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Understanding small crack effects on failure & threshold diagrams

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Crack Length Effects on Failure and Threshold Diagrams

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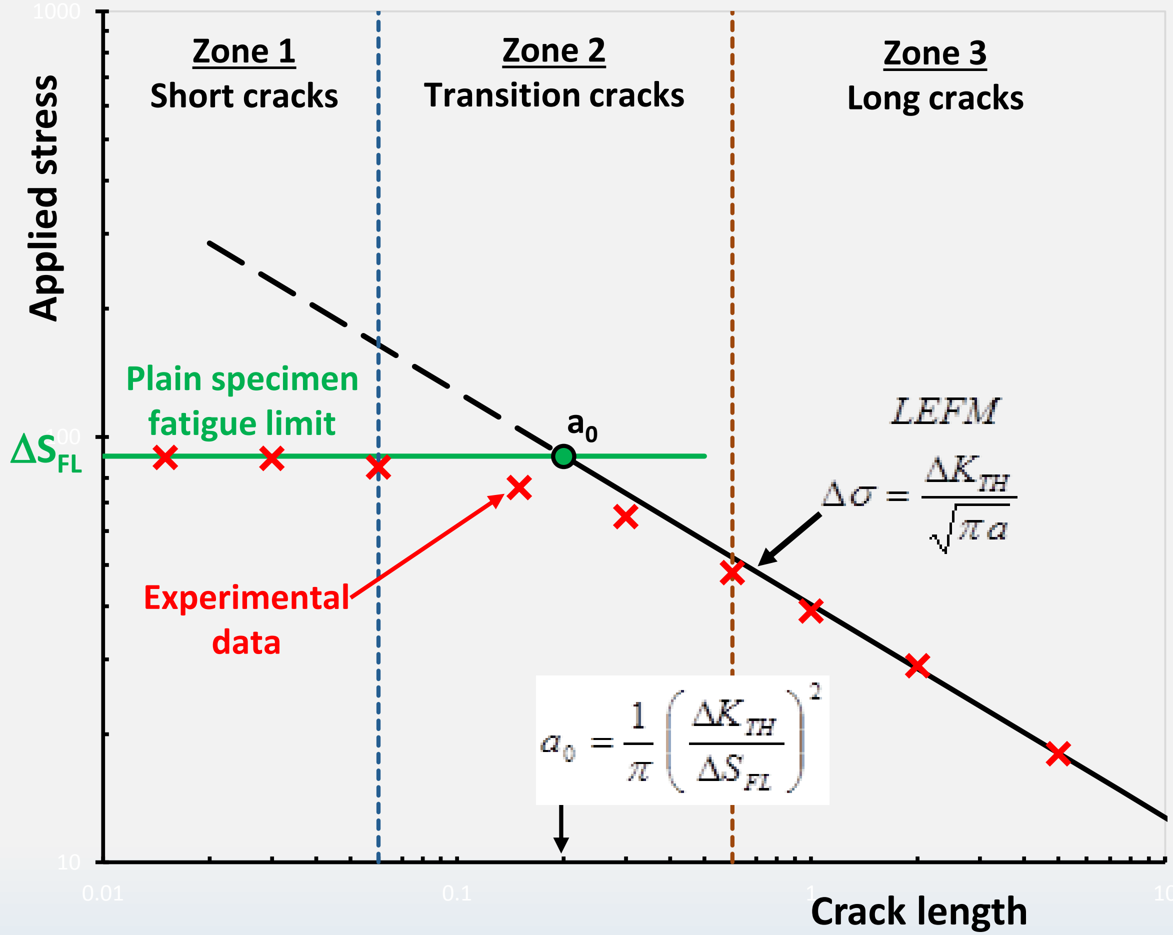
INTERNATIONAL WORKSHOP
on
Stress Assisted Environmental Damage in Structural Materials
Cork, Ireland
29th May – 3rd June 2016

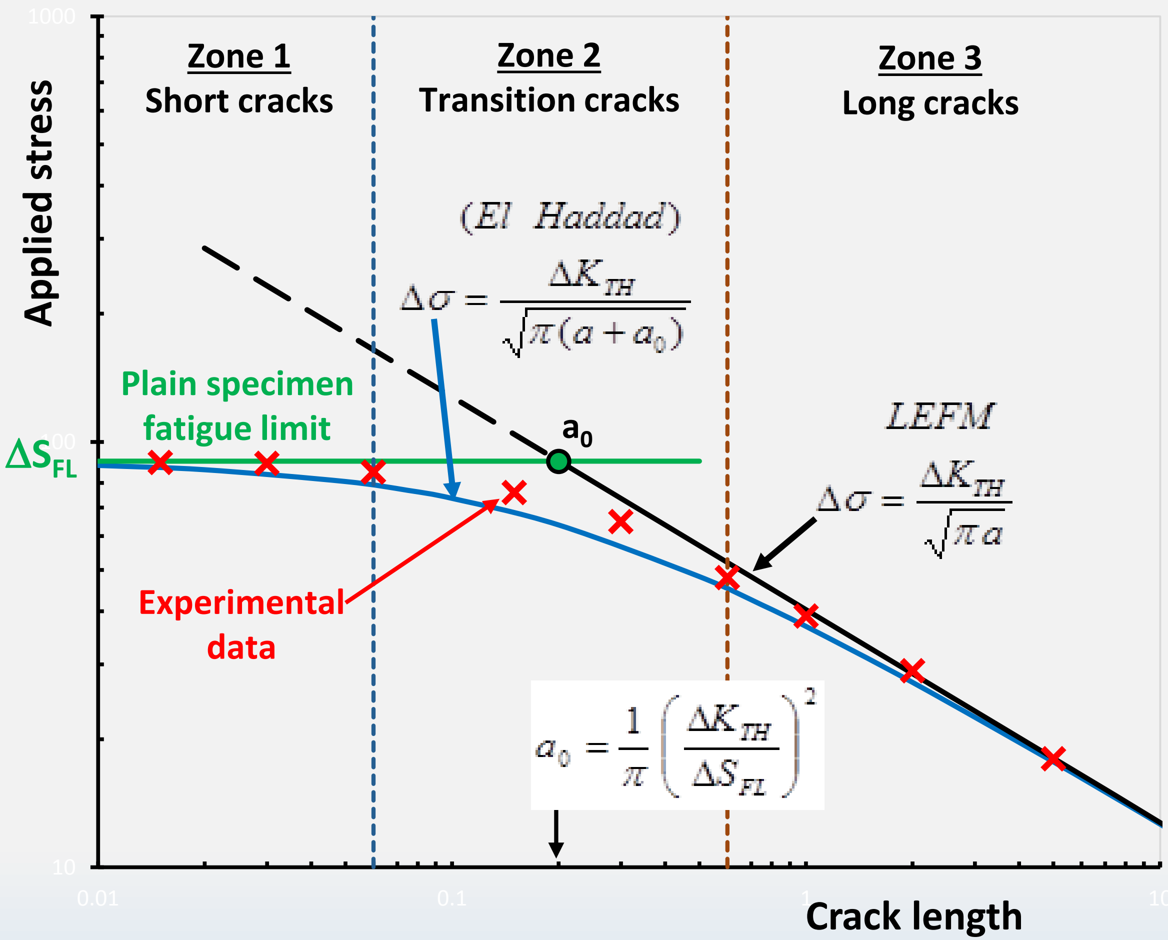
Crack length effects on fatigue threshold stress

Schematic of Kidagawa-Takahashi diagram



Crack length effects on fatigue threshold stress

Schematic of Kidagawa-Takahashi diagram



El Haddad's model

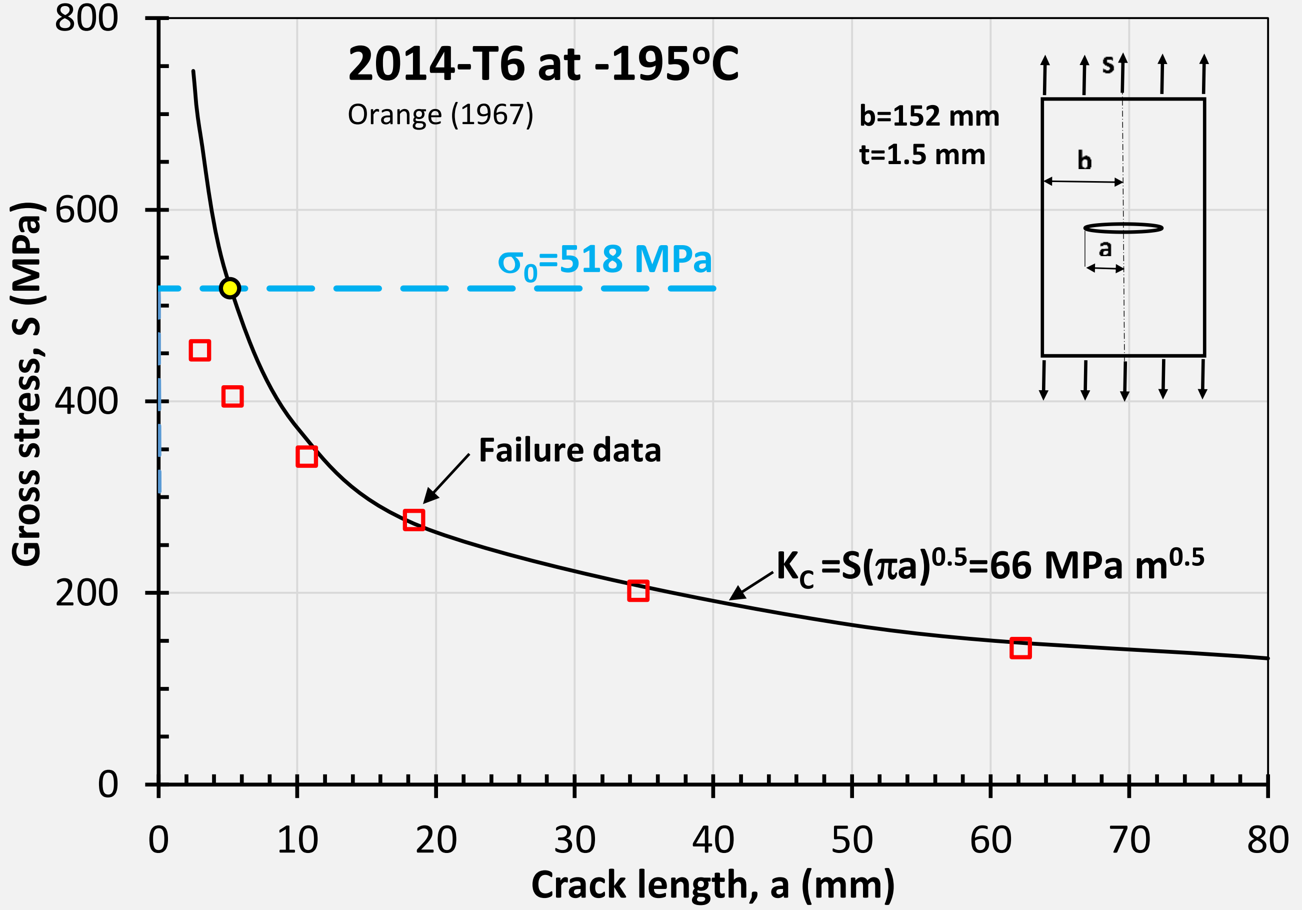
$$a_{eff} = a + a_0$$

where

$$a_0 = \frac{1}{\pi}\left(\frac{\Delta K_{TH}}{\Delta S_{FL}}\right)^2$$

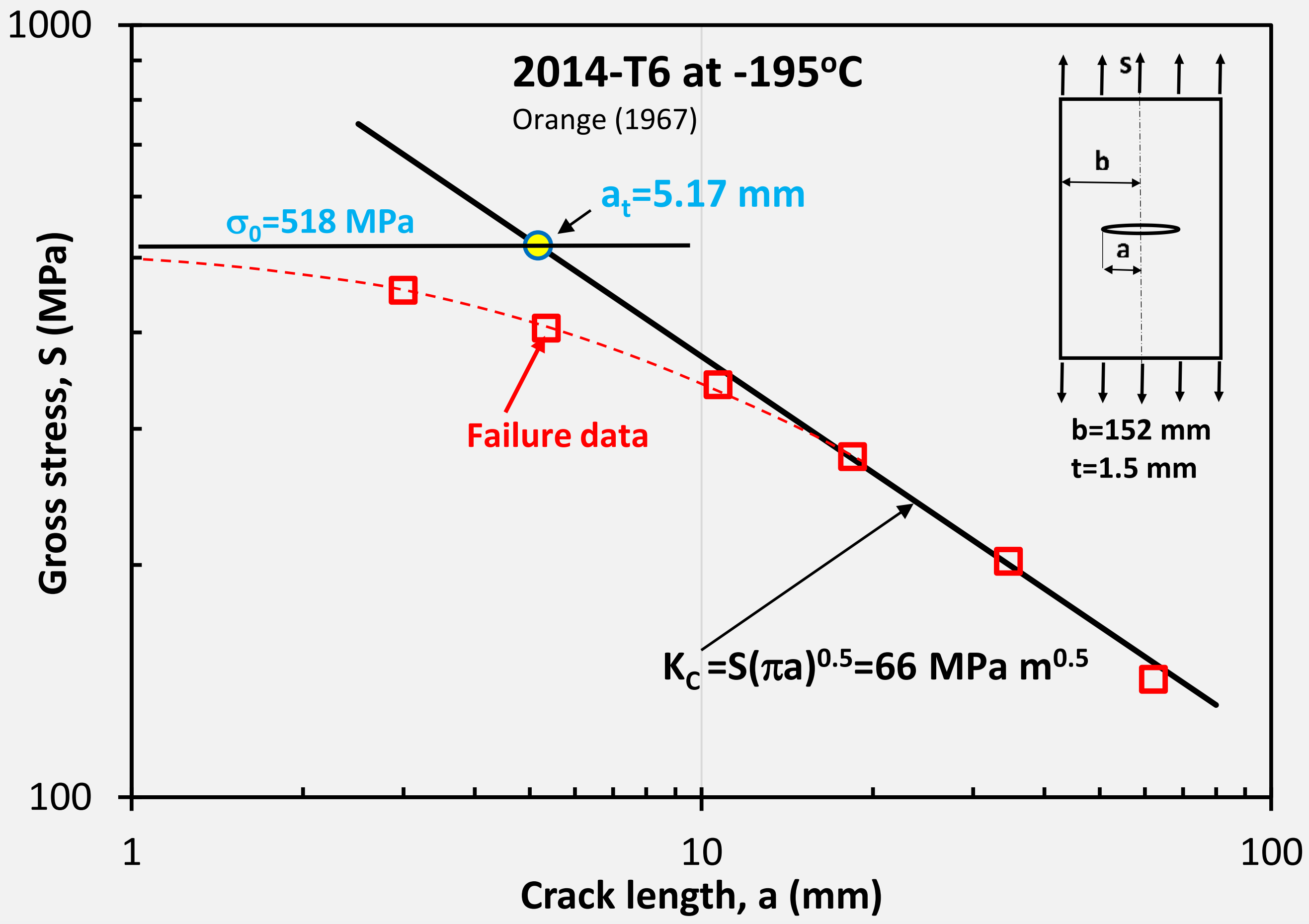
(a curve fitting approach)

Crack length effects on failure stress



Crack length effects on failure stress

(log-log plot resembles Kitagawa-Tagahashi diagram)



Transition crack length

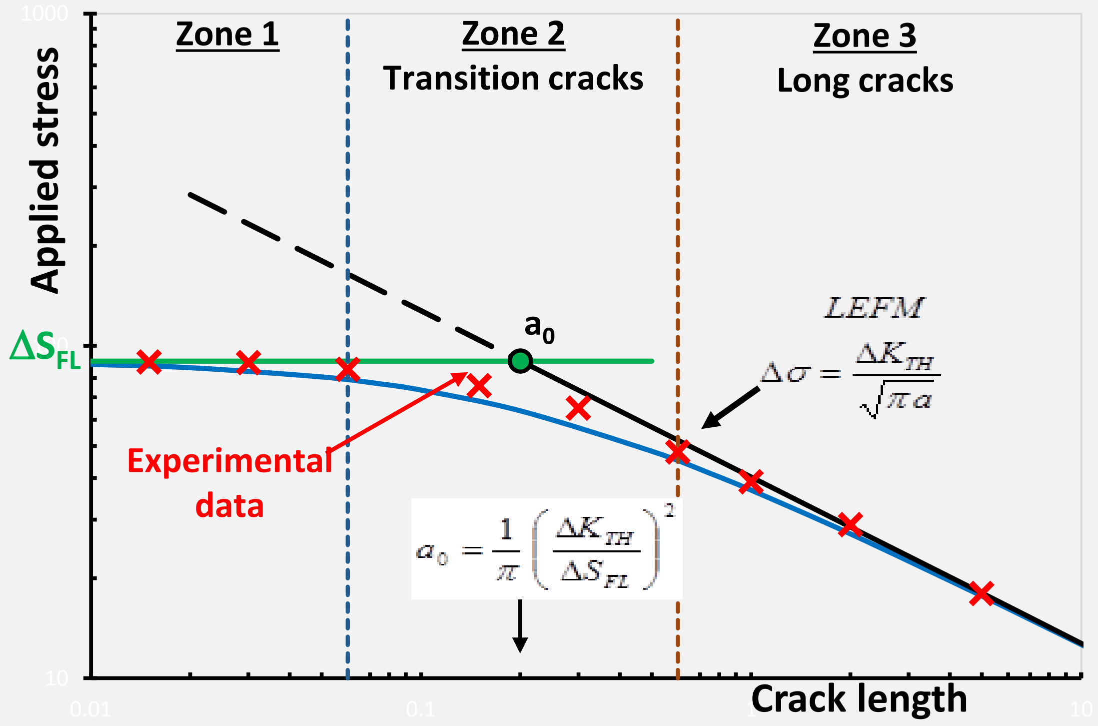
$$a_t = \frac{1}{\pi}\left(\frac{K_C}{\sigma_0}\right)^2$$

Interpretation of a_t based on LEFM:

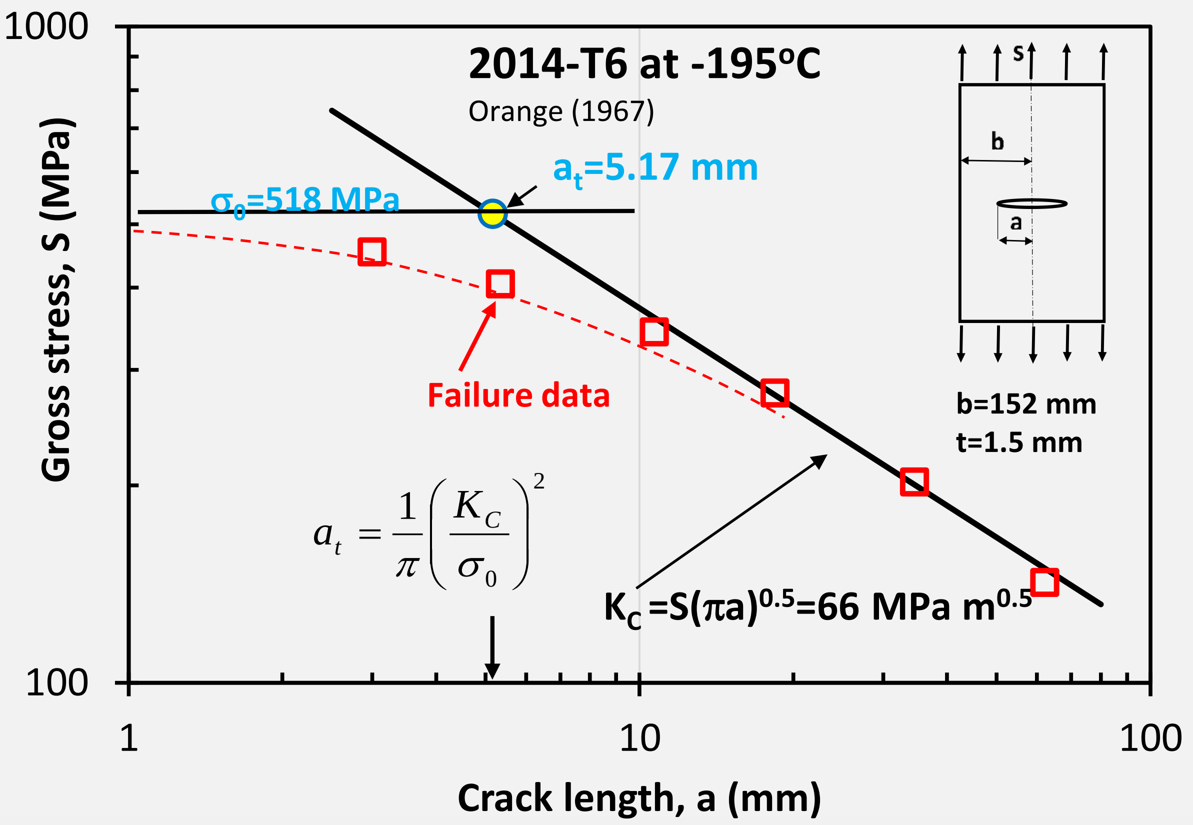
- **$a > a_t$ failure is due to fracture mechanics**
- **$a < a_t$ failure is due to yielding**

Common characteristics of crack length effects

Threshold stress



Fracture stress

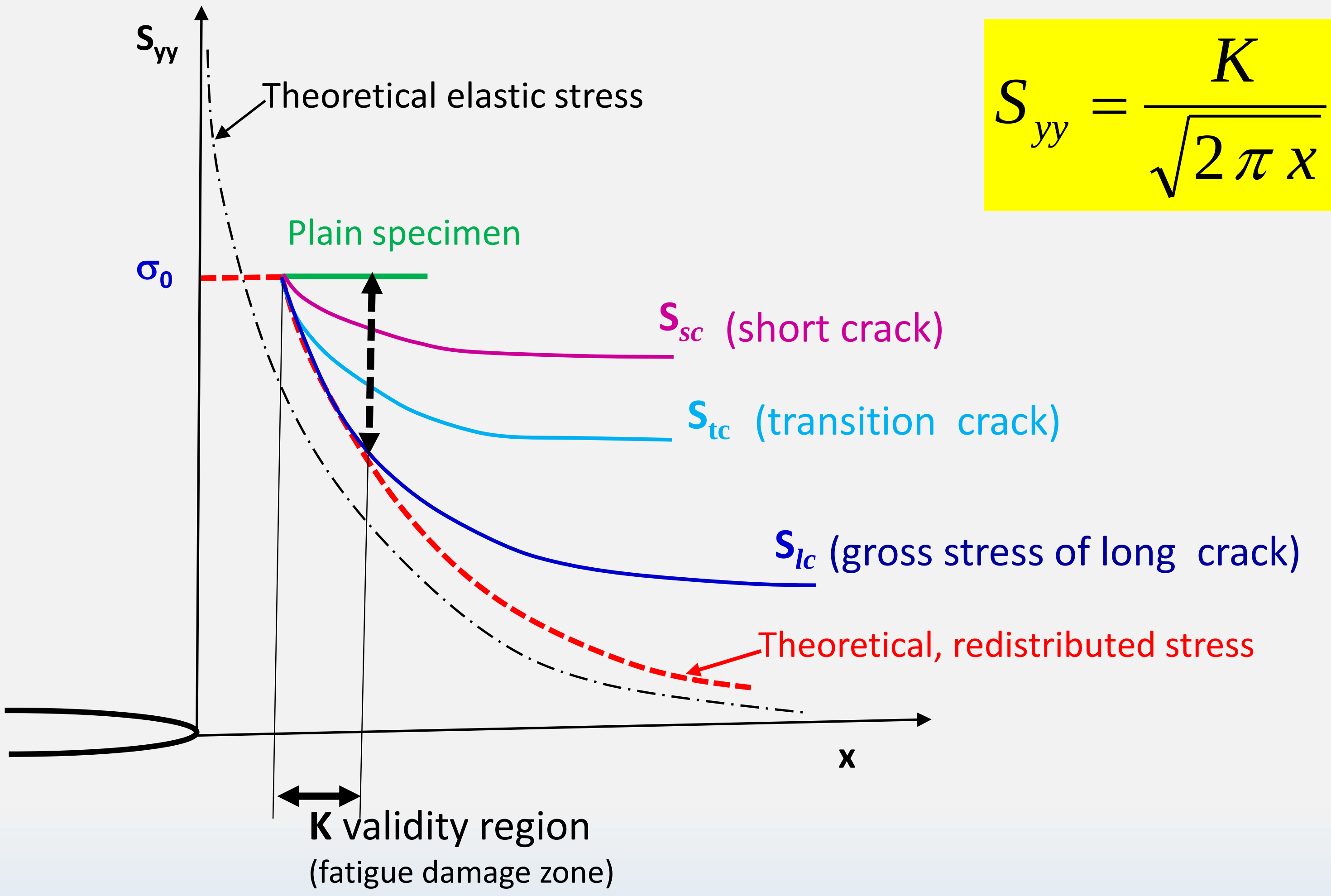


Note:

Both $\mathbf{a_t}$ and $\mathbf{a_0}$ represent a "**length dimension**" which scales the transition from SIF to applied stress behavior.

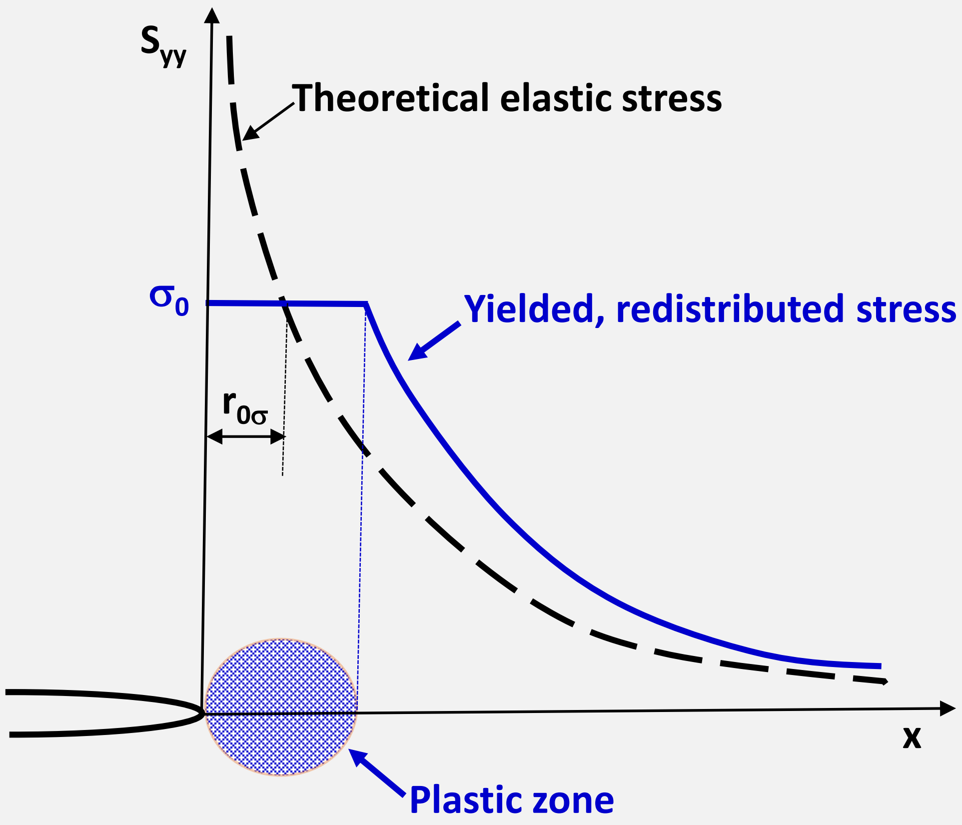
Damage transition from SIF to applied stress

long cracks transition to short cracks



$$S_{yy} = \frac{K}{\sqrt{2\pi x}}$$

Irwin's plastic zone correction



For plain stress

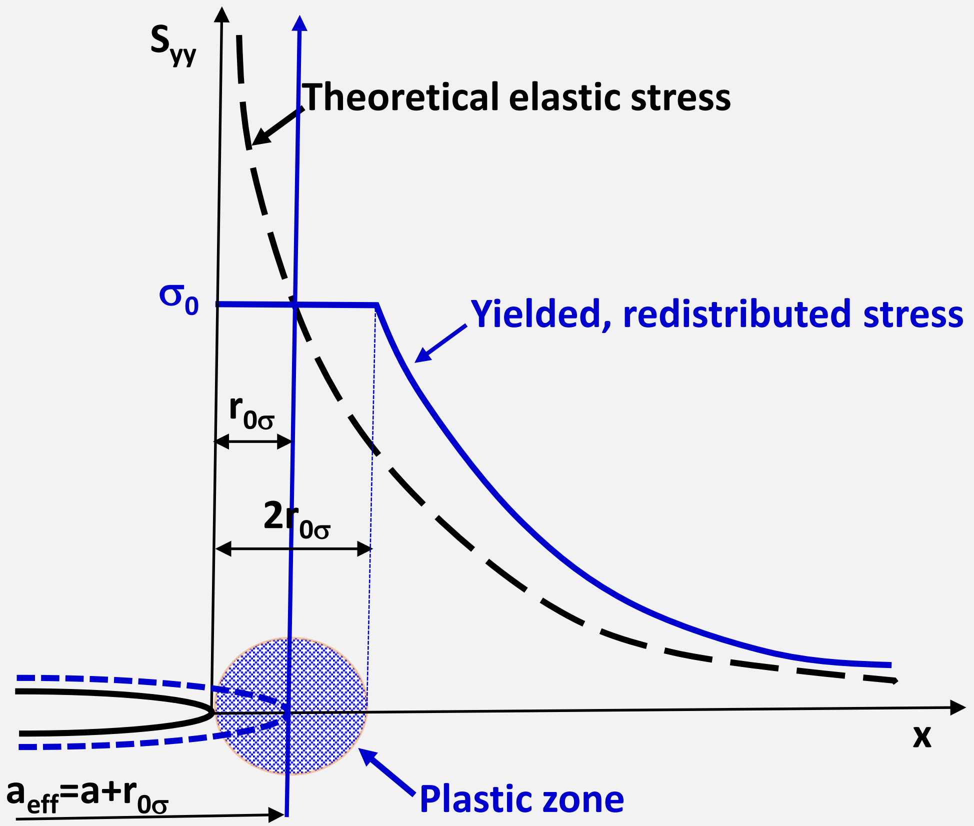
$$S_{yy} = \frac{K}{\sqrt{2\pi x}} \quad taking \ S_{yy} = \sigma_0$$

$$r_{0\sigma} = \frac{1}{2\pi}\left(\frac{K}{\sigma_0}\right)^2$$

For plain strain

$$r_{0\varepsilon} = \frac{1}{6\pi}\left(\frac{K}{\sigma_0}\right)^2$$

Irwin's plastic zone correction



For plain stress

$$S_{yy} = \frac{K}{\sqrt{2\pi x}} \quad taking\ S_{yy} = \sigma_0$$

$$r_{0\sigma} = \frac{1}{2\pi}\left(\frac{K}{\sigma_0}\right)^2$$

Due to stress redistribution

$$2r_{0\sigma} = \frac{1}{\pi}\left(\frac{K}{\sigma_0}\right)^2$$

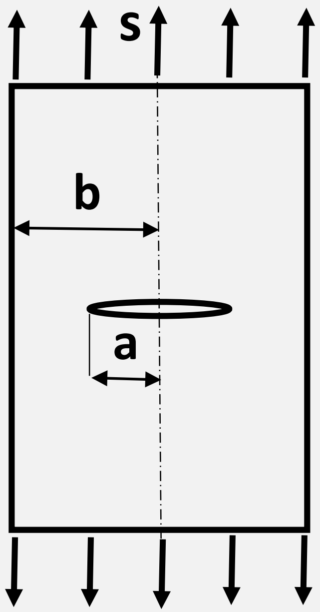
$$where\ \ a_{eff} = a + r_{0\sigma}$$

$$Note\ that\ 2r_{0\sigma} = a_t$$

Note:

Transition crack length a_t is equal to plastic zone size $2r_{0\sigma}$ at K=K_C

F(α=a/b) Correction factor for final width

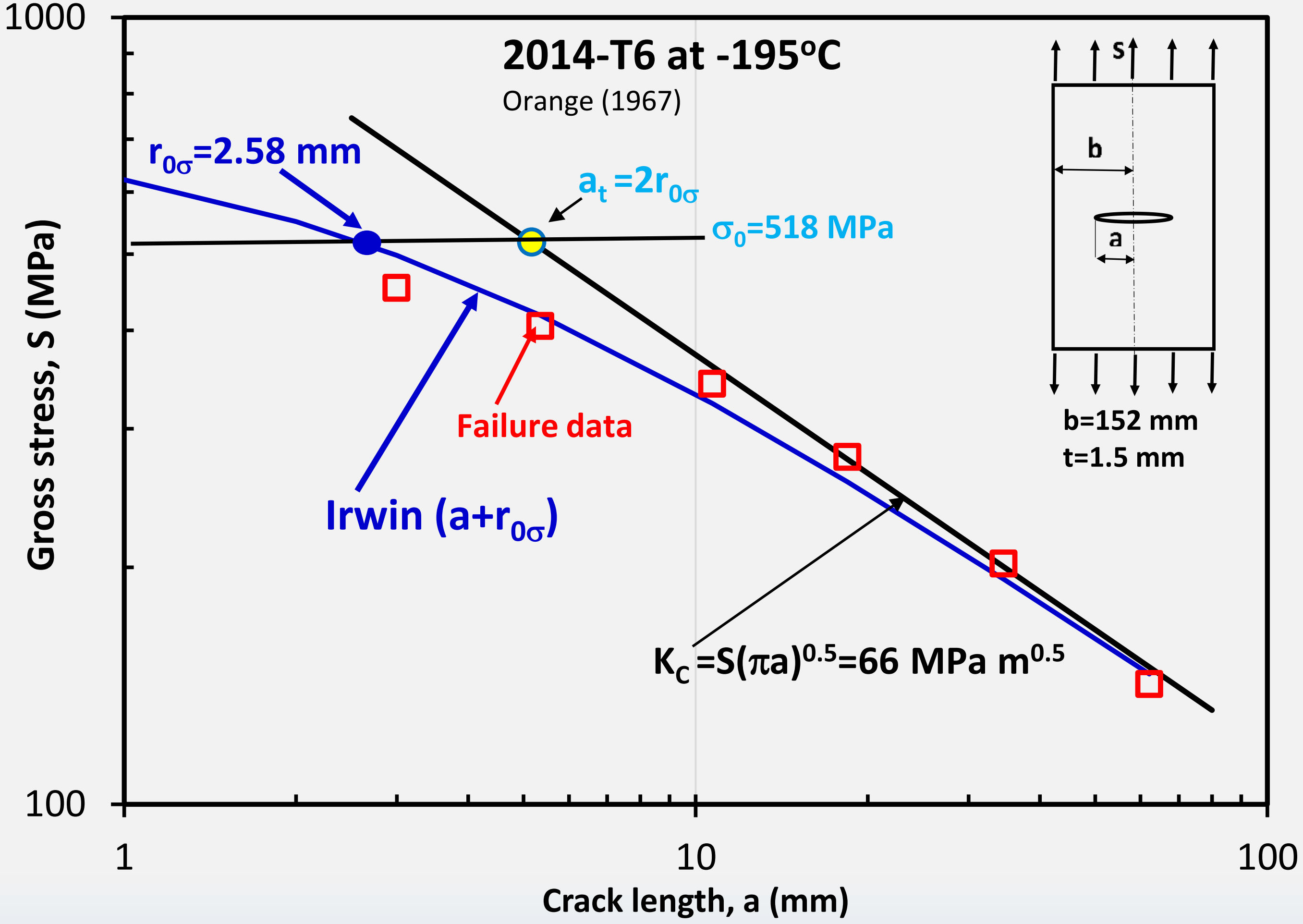


$$K_{Irwin} = F(\alpha_{eff})S\sqrt{\pi a_{eff}}$$

$$F = \frac{1-0.5\alpha+0.326\alpha^2}{\sqrt{1-\alpha}}$$

$$where \quad \alpha = a/b$$

Using Irwin's plastic zone correction



Irwin's plastic zone correction provides reasonable estimations of failure stresses for

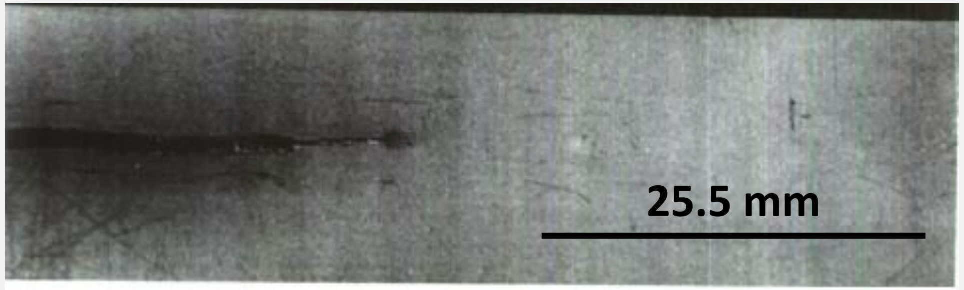
$a > a_t$

<u>but not conservative for</u>

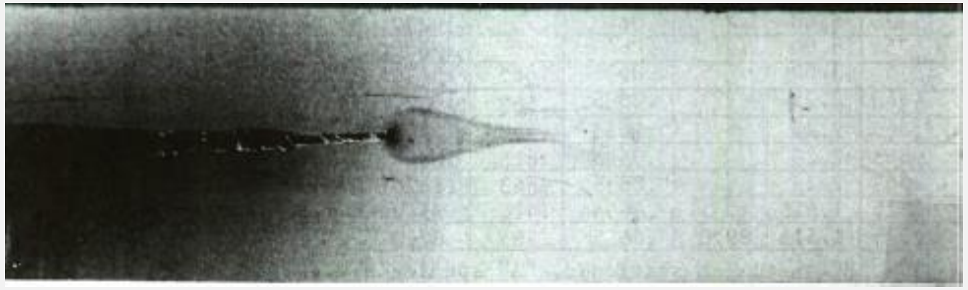
$a < a_t$

Yield zone photographs of thin cracked steel sheet

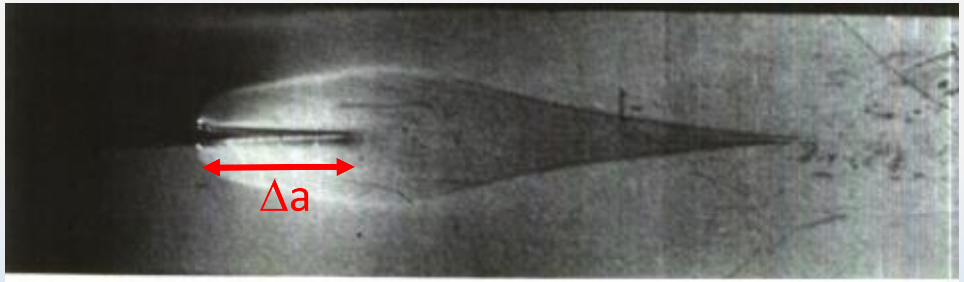
AM350CRT steel, t = 0.508 mm, σ_0 = 1,383 MPa, σ_u = 1,456 Mpa,



S = 264.8 MPa
K = 71.5 MPa $m^{0.5}$
a = 63.5 mm



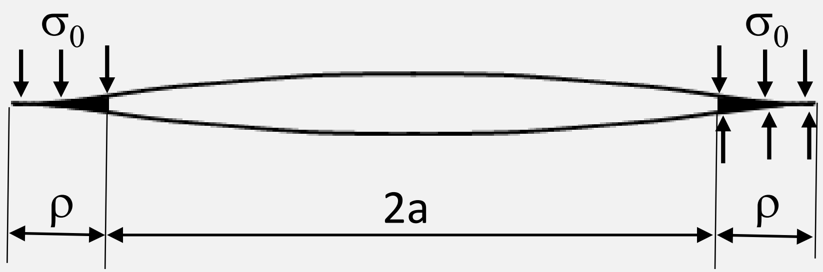
S = 501.3 MPa
K = 145.2 MPa $m^{0.5}$
a = 63.5 mm



S = 693 MPa
K = 208 MPa $m^{0.5}$
a = 72.9 mm

Forman (1966)

Strip-yield model (Dugdale-Barenblatt, 1962)



$$a+\rho = a\sec\left(\frac{\pi\,\sigma}{2\,\sigma_0}\right)$$

$$Setting\ \ a_{eff} = a+\rho$$

$$K_{eff\ DB} = S\sqrt{\pi\,a\ \sec\left(\frac{\pi\,\sigma}{2\,\sigma_0}\right)}$$

Accounting for compressive σ_0

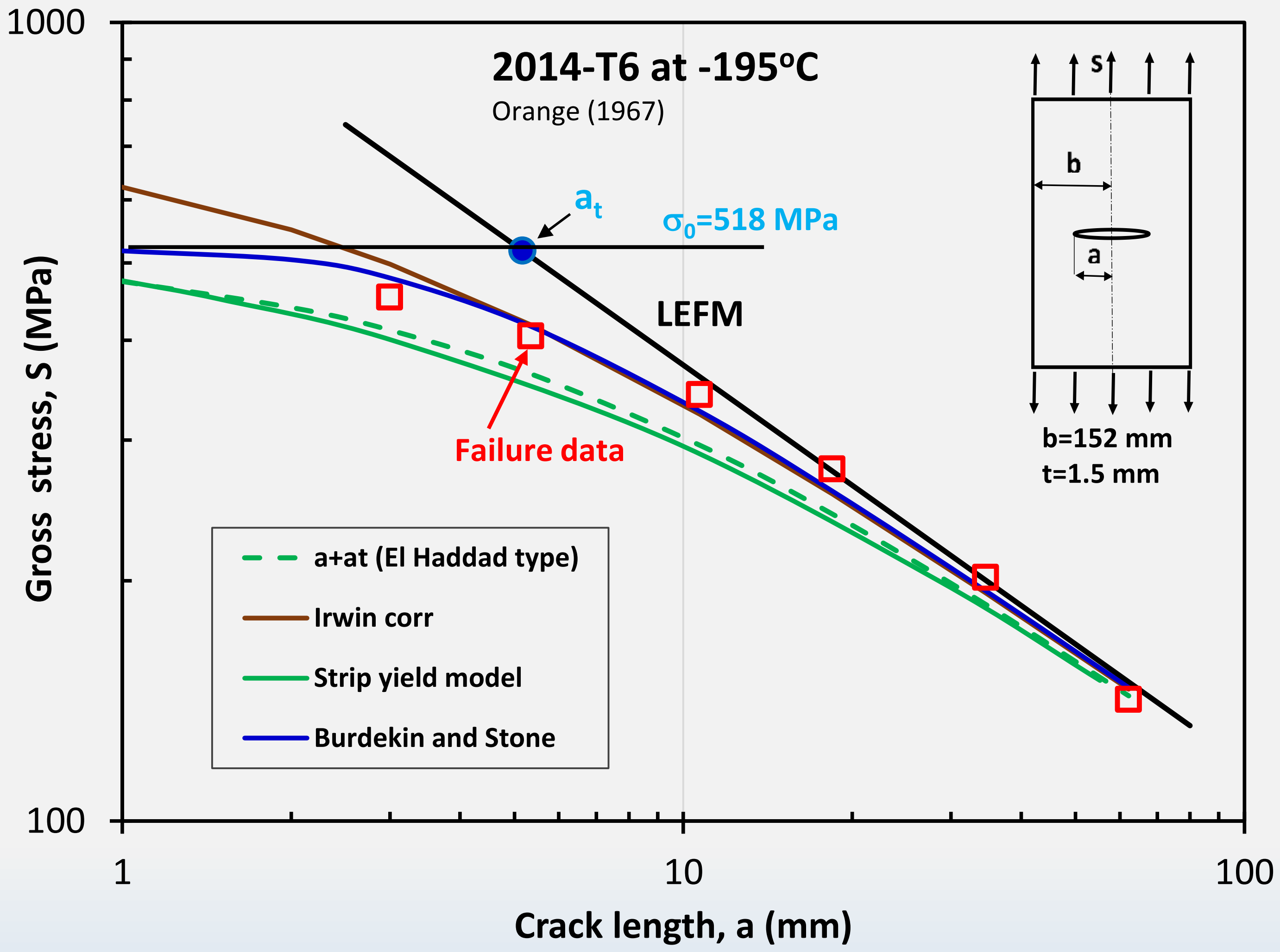
Burdekin and Stone (1966)

$$K_{eff\ BS} = \sigma_0\sqrt{\pi\,a}\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi\,\sigma}{2\,\sigma_0}\right)\right]^{0.5}$$

Note: $K_{eff\ BS} < K_{eff\ DB}$

This traditional use of $a_{eff} = a+\rho$ from strip-yield model overestimates K_{eff} since is not accounting for the effect of compressive σ_0 stresses.

Comparison of different plasticity correlations

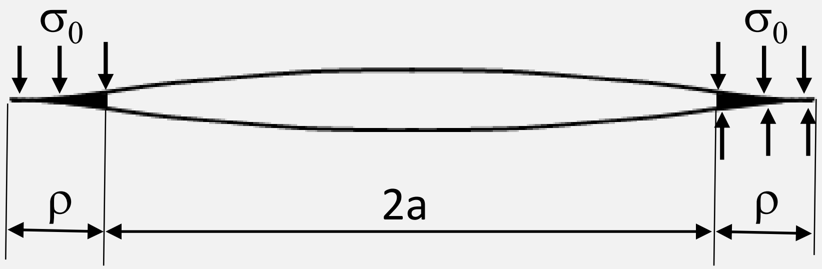


- **For SSY El Haddad's approach is equivalent to the yield-strip model since**

$$a_{eff} = a + a_t \cong a + \rho$$

- **Irwin's and Budekin & Stone's are equivalent for a > a_t**

Modified strip-yield model

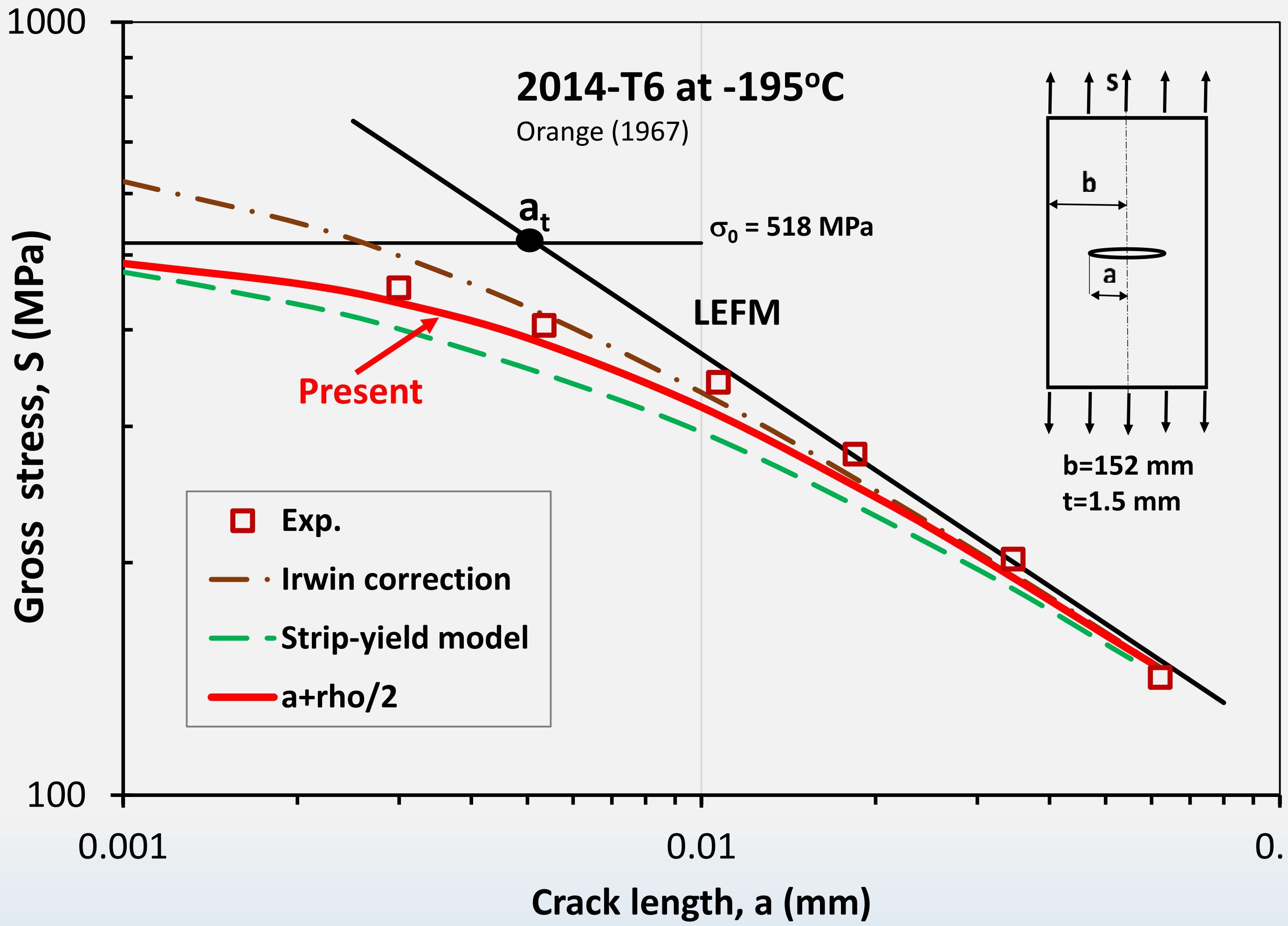


$$\rho = a\sec\left(\frac{\pi\sigma}{2\sigma_0}\right) - a$$

$$Setting \quad a_{eff} = a + \rho/2$$

$$K_{eff} = S\sqrt{\frac{\pi a}{2}\left(\sec\frac{\pi S}{2\sigma_0} + 1\right)}$$

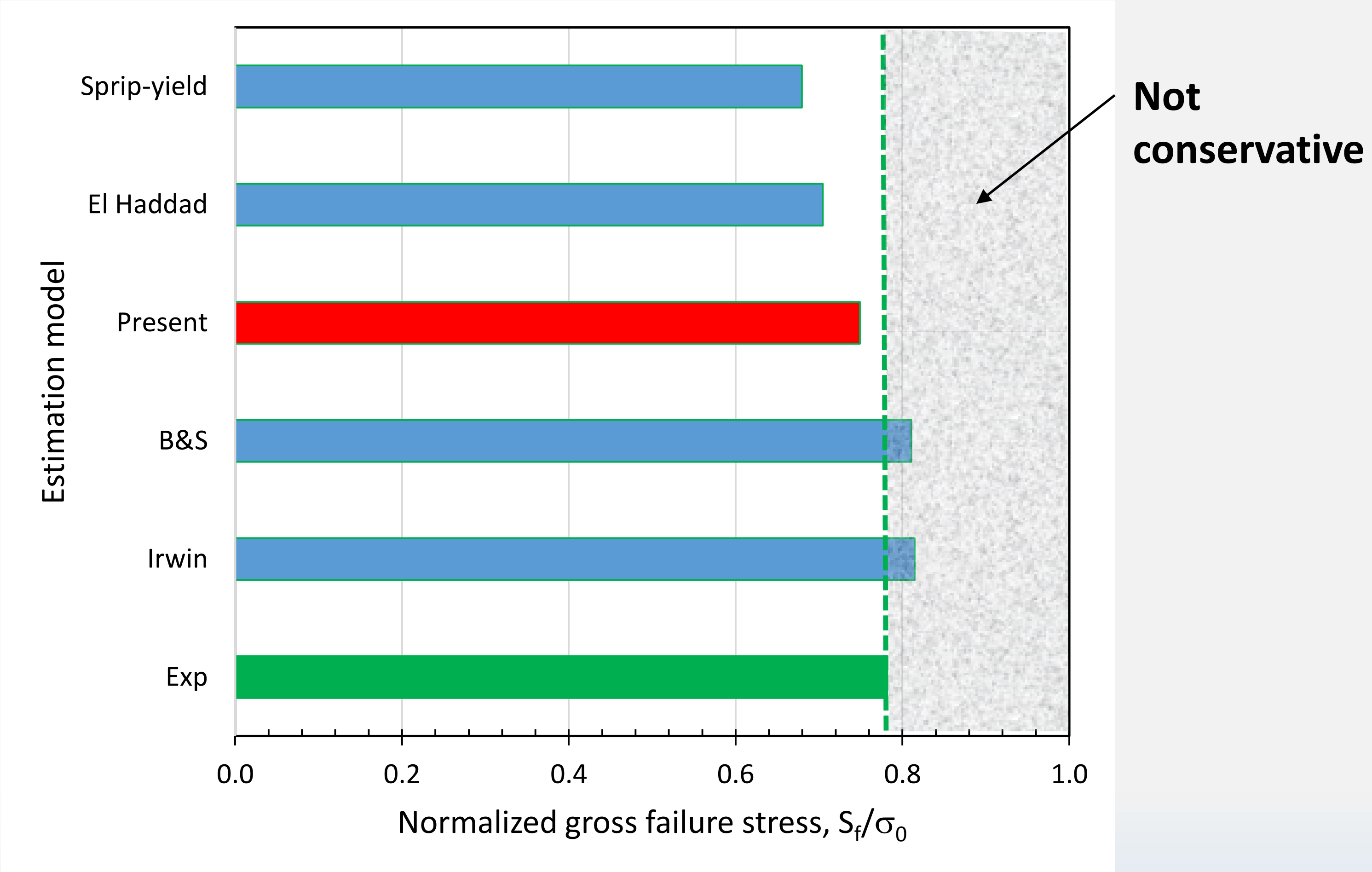
Experiments vs. Different plasticity corrections



Proposed strip-yield model with a_{eff} = a+ρ/2 provides a fair conservative prediction for **a < a_t and a > a_t**

Normalized gross failure stress, S_f/σ_0

Experiment vs. predictions for $a=a_t=5.17$ mm



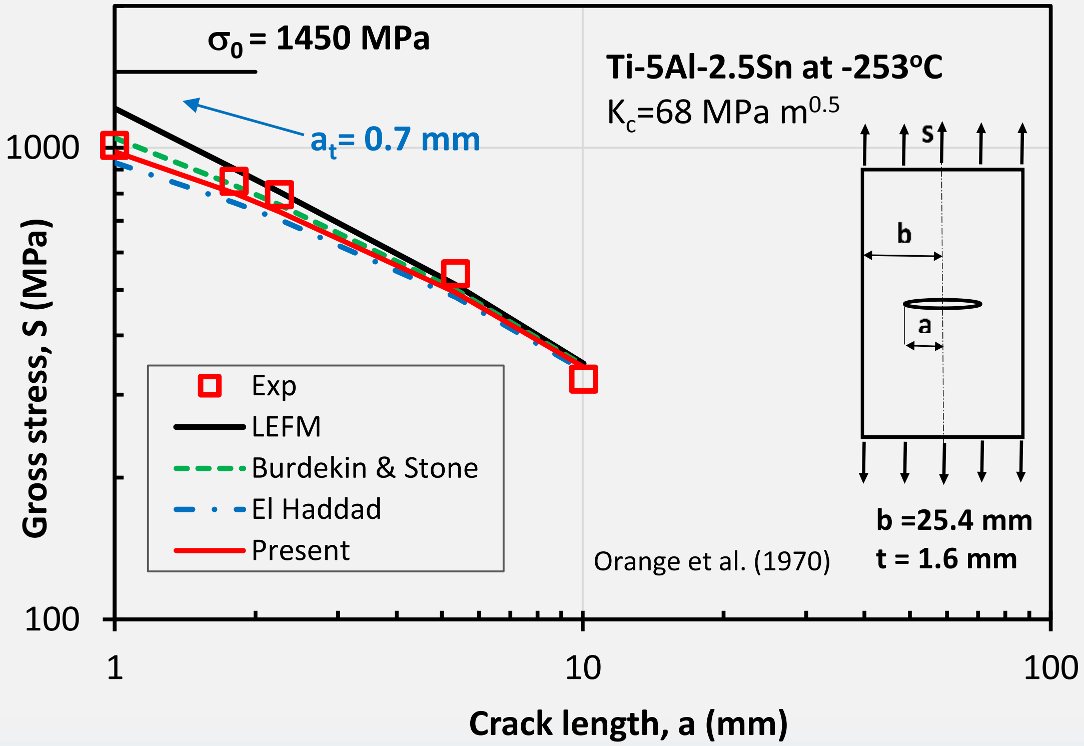
NASA data on Ti & Al alloys

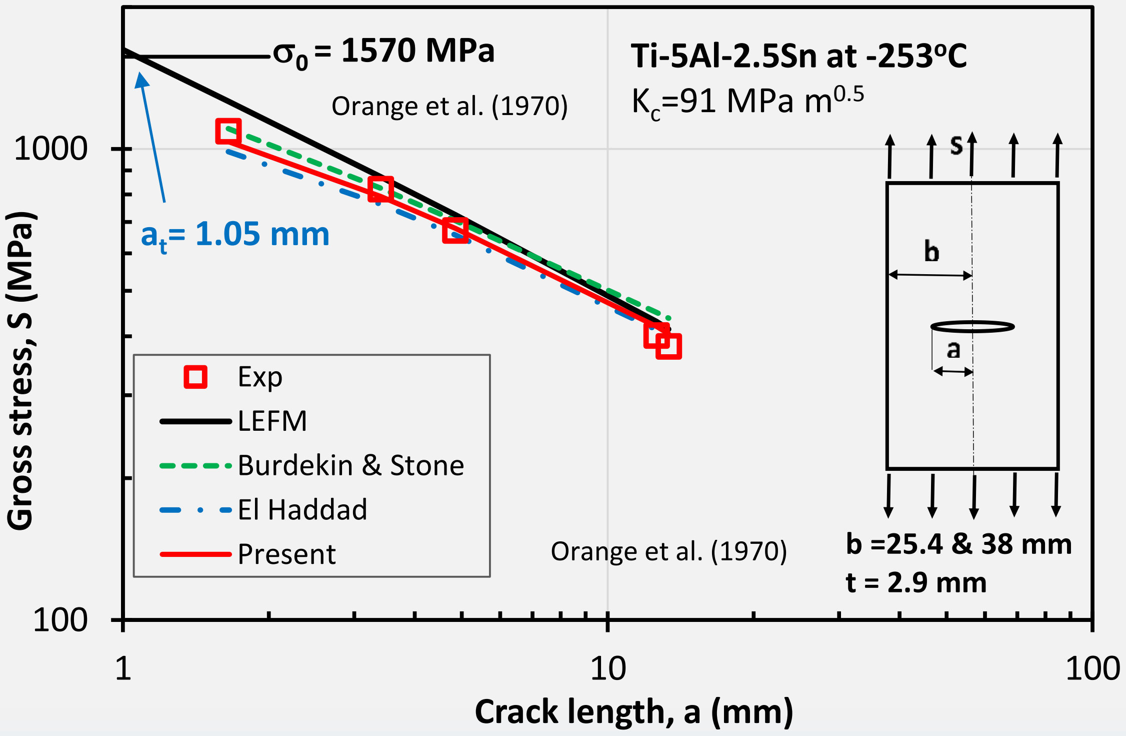
- **Materials & Specimens**
  - Ti-5Al-2.5Sn & 2014-T6
  - Thin plates with through thickness cracks
  - Specimens' thicknesses t = 1.5 to 2.9 mm

- **Test Procedure**
  - Precraced in fatigue to different crack length
  - Fractured under monotonic load
  - Tested at different temperatures: from RT to – 254^{o}C

Experiments vs. Predictions

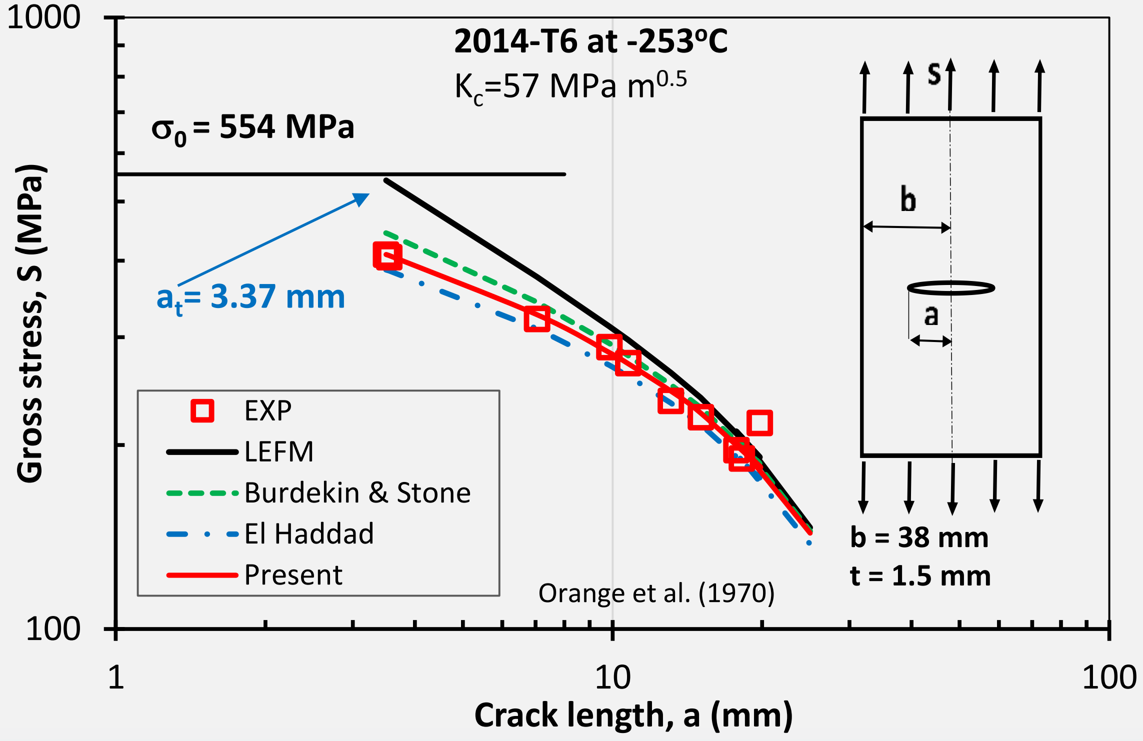
Ti-5Al-2.5Sn plate t = 2.9 mm

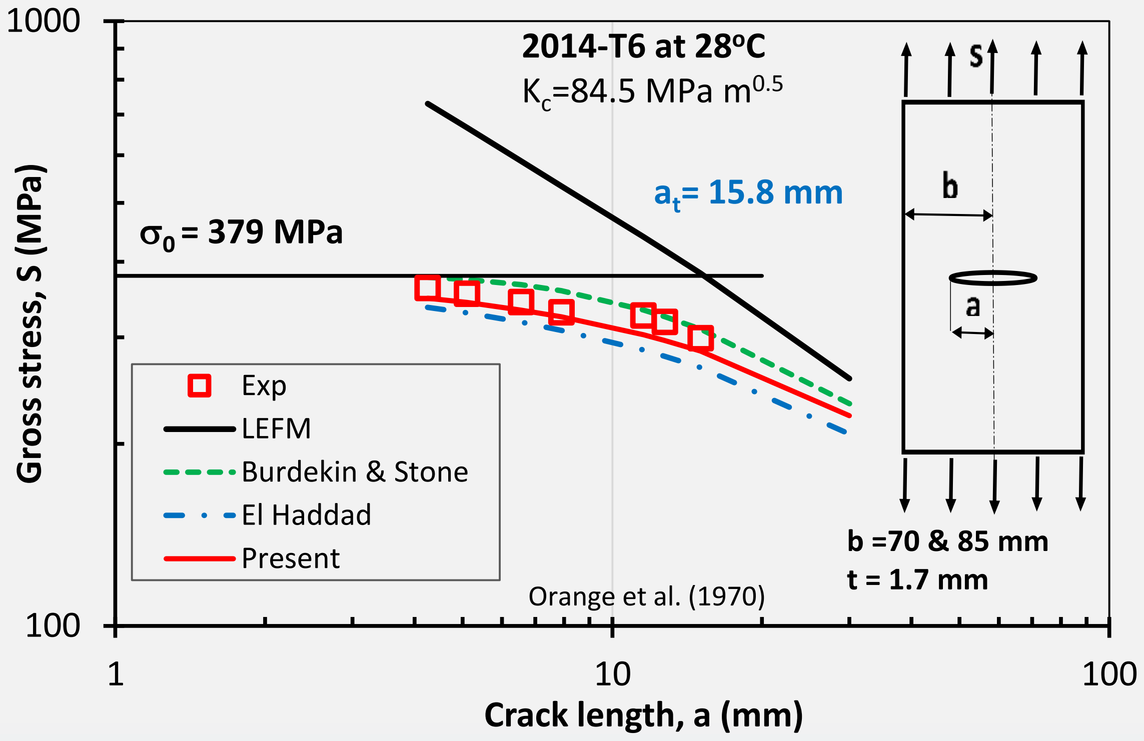




Experiments vs. Predictions

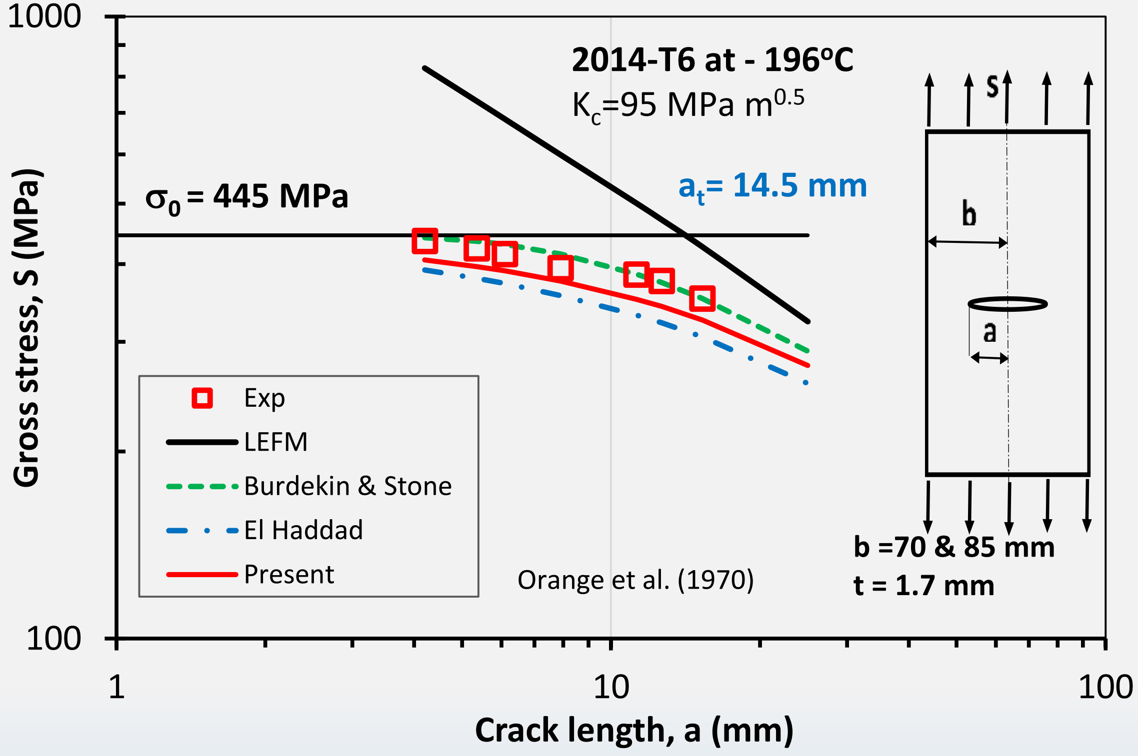
2014-T6 Al plate t = 1.5 &1.7 mm

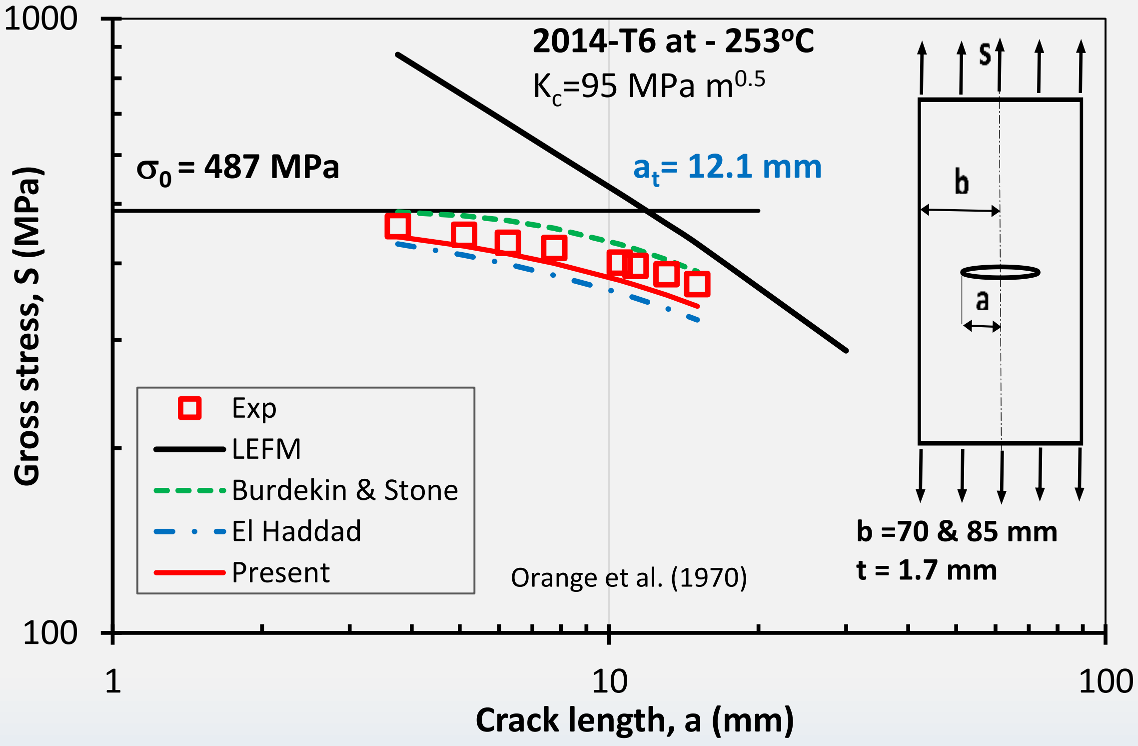




Experiments vs. Predictions

2014-T6 Al plate t =1.7 mm





Can this be used for SCC?

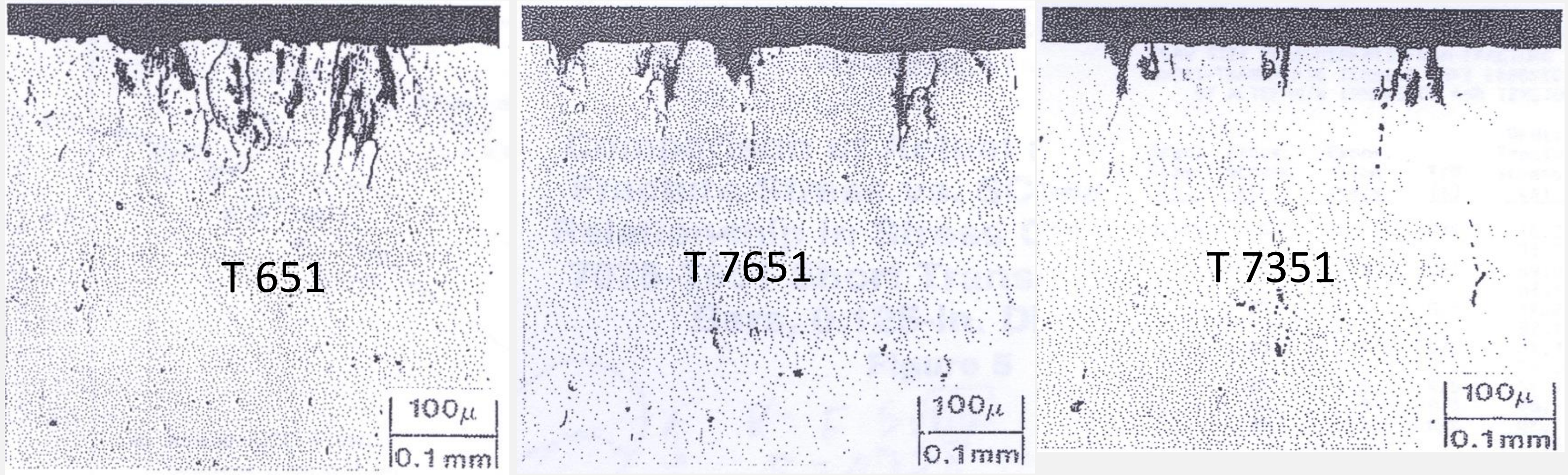
ALCOA breaking load method for assessing SCC resistance

- **Materials & Specimens**
  - 7075- T651, 7075-T7X1, 7075-T7X2
  - Round, smooth dog-bone specimens
  - Two diameters d=3.18 & 5.72 mm were used

- **Test Procedure**
  - Exposed to 3.5% NaCl for different duration
  - Then monotonically loaded to fracture at air
  - Fracture stress and the actual deepest SCC flaw was measured from fracture surface

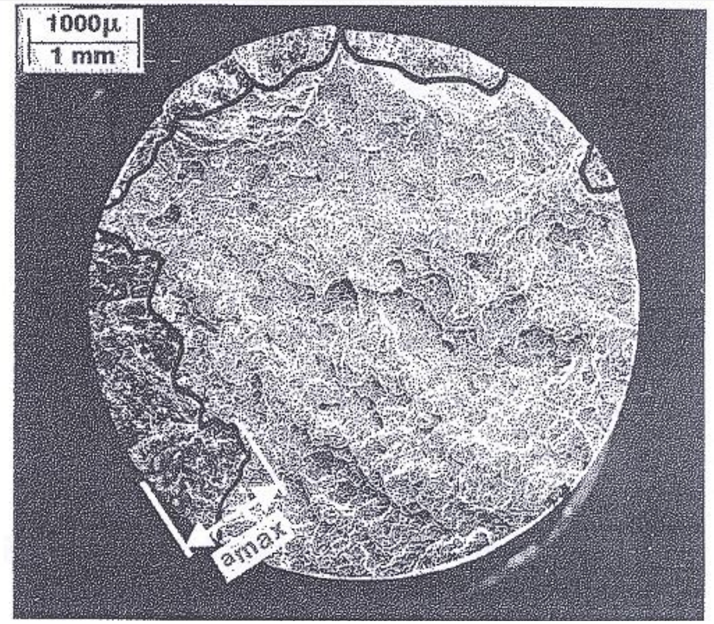
Typical surface attack and fracture surface

Typical surface attack in the three tempers of 7075 plate exposed to 3.5% NaCl solution by alternate immersion



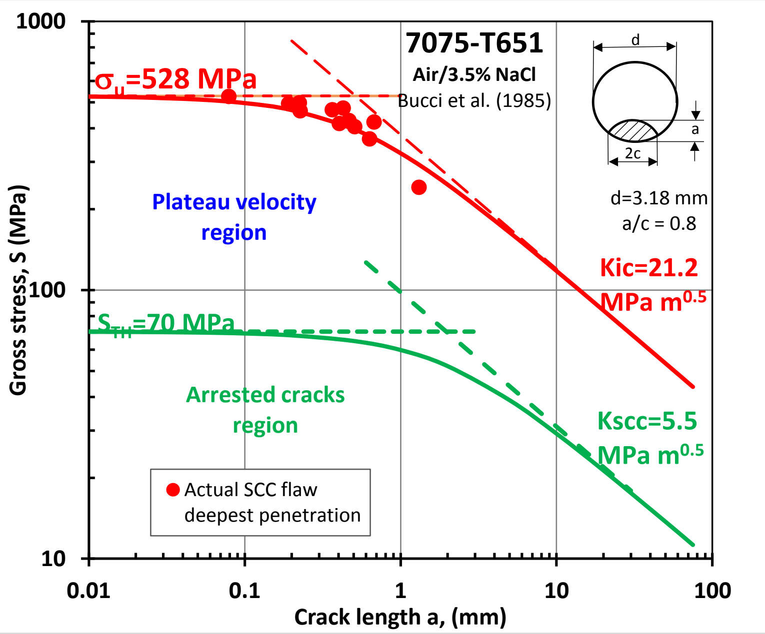
Short transvers plate direction

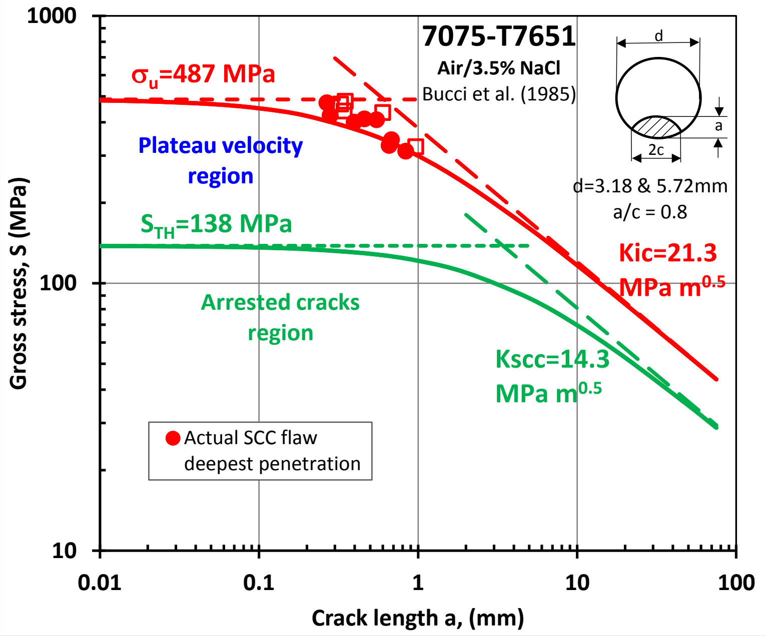
Fracture surface with border of stress corrosion flaw outlined

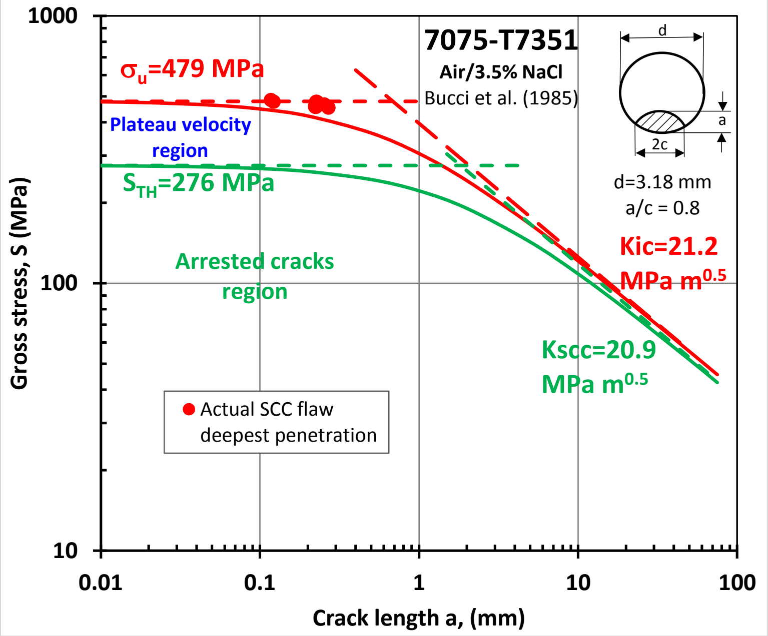


7075-T7651, 5.17 mm diameter specimen
Exposed 9 days at 276 MPa, fractured stress 324.1 MPa

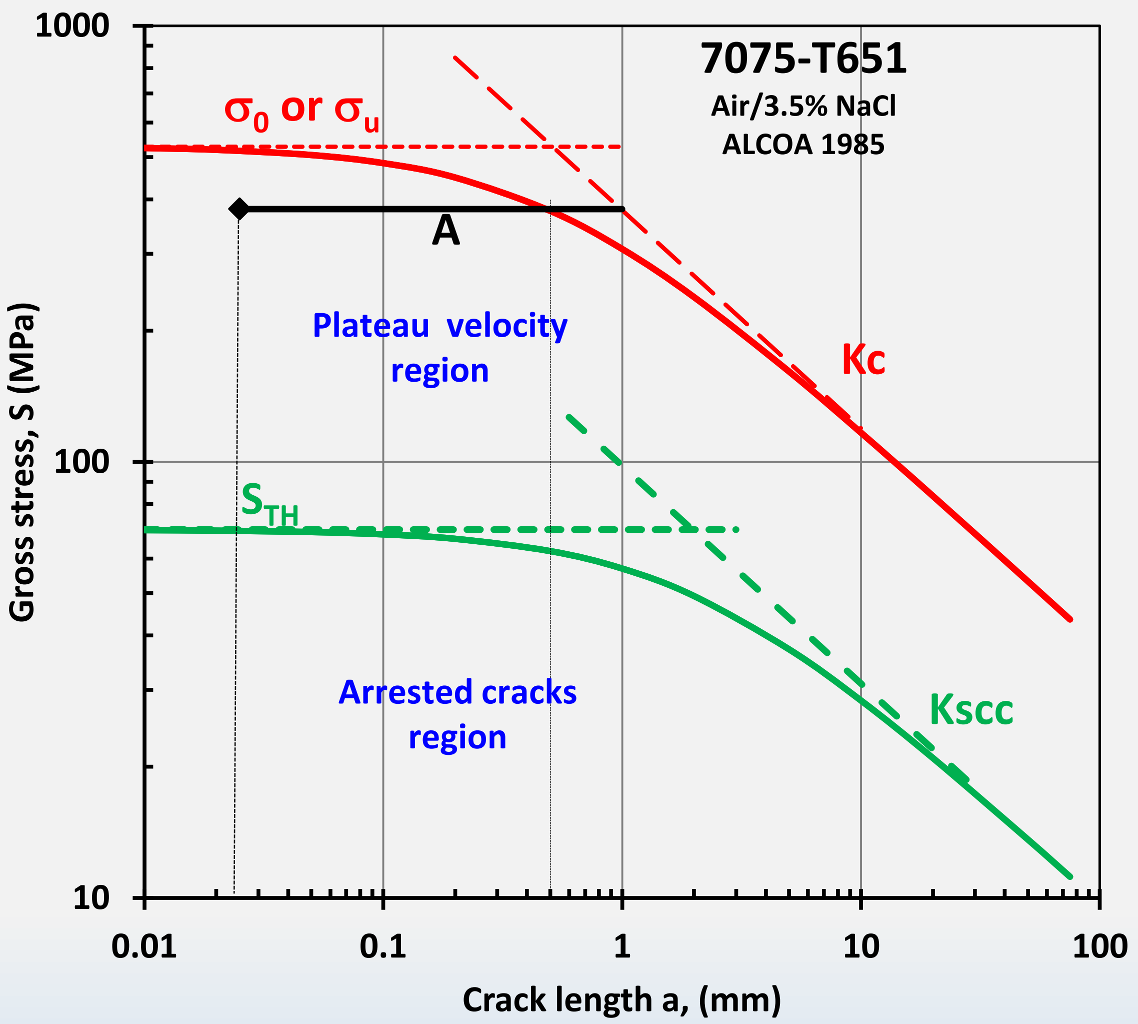
Fracture stress vs. SCC flow depth relationship







Application of SCC diagram to design



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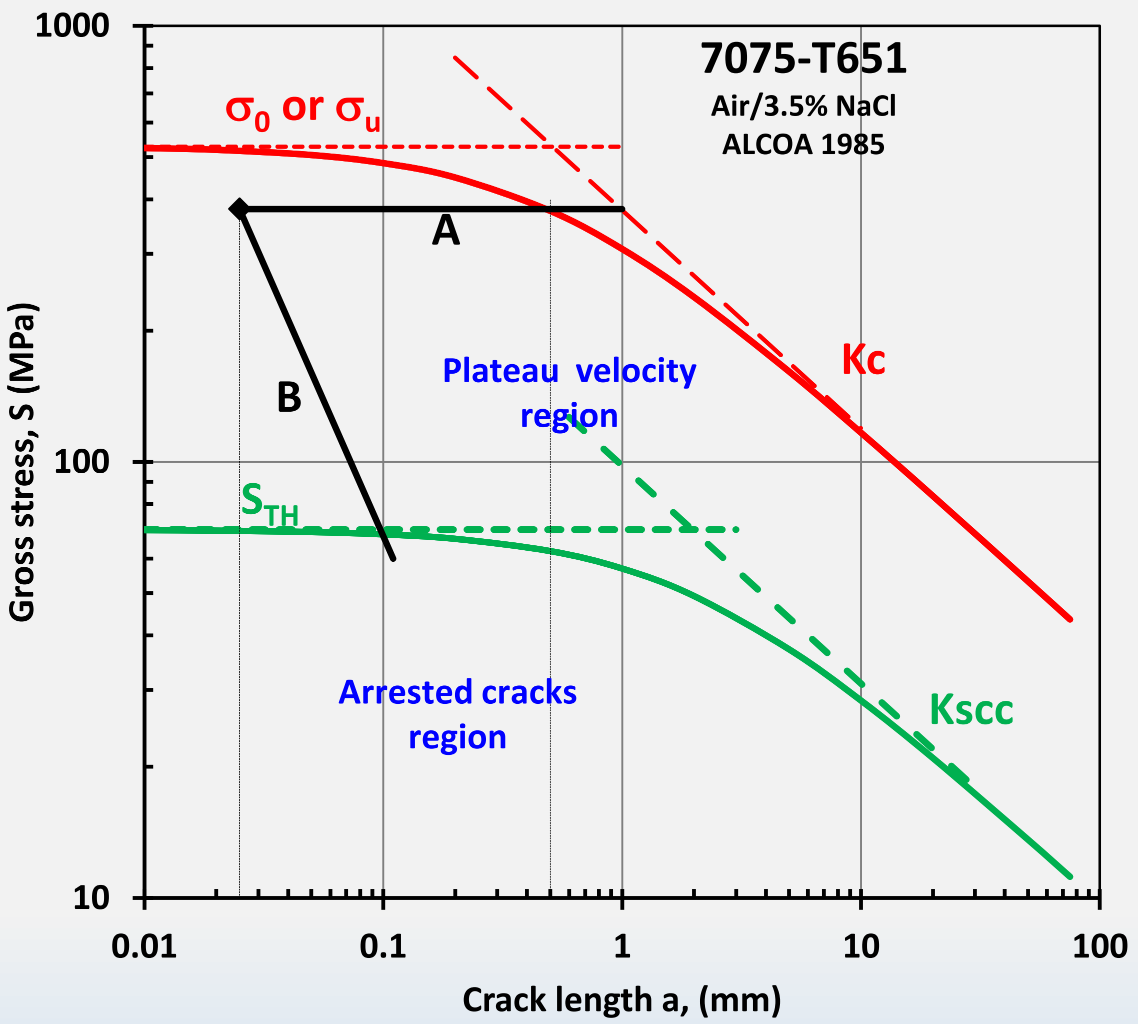
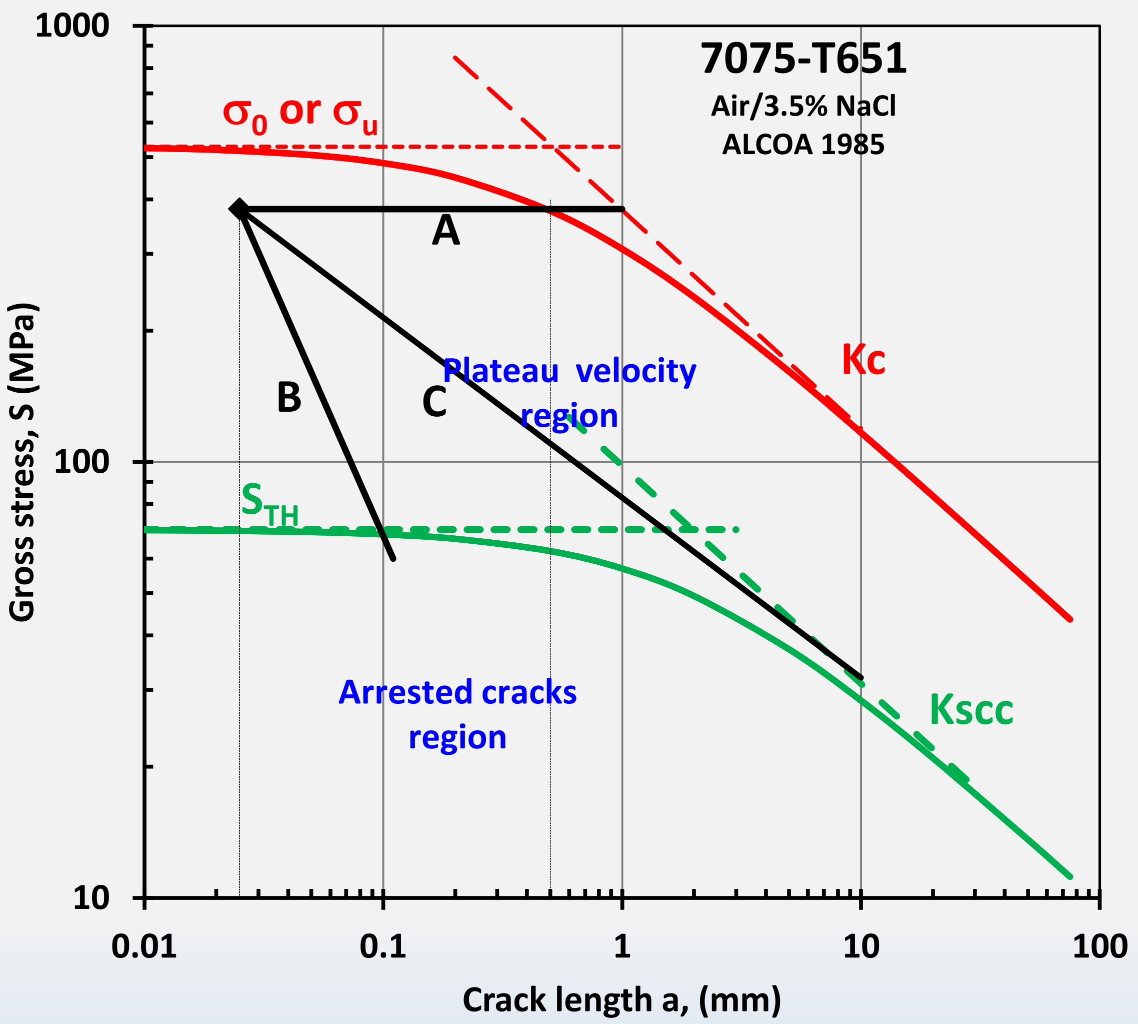


Application of SCC diagram to design



Conclusions

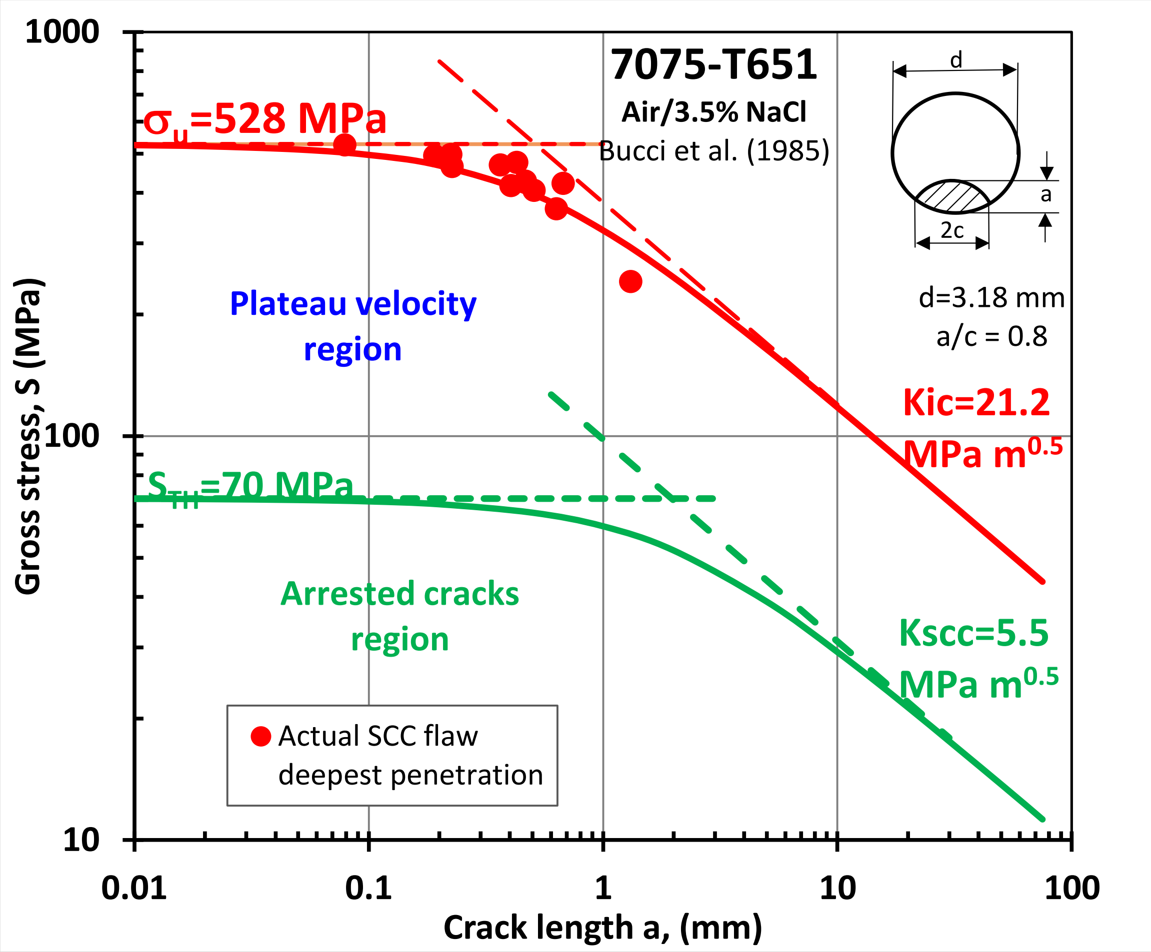
- Design diagram for failure stress and SCC is proposed which consists of:
    - SCC threshold curve
    - Final fracture curve
    - Both curves have common characteristics
- Proposed approach accounts for inter-relations among:
    - Environment
    - Applied stress
    - Crack and/or SCC flaw size

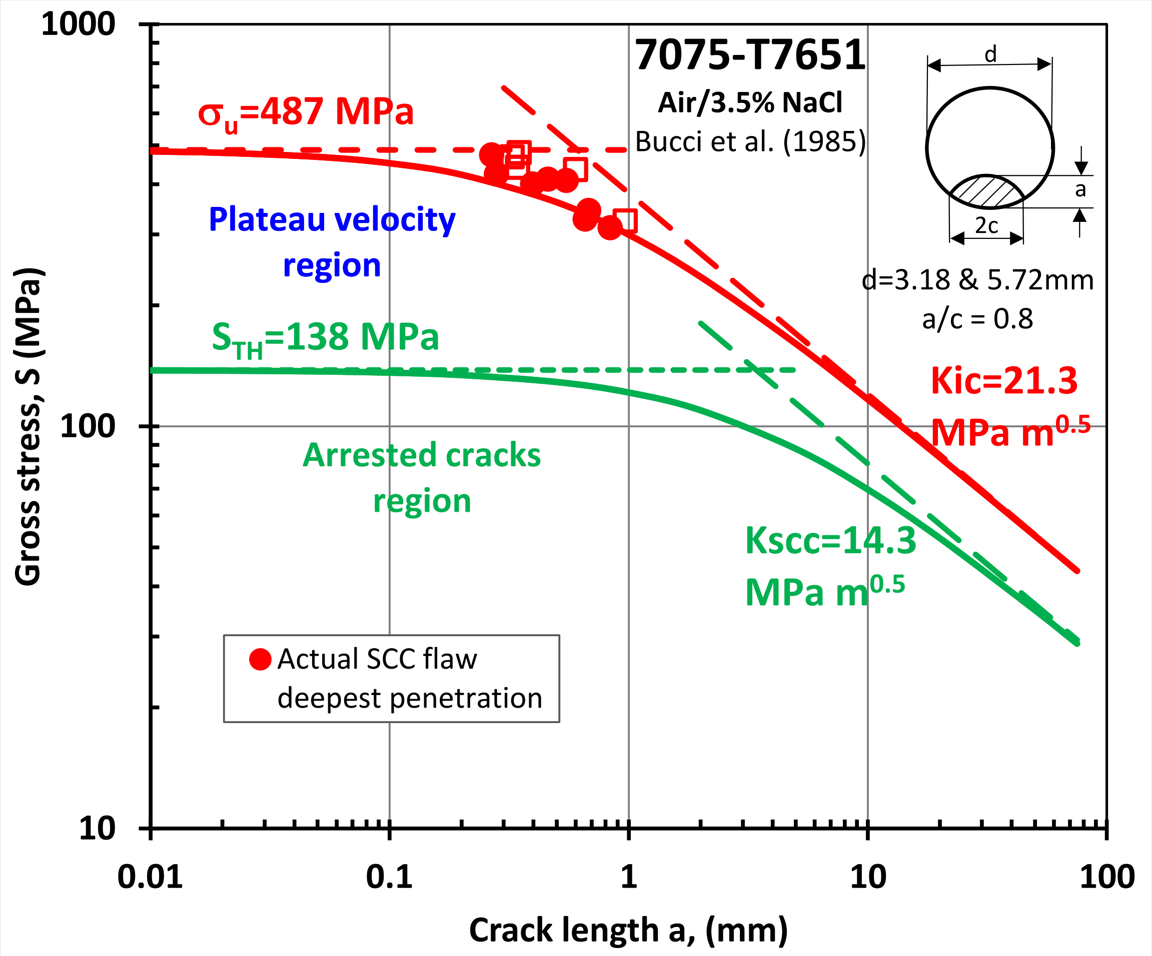
Thank You

Albert Einstein 'Between Theorems'

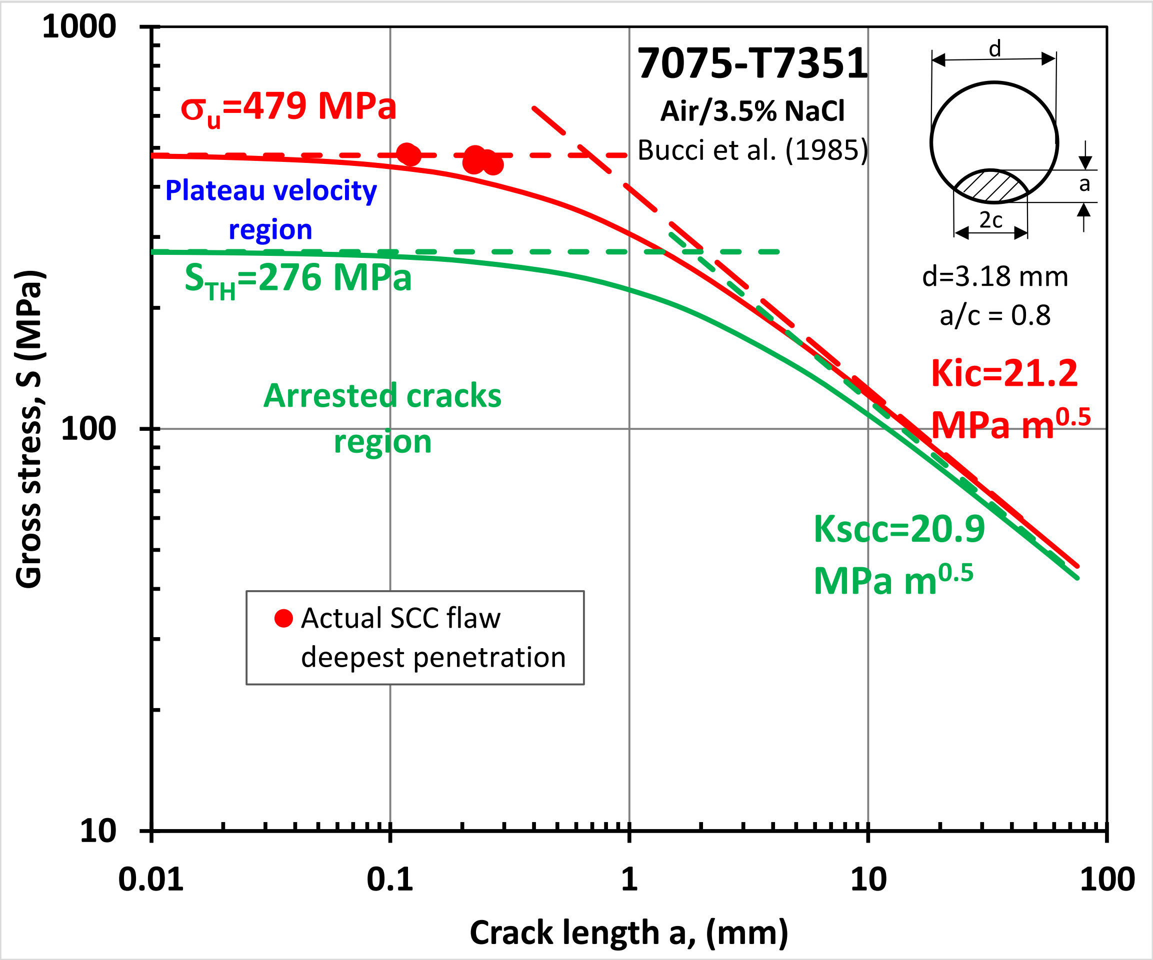
Back-up Slides

Fracture stress vs. SCC flow depth relationship





Fracture stress vs. SCC flow depth relationship



Ratios of σ_0/σ_u for Ti and Al alloys

Alloy	Temp (^oK)	σ_0 (MPa)	σ_u (MPa)	s_u/s_0
Ti-5Al-2.5Sn t=1.6 mm	300	821	887	1.08
	77	1330	1390	1.05
	20	1570	1710	1.09
Ti-5Al-2.5Sn t=1.6 mm	300	727	785	1.08
	77	1230	1300	1.06
	20	1450	1540	1.06
2014-T6 Al t=1.6 mm	300	448	499	1.11
	77	519	598	1.15
	20	554	687	1.24