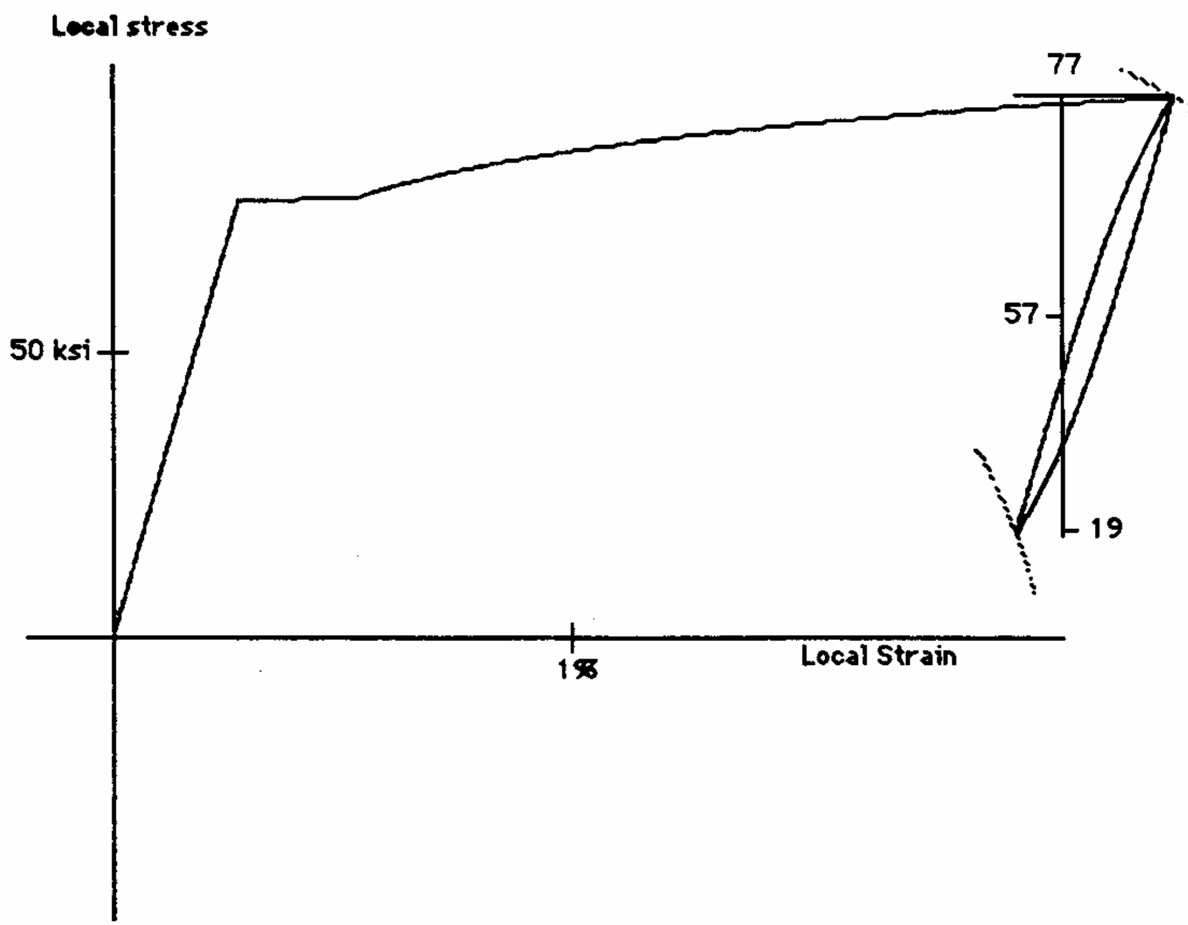
Thickness = 2.0-in.
K_{feff} = 3.4

RS.Weld = 36 ksi
RS.Fabric = 0 ksi

N_t = 340,000

N_i = 240,000
N_p = 100,000

Residual stress effects - 2-in



Mild steel Cruciform
?S = 25 ksi
Axial R = 0
Flank angle = 40°

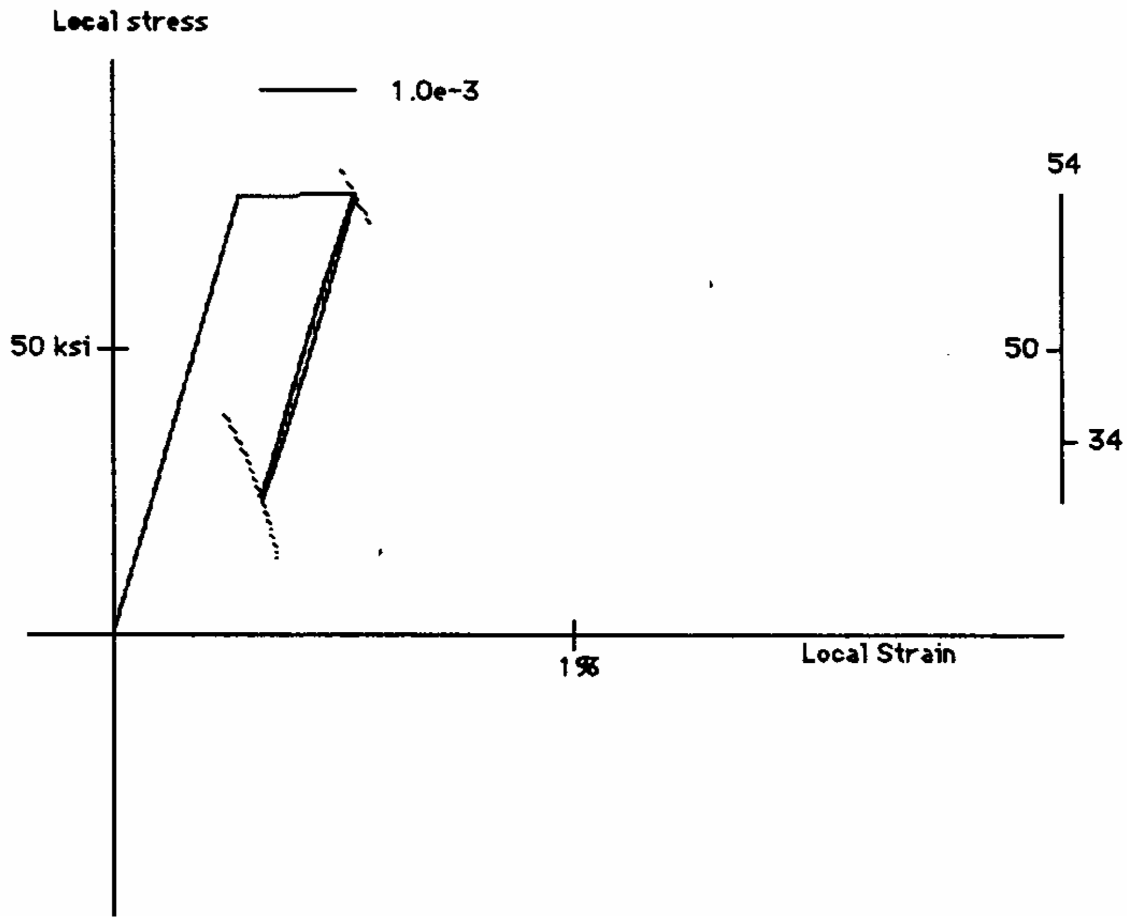
Thickness = 2.0-in.
K_{feff} = 3.4

RS.Weld = 36 ksi
RS.Fabric = 36 ksi

N_t = 200,000

N_i = 170,000
N_p = 30,000

Mean stress - 1/2-in



Mild steel Cruciform
?S = 25 ksi
Axial R = 0
Flank angle = 40°

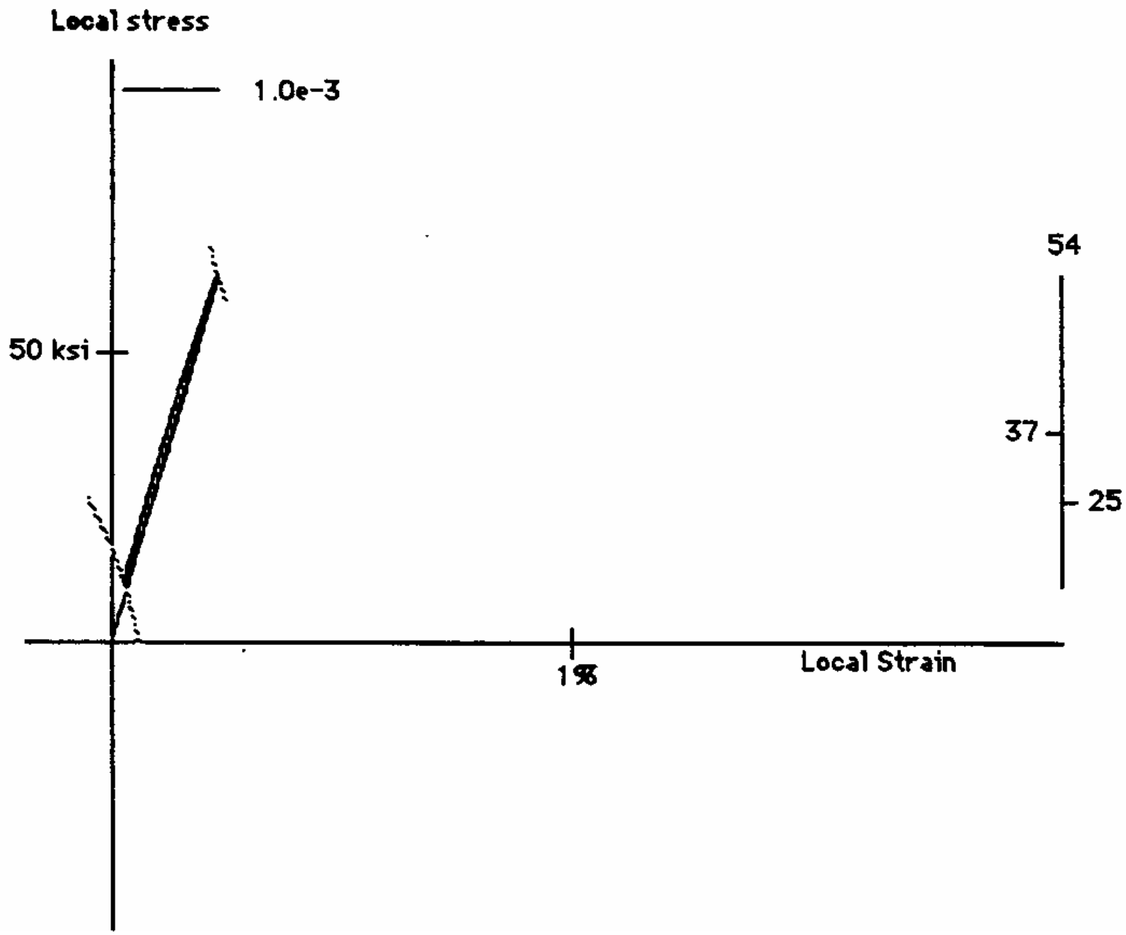
Thickness = 0.5-in.
K_{feff} = 2.2

RS.Weld = 36 ksi
RS.Fabric = 0 ksi

N_t = 2,400,000

N_i = 2,200,000
N_p = 170,000

Mean stress - 1/2-in



Mild steel Cruciform
?S = 25 ksi
Axial R = -1
Flank angle = 40°

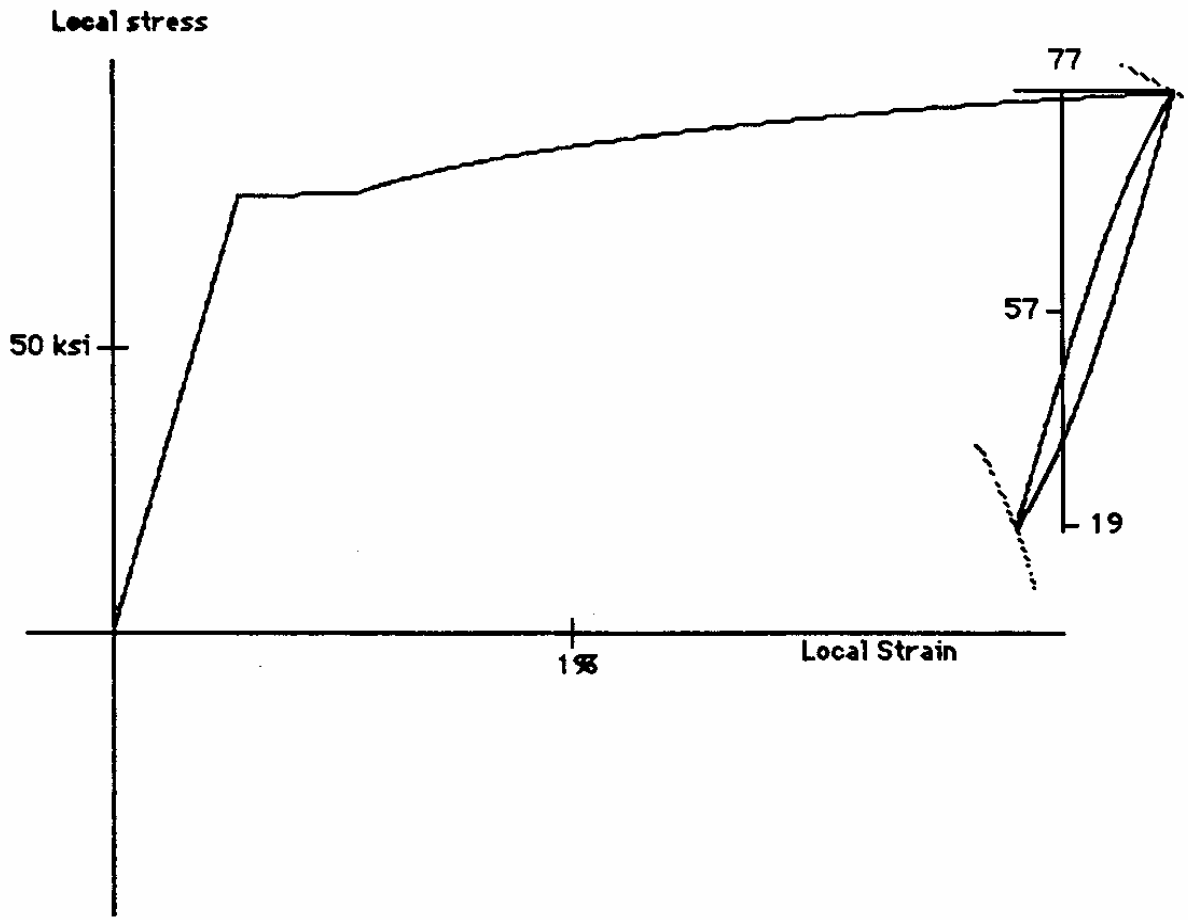
Thickness = 0.5-in.
K_{feff} = 2.2

RS.Weld = 36 ksi
RS.Fabric = 0 ksi

N_t = 7,800,000

N_i = 7,700,000
N_p = 170,000

Mean stress - 2-in



Mild steel Cruciform
?S = 25 ksi
Axial R = 0
Flank angle = 40°

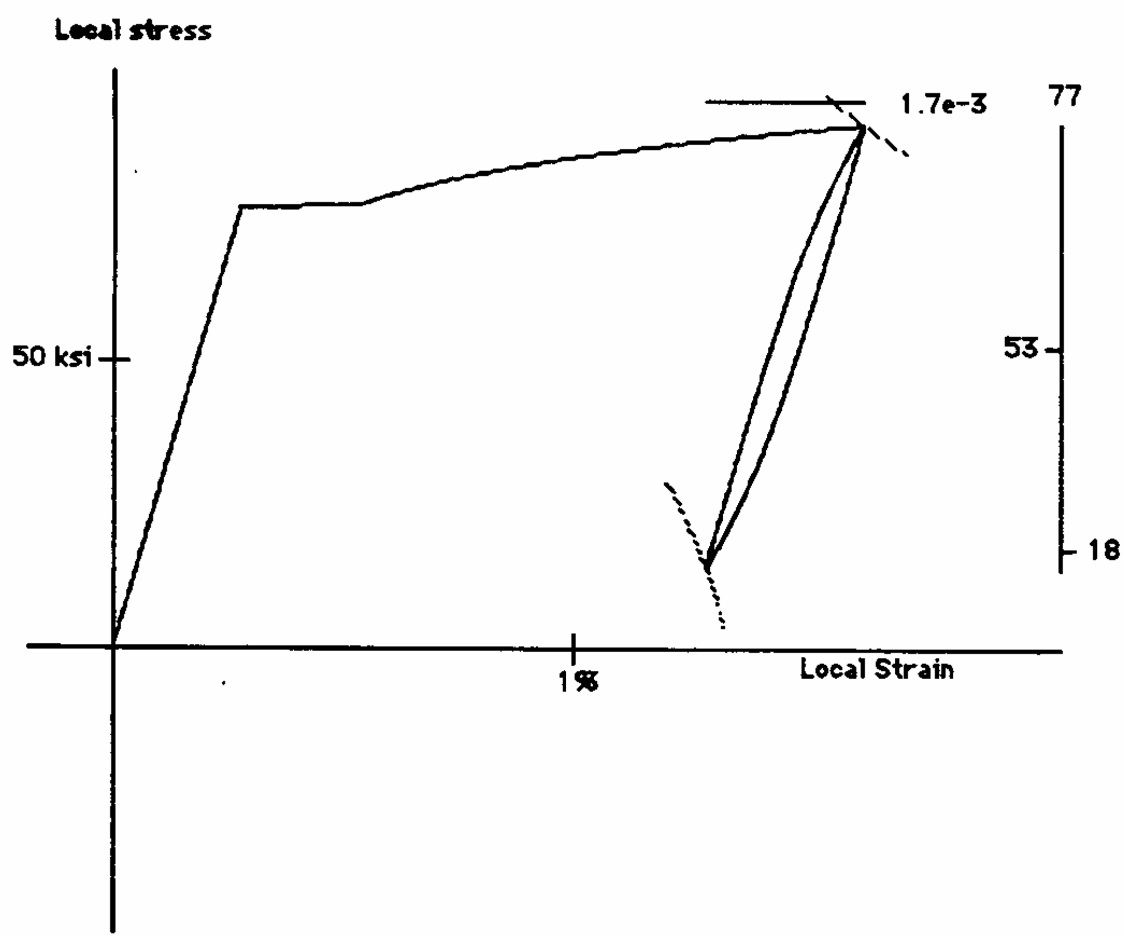
Thickness = 2.0-in.
K_{feff} = 3.4

RS.Weld = 36 ksi
RS.Fabric = 36 ksi

N_t = 200,000

N_i = 170,000
N_p = 30,000

Mean stress - 2-in



Mild steel Cruciform
?S = 25 ksi
Axial R = -1
Flank angle = 40°

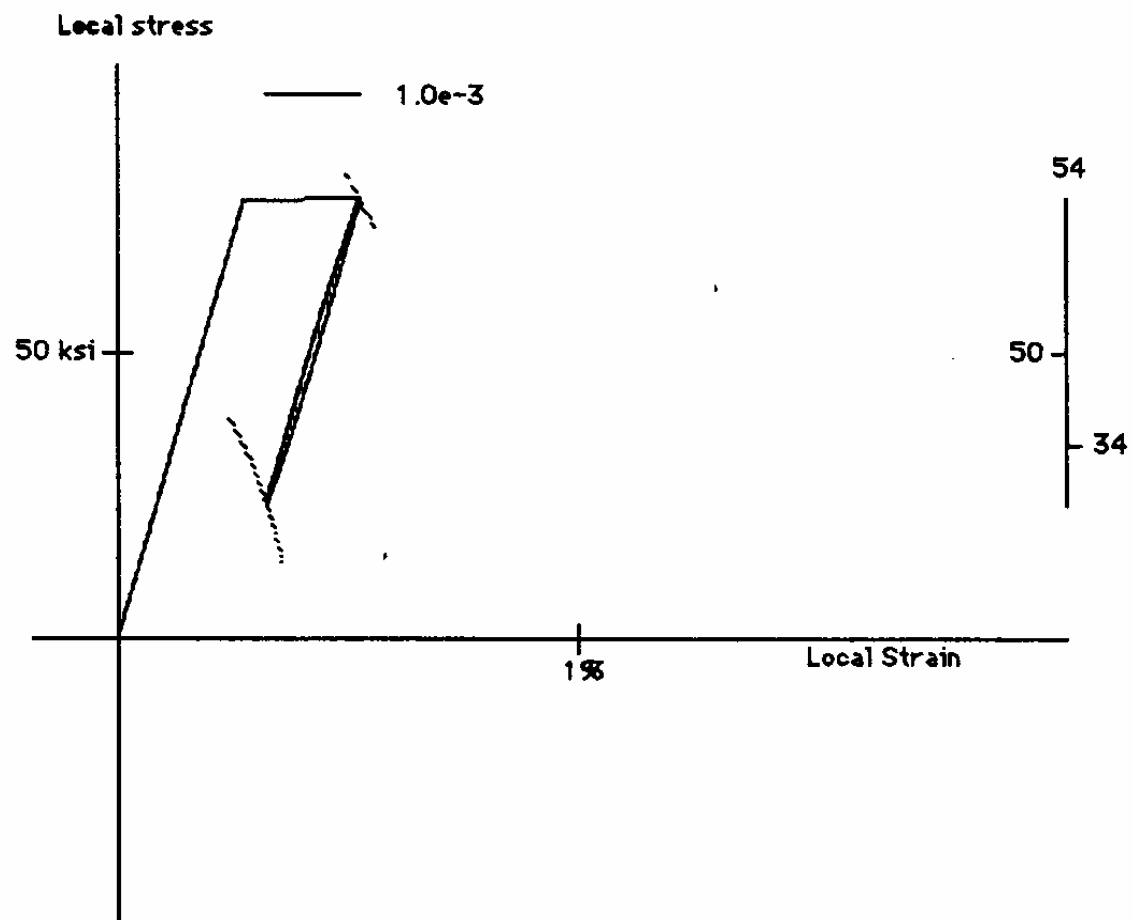
Thickness = 2.0-in.
K_{feff} = 3.4

RS.Weld = 36 ksi
RS.Fabric = 36 ksi

N_t = 210,000

N_i = 180,000
N_p = 32,000

Size effects - 1/2-in



Mild steel Cruciform
? S = 25 ksi
Axial R = 0
Flank angle = 40°

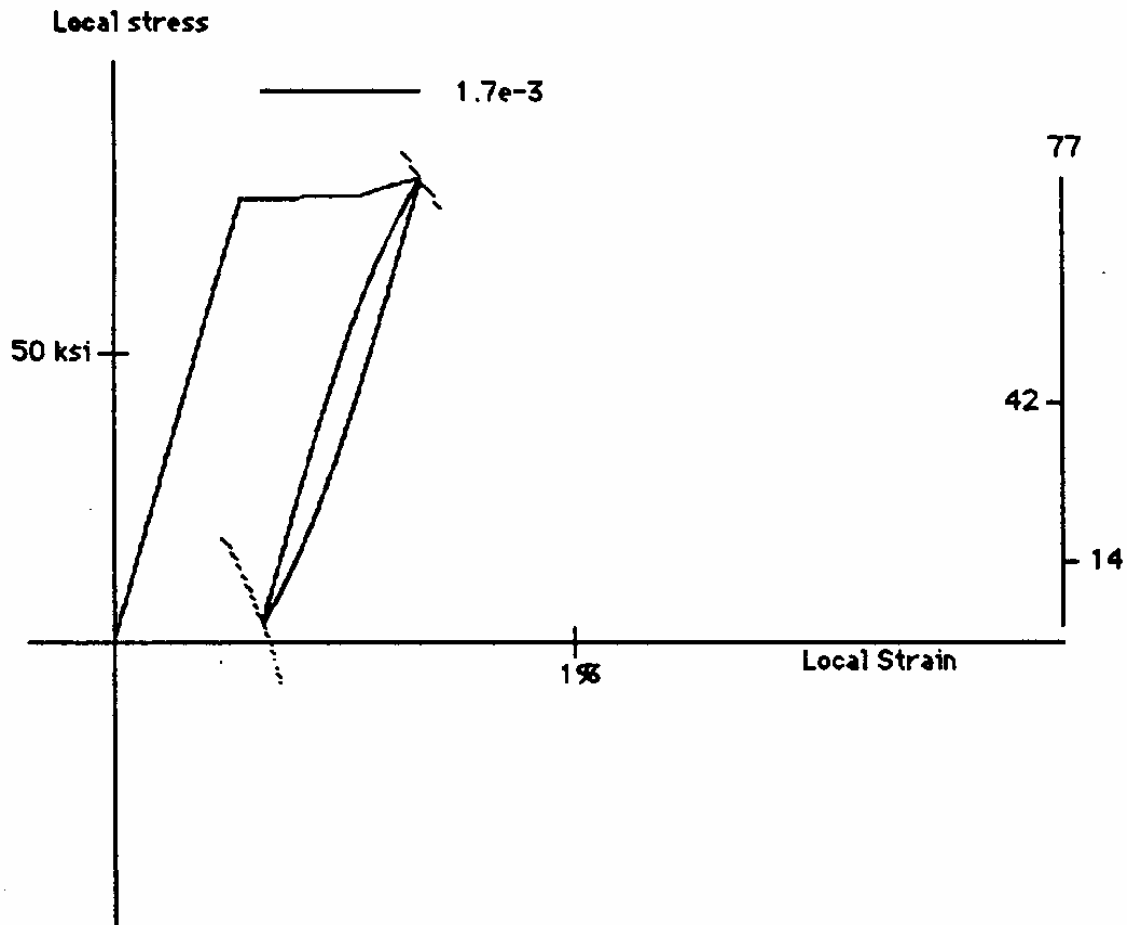
Thickness = 0.5-in.
K_{feff} = 2.2

RS.Weld = 36 ksi
RS.Fabric = 0 ksi

N_t = 2,400,000

N_i = 2,200,000
N_p = 170,000

Size effects - 2-in



Mild steel Cruciform
? S = 25 ksi
Axial R = 0
Flank angle = 40°

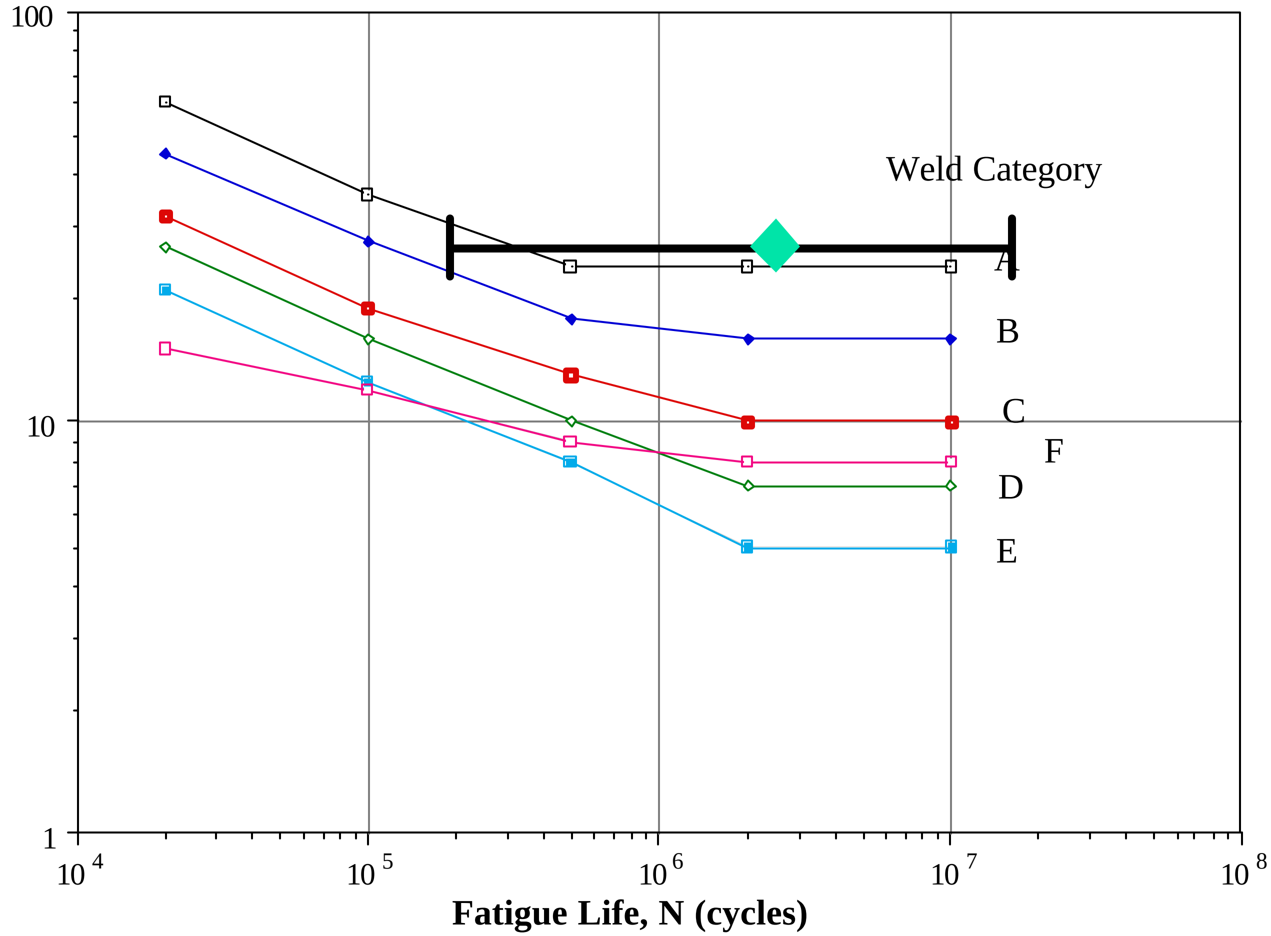
Thickness = 2.0-in.
K_{feff} = 3.4

RS.Weld = 36 ksi
RS.Fabric = 0 ksi

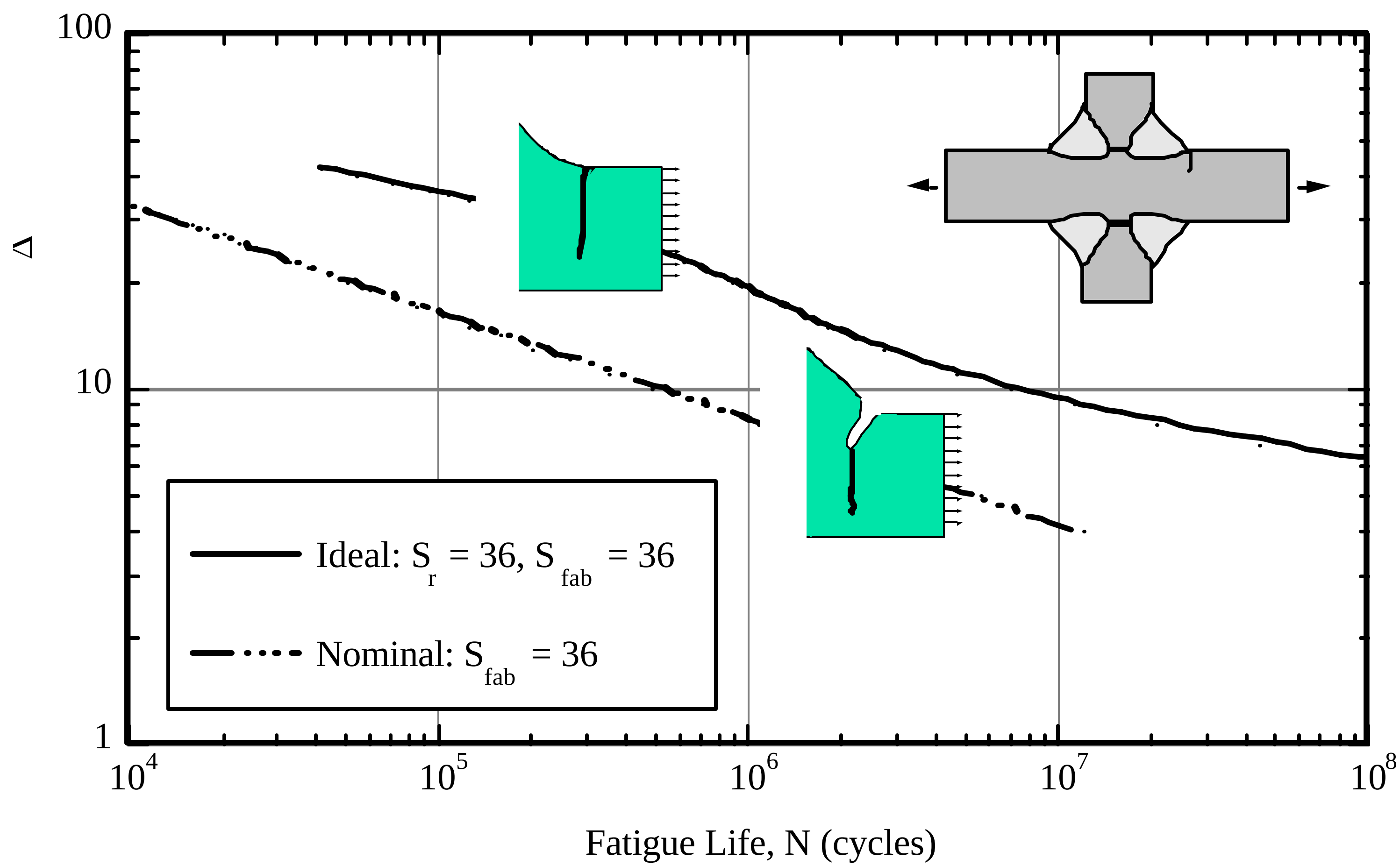
N_t = 340,000

N_i = 240,000
N_p = 100,000

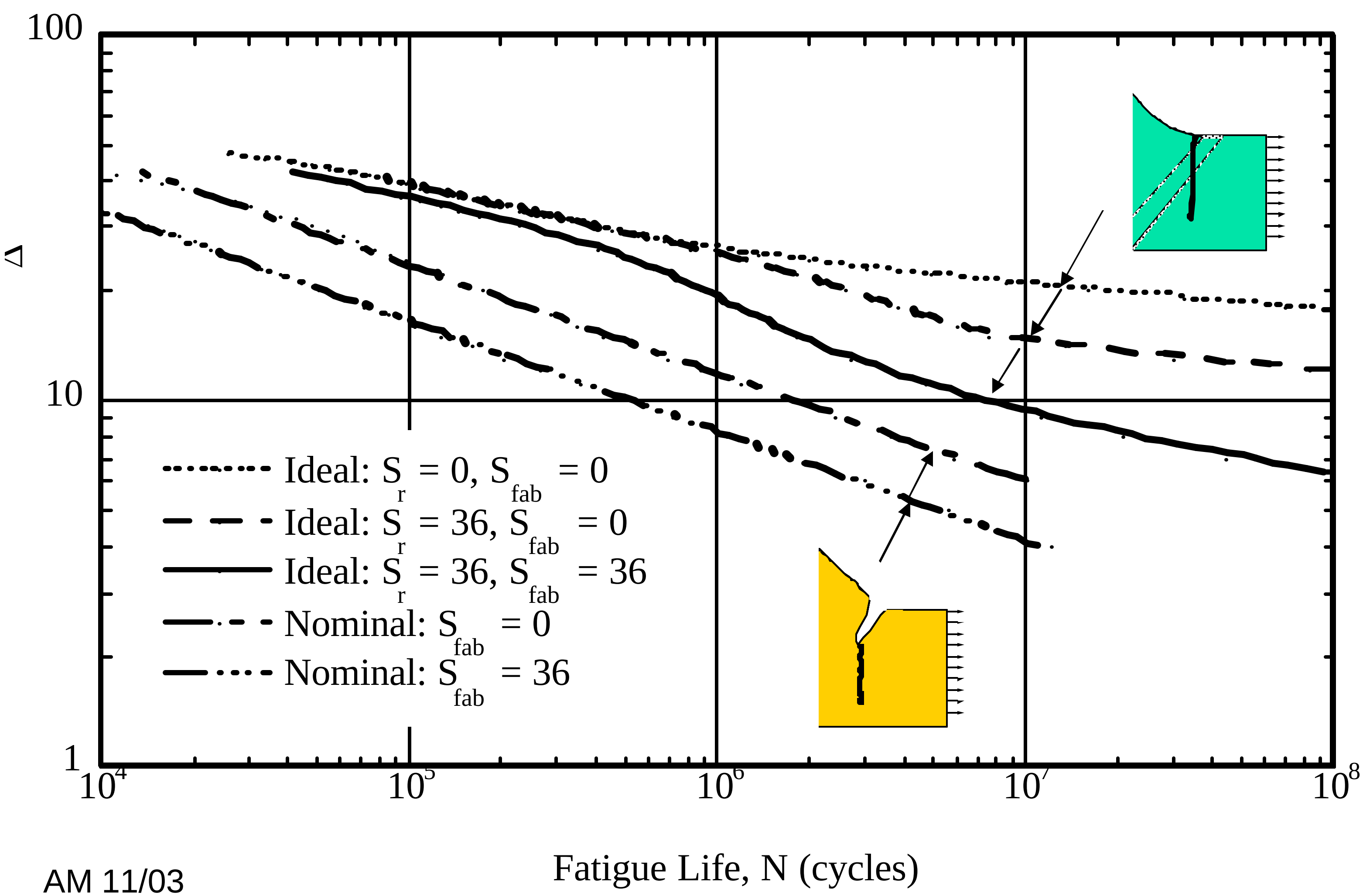
Range of predicted behavior at 25 ksi.



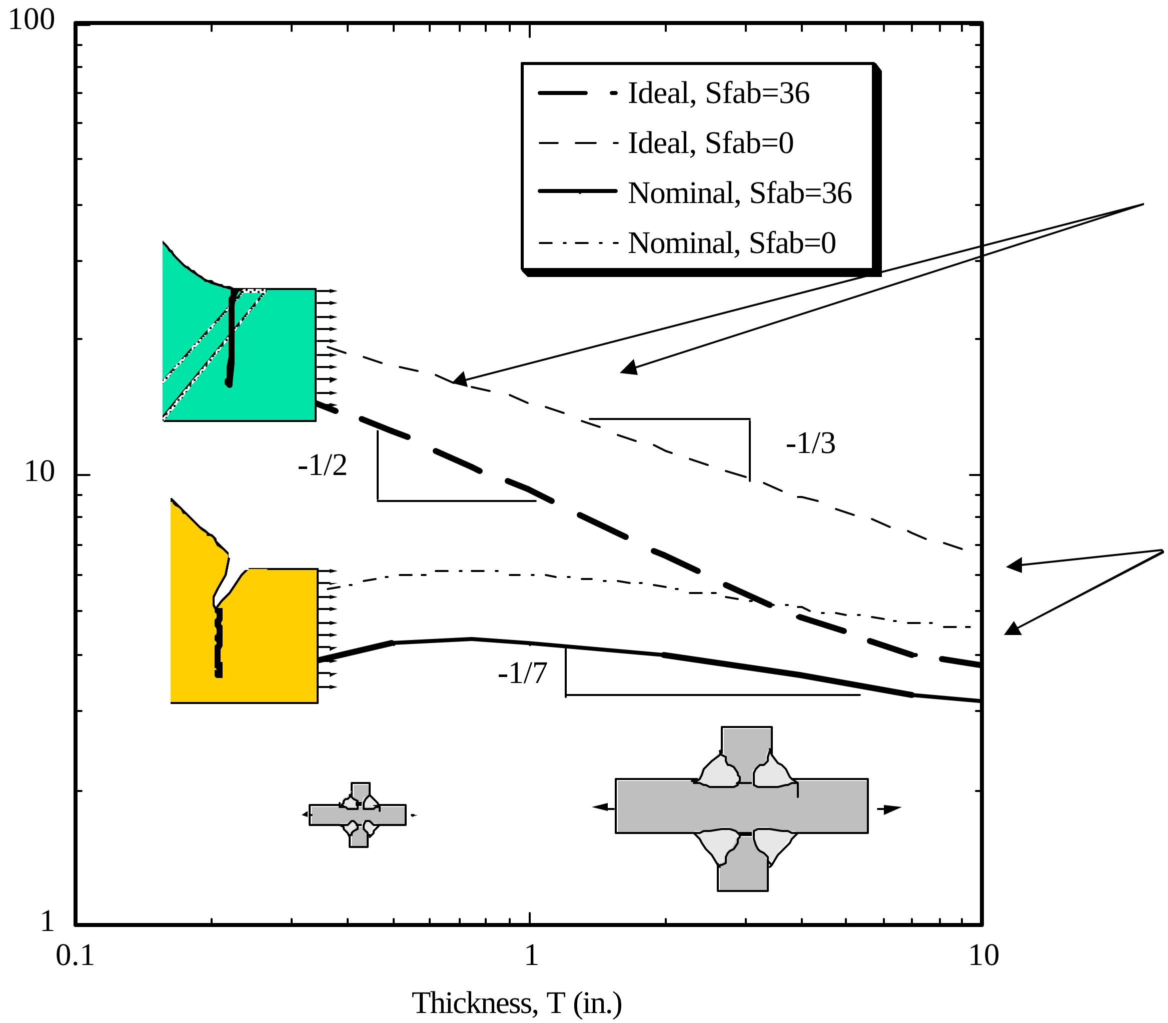
Predicted effect of weld quality



Predicted effect of mean, fabrication, and residual stresses.

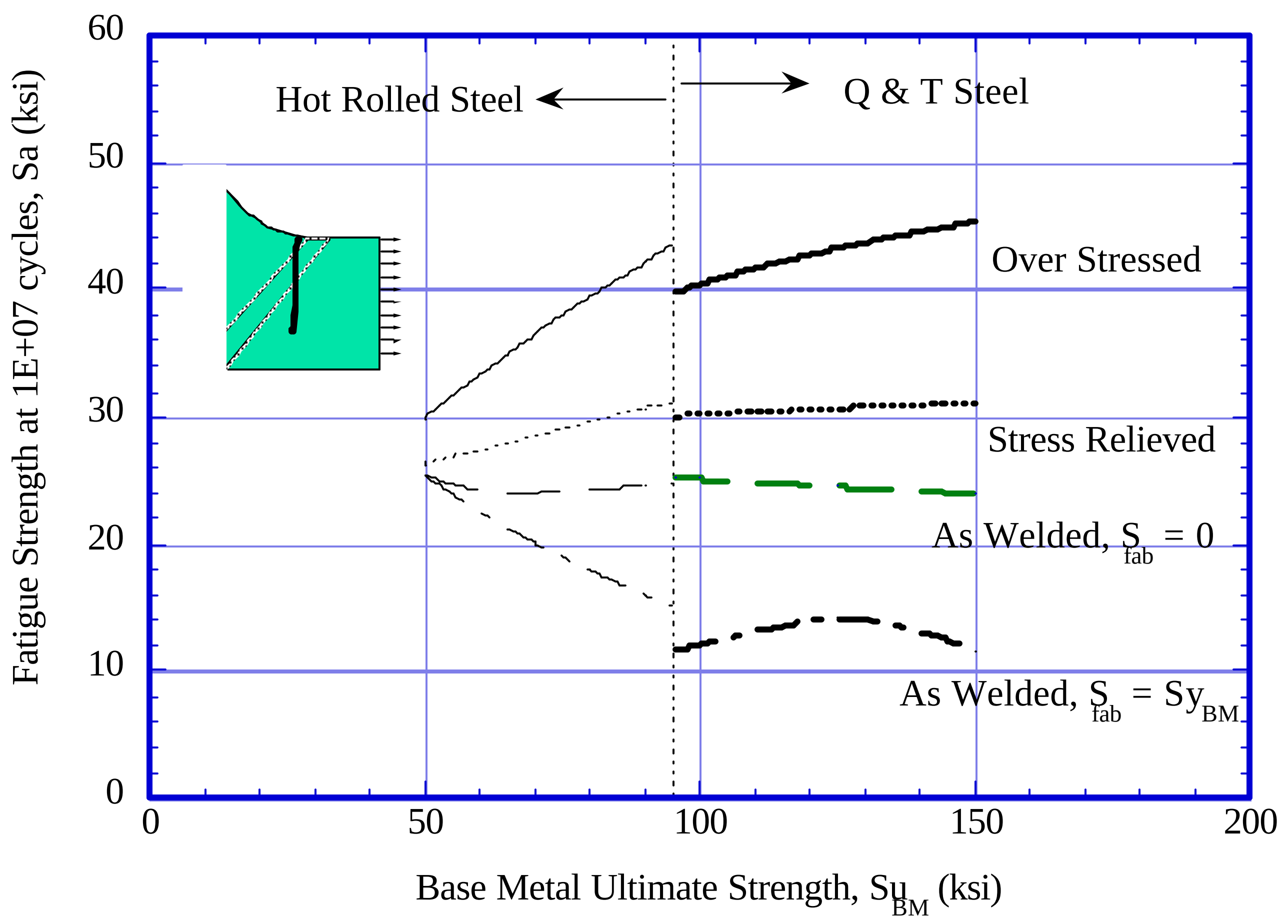


Predicted size effect



Ideal weldments are predicted to be more affected by the size effect than Nominal weldments.

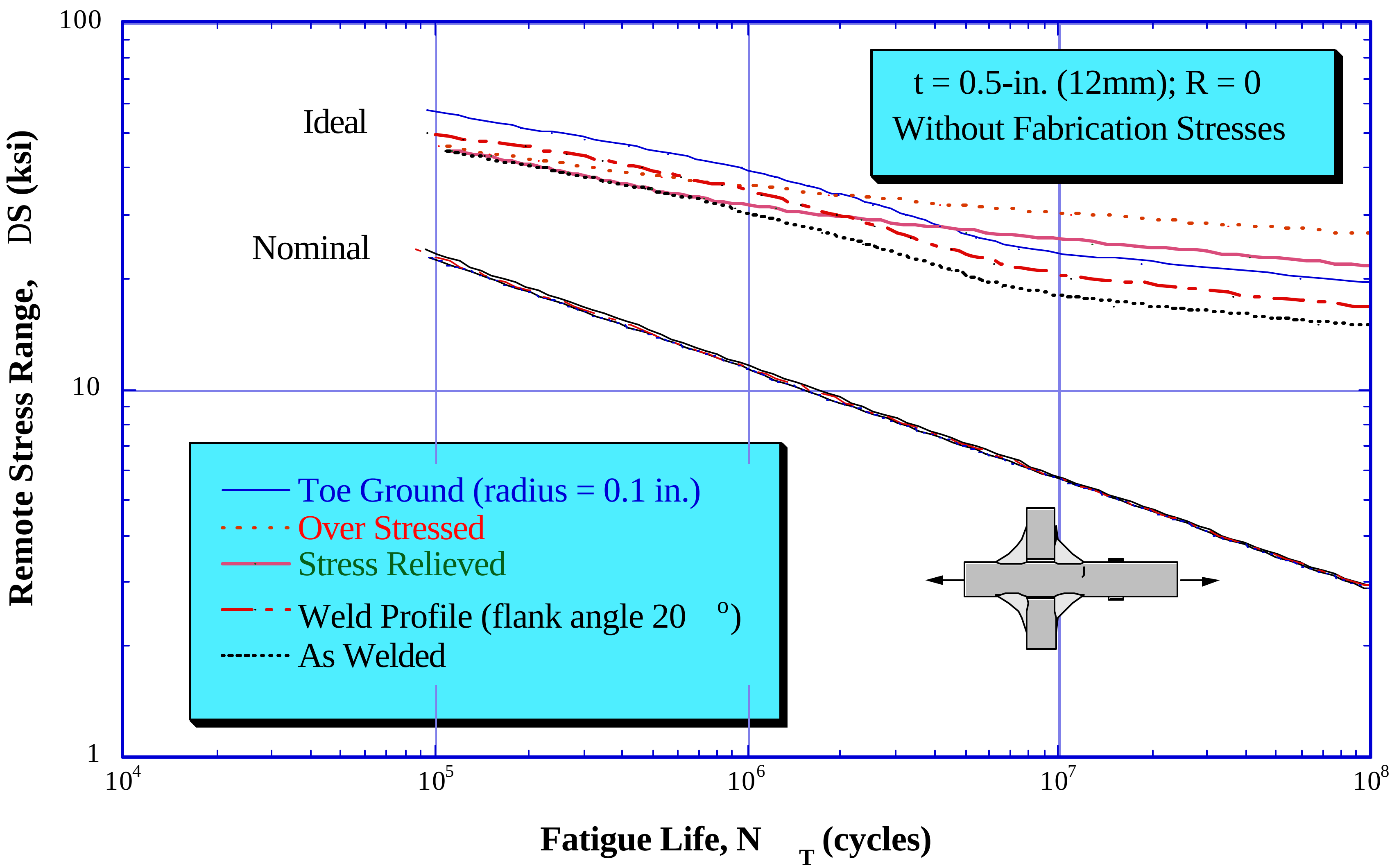
Predicted effect of S_{uBM}



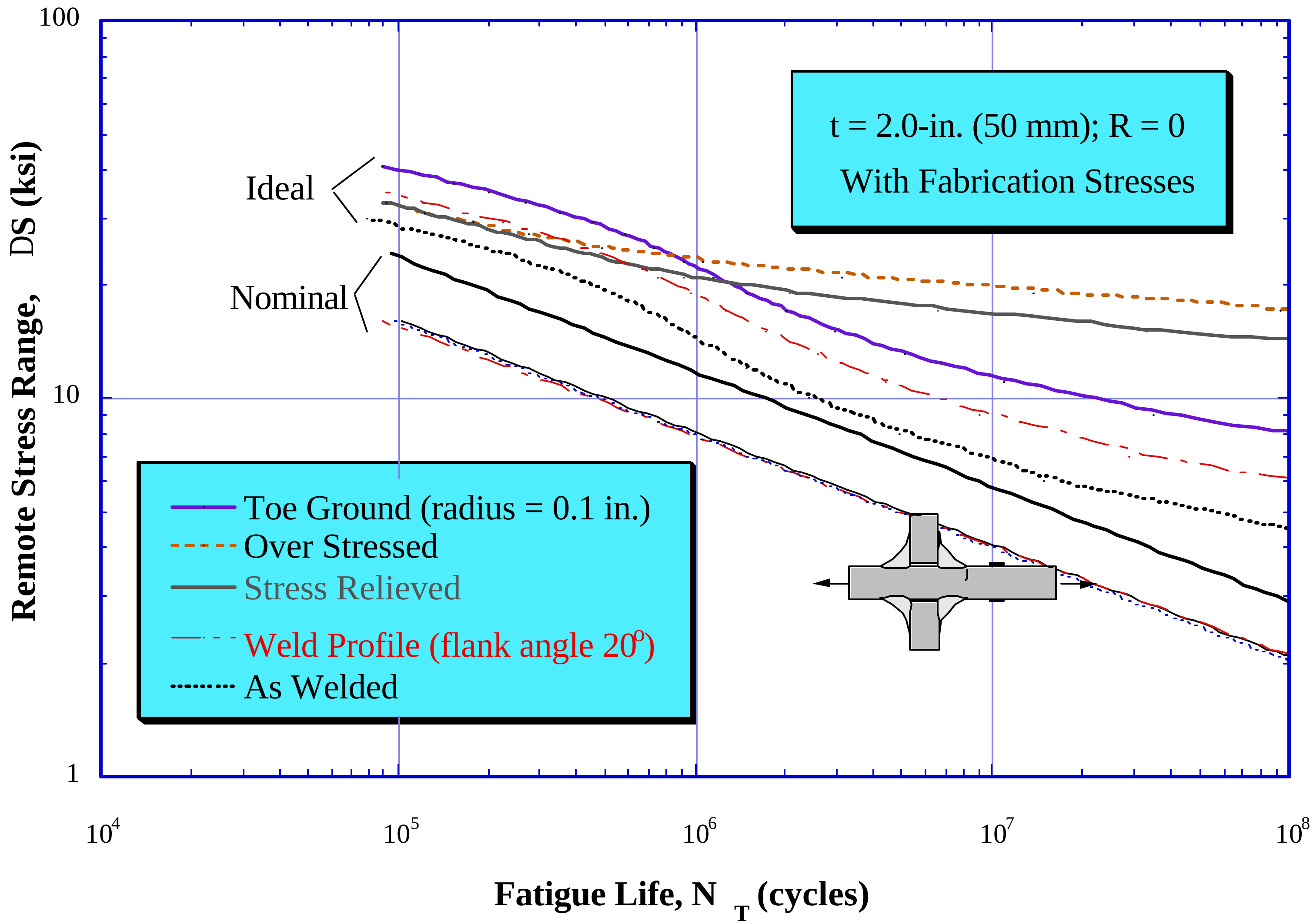
Trends in "Ideal" 1.0-in plate thickness, non-load carrying cruciform weldments fatigue strength.

- R = 0
- Welding residual stresses = 50% of SYBM
- S_{fab} ~ SYBM

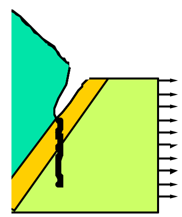
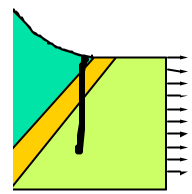
Predicted behavior of light industry weldments.



Predicted behavior of heavy industry weldments.



Modeling results

Symbol		
Application	Civil Eng. "Heavy Industry" "Nominal"	Mechanical Eng. "Light Industry" "Ideal"
Welding Residual Stresses	Unimportant	Very important
Mean and Fabrication Residual Stresses	Important	Very important
Weld toe geometry	Unimportant	Very important

Summary

- While not perfect, the IP model predicts the fatigue behavior of “ideal’ weldment and thus suggests the upper bound of weldment fatigue behavior.
- The role of residual stresses is subtle and depends upon weldment size and weld quality.