Fracture Analyses of Thin-Ductile Aerospace Materials

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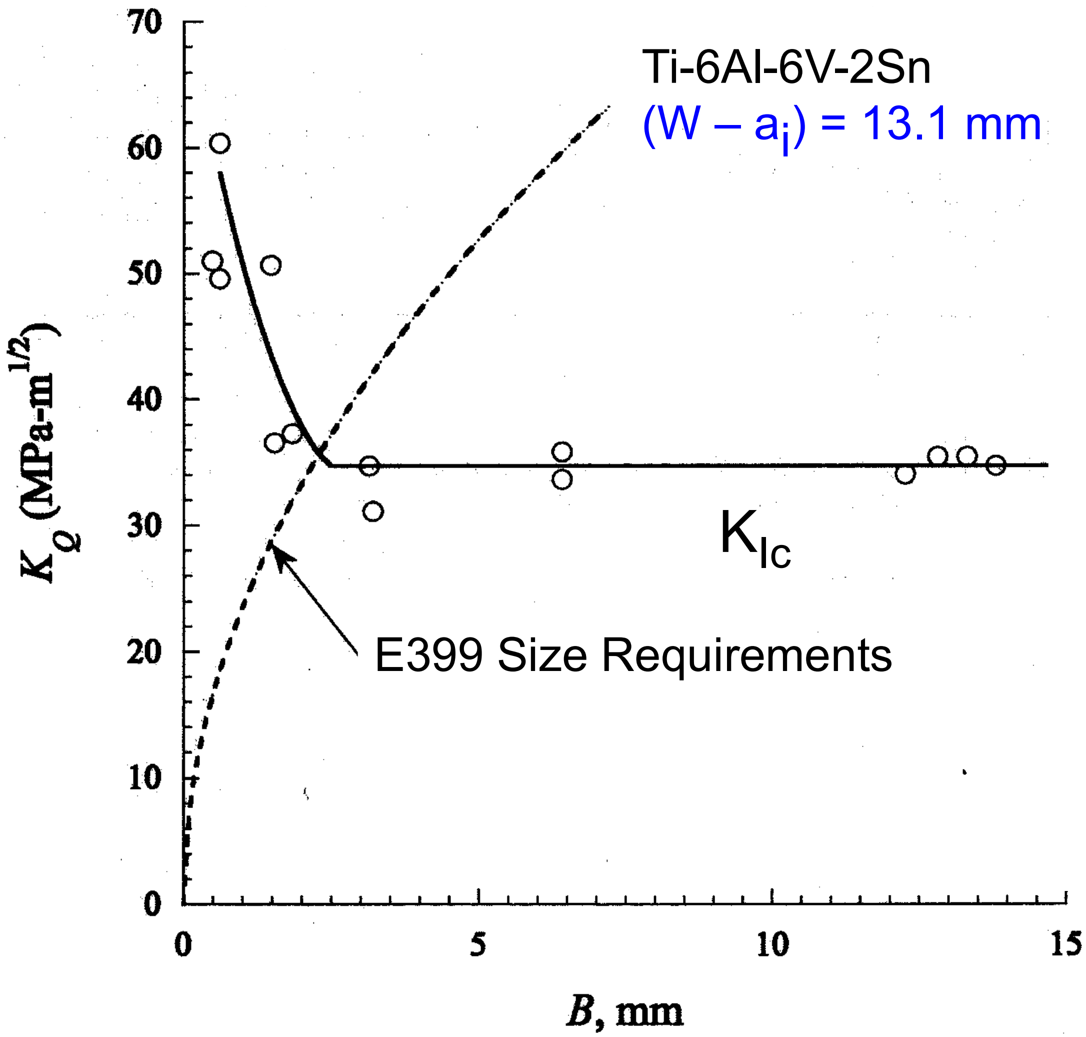
Two-Parameter **Fracture Mechanics for Residual Strength**

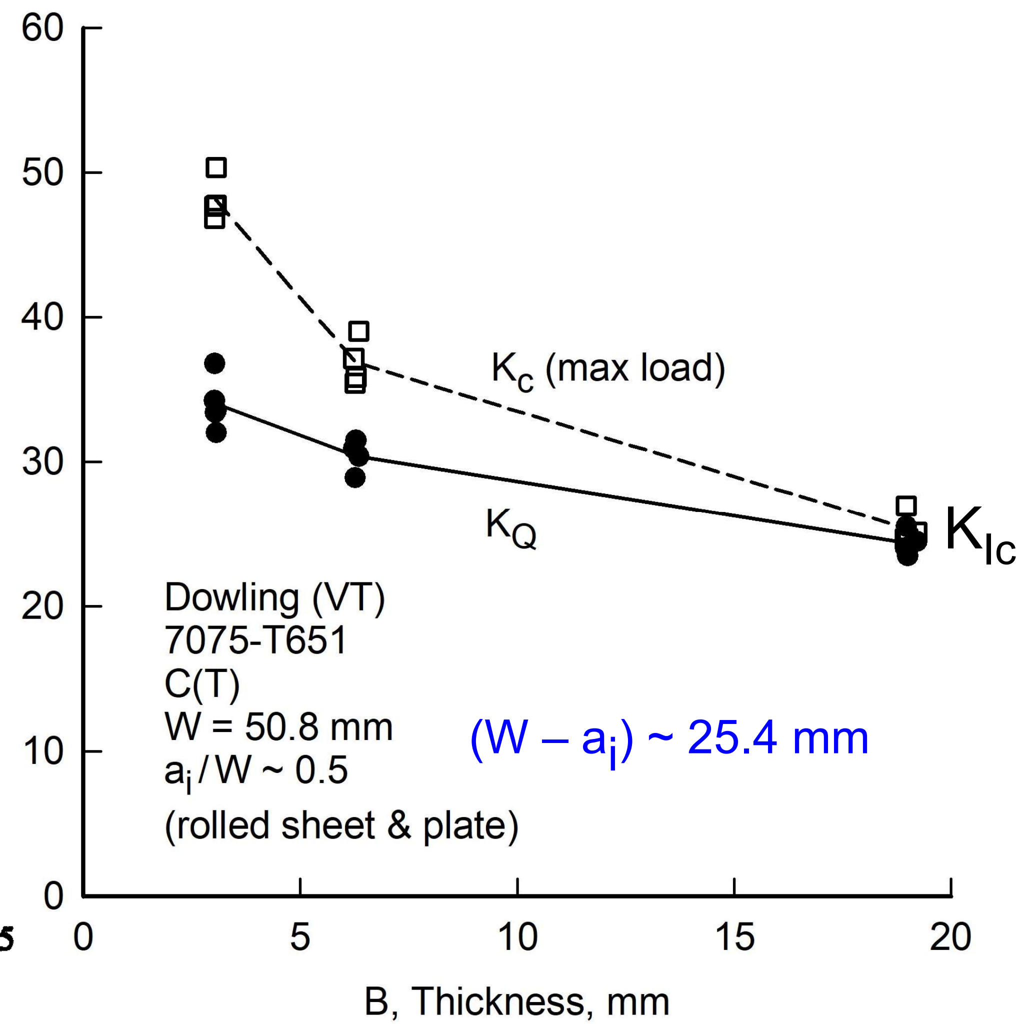
- K_R - Curve (Irwin and Kies, 1954) $K_R \sim C(\Delta a)^n$
- **K_c - *Plane-stress fracture toughness (Irwin, 1957) – not constant***
- K_{Ic}, B - Plane-strain fracture toughness (Brown-Srawley, 1964) →

K_{Ic} Test Results on Two Materials

Jones & Brown, NASA LeRC, 1970



Dowling, VT, ~2000



B is the governing parameter for K_{Ic} and “not” un-cracked ligament (W – a_i)!

Two-Parameter Fracture Mechanics for Residual Strength

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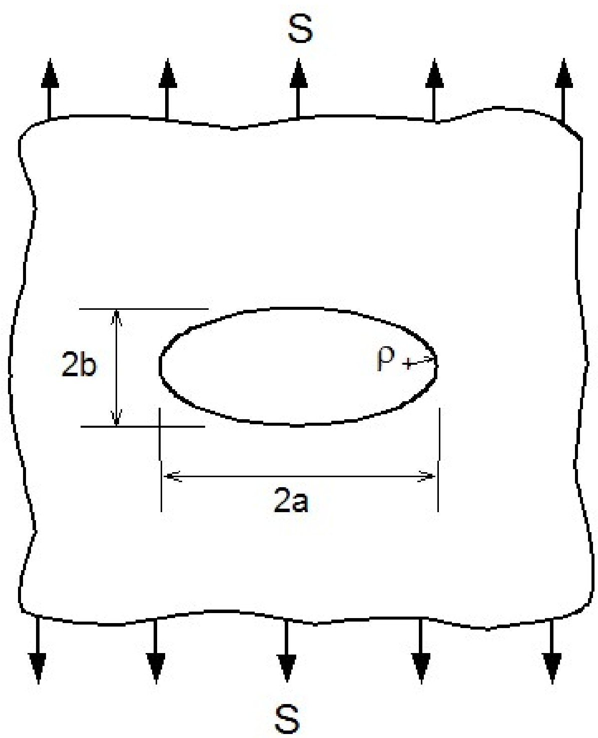
- K_c - *Plane-stress fracture toughness (Irwin, 1957) – not constant*
- K_{Ic}, B - Plane-strain fracture toughness (Brown-Srawley, 1964)
- K_u, ρ' - Notch-Strength Analysis (NSA; Kuhn and Figge, 1964)
- K and T (Larrson & Carlsson, 1973; Hancock et.al., 1991)
- K_F, m - Two-parameter fracture criterion (Newman, 1973)
- Two-criteria (K & S) approach (Dowling and Townley, 1975)
- J_R - Curve (Albrecht et.al., 1982) $J_R \sim C(\Delta a)^n$
- J and Q (Shih & O'Dowd, 1990)
- CTOA (ψ_c) and PSC (plane-strain core) (Newman et.al., 1993)
- J and Stress tri-axiality parameter (Brocks et.al., 1995)

Modern Fracture Mechanics

Inglis (1913)
Griffith (1920)



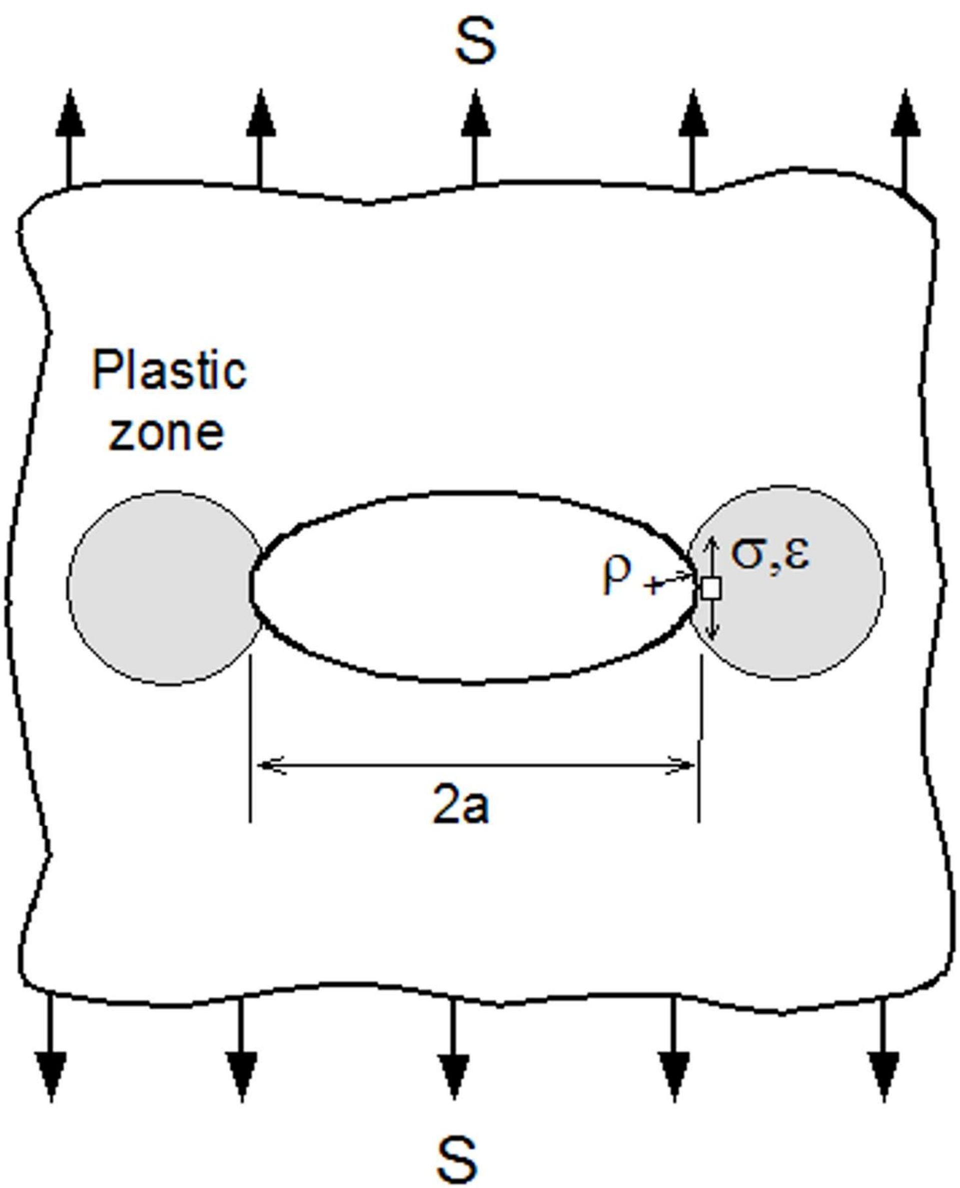
$$K_T = 1 + 2\sqrt{a/\rho}$$

$$\sigma_e = S + 2S\sqrt{a/\rho}$$

Paul Kuhn
Notch Strength Analysis

George Irwin
Fracture Mechanics

Elastic-Plastic Stress- and Strain-Concentration Factors using Neuber's Equation



Neuber (1961):

$$K_\sigma K_\varepsilon = K_T^2$$

$$\sigma \, \varepsilon \, E = \sigma_e^2$$

Crews (1974) experimentally validated Neuber's equation for ***elliptical hole*** in finite plate under remote uniform stress

Hutchinson (1968) showed that the stress-strain field for a ***crack*** in a non-linear elastic material verified Neuber's equation

Two-Parameter Fracture Criterion (Newman, 1973)

- Inglis' stress-concentration equation for elliptical hole:

$$K_T = 1 + 2 \sqrt{(c/\rho)}$$

- Neuber's equation: $K_\sigma K_\varepsilon = K_T^2$

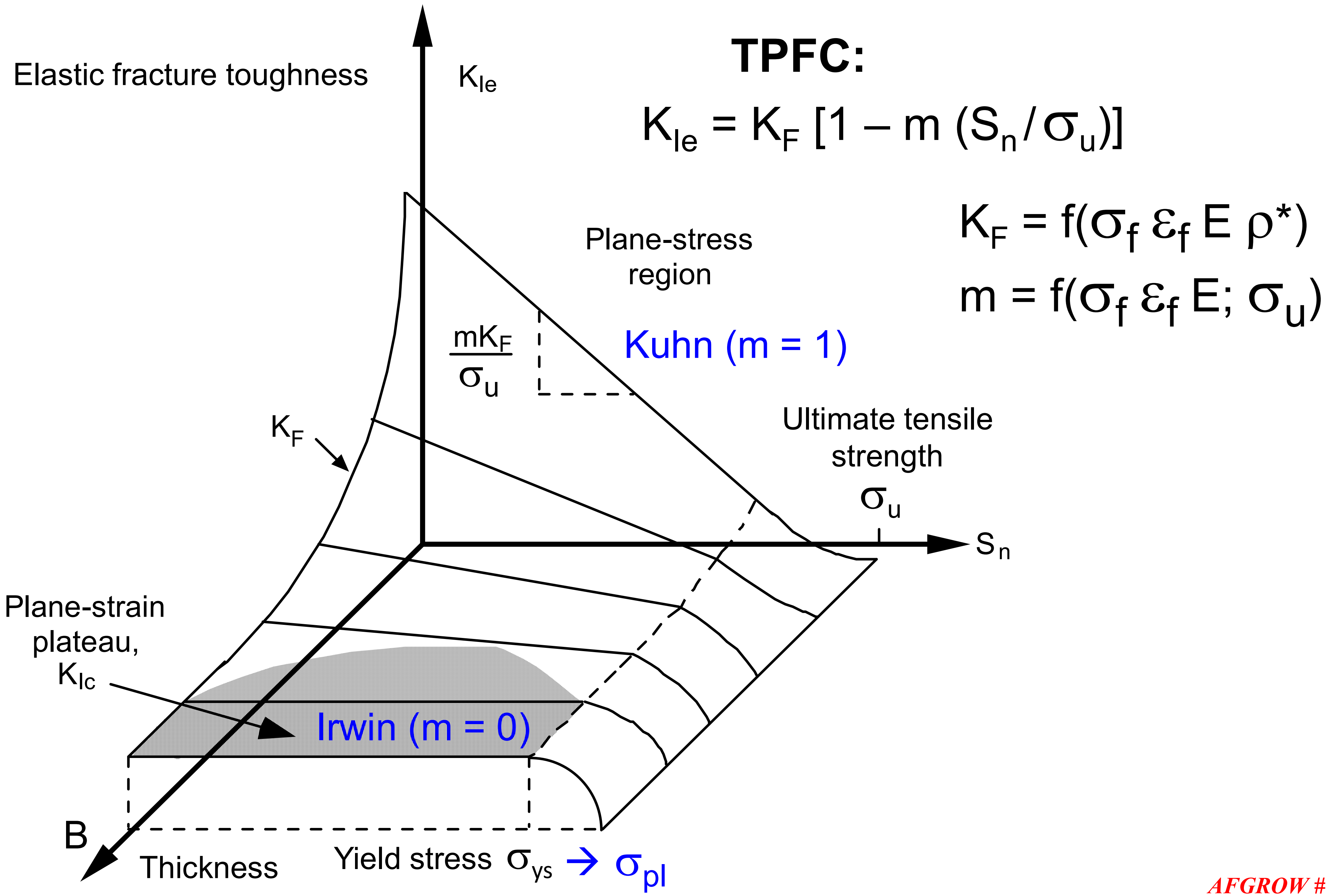
$$K_F = K_{Ie} / \Phi$$

$$\Phi = 1 - m\,(S_n / \sigma_u) \quad \text{for} \;\; S_n < \sigma_{ys} \quad \rightarrow \sigma_{pl}$$

$$\Phi \approx (\sigma_{ys} / S_n)\,[1 - m\,(S_n / \sigma_u)] \quad \text{for} \;\; S_n \geq \sigma_{ys}$$

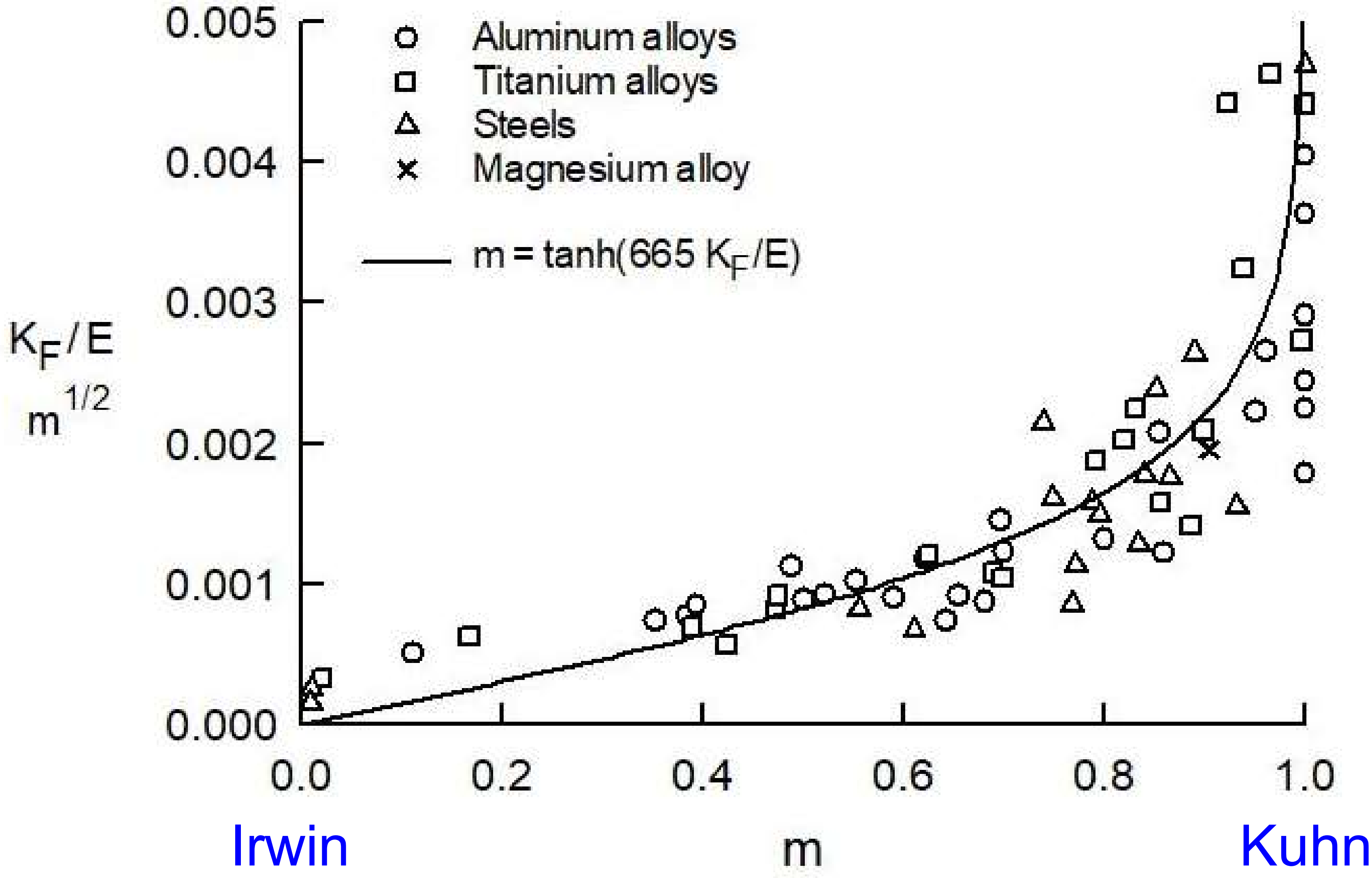
Simple approximation for "*tension*"—more work needed, especially for "*bending*".

Fracture Locus for Thin Sheet to Thick Plate Materials

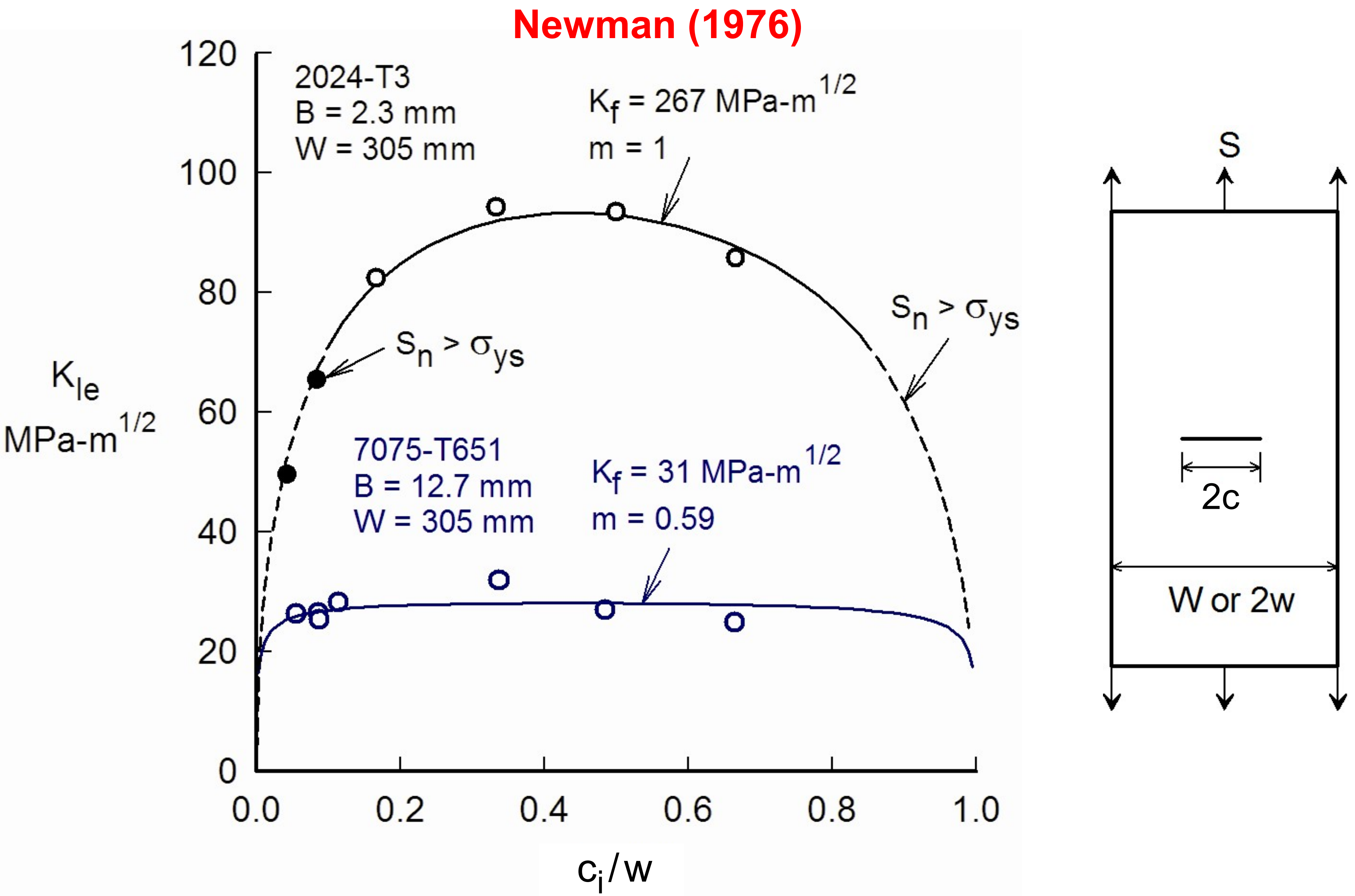


Relationship between K_F/E and m for Wide Variety of Materials for *Through- and Surface-Crack* Configurations

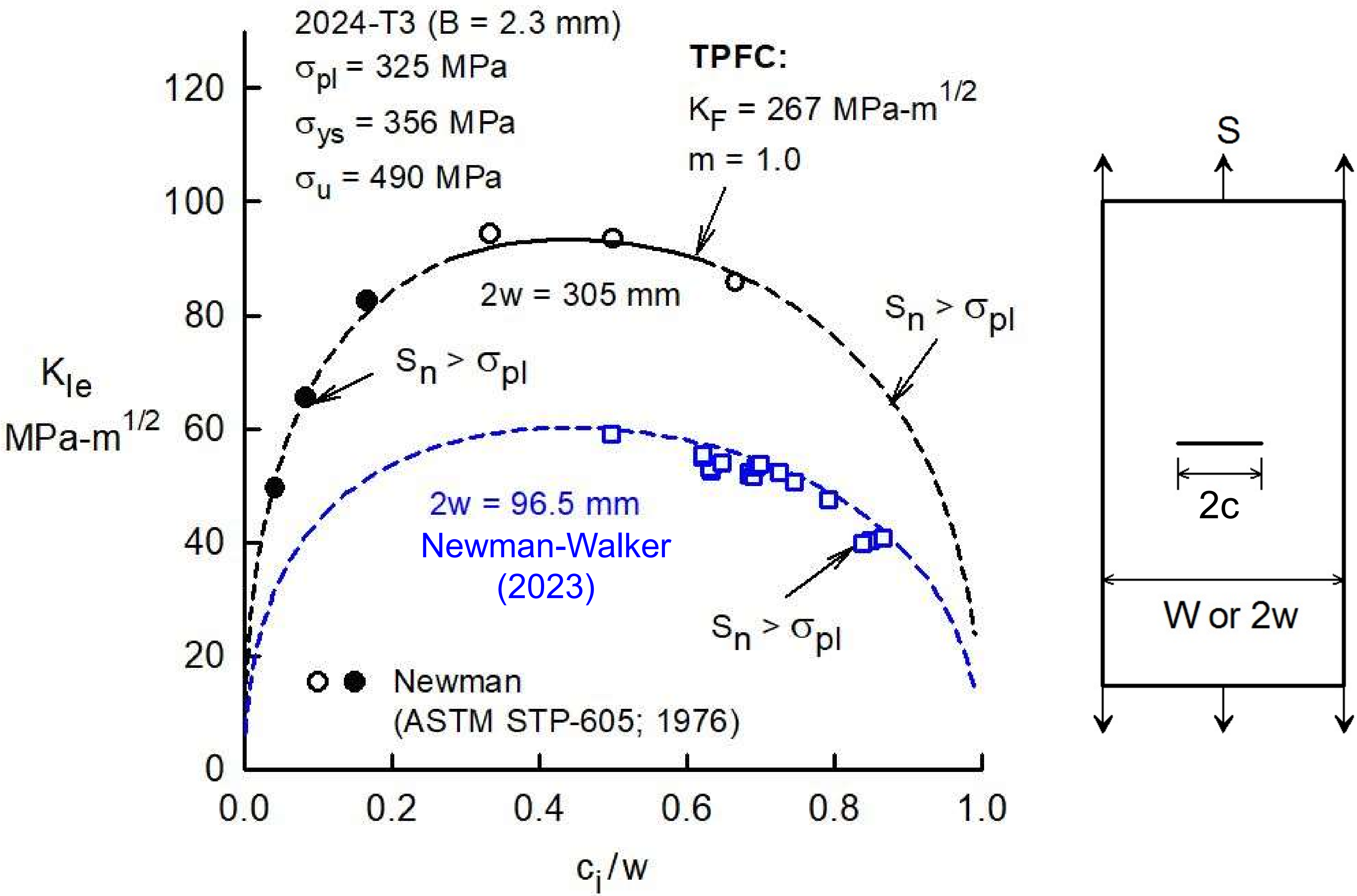
Newman (1973)



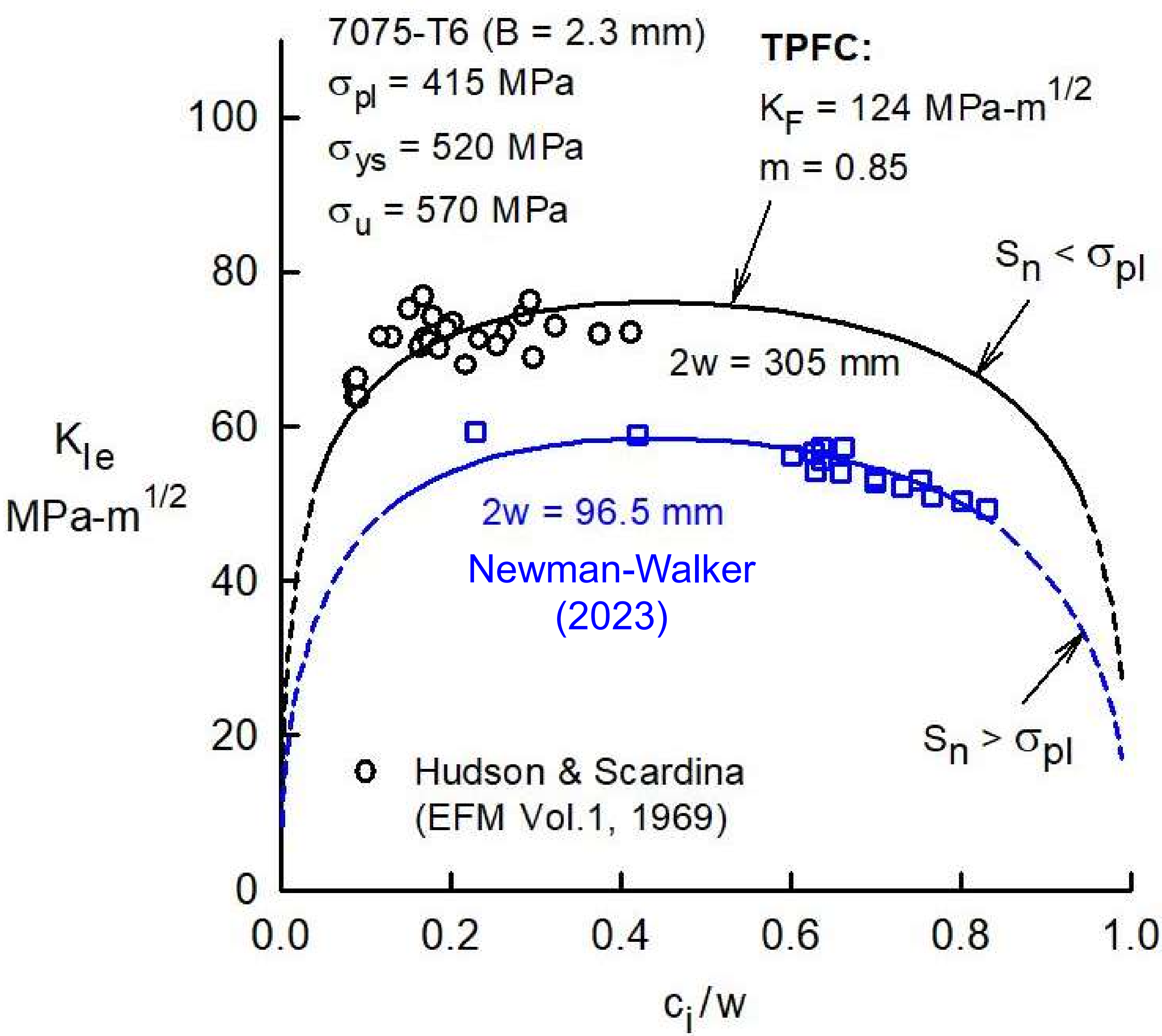
Fracture of 2024-T3 Thin Sheet and 7075-T651 Thick Plate M(T) Specimens for Large Width

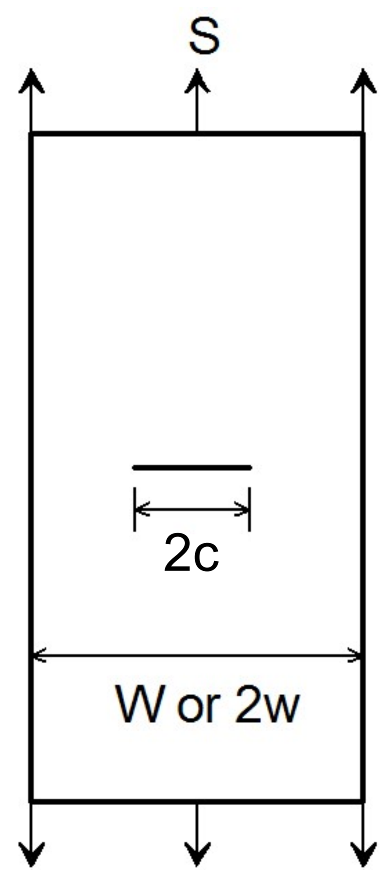


Fracture of 2024-T3 Thin Sheet M(T) Specimens for Two Widths



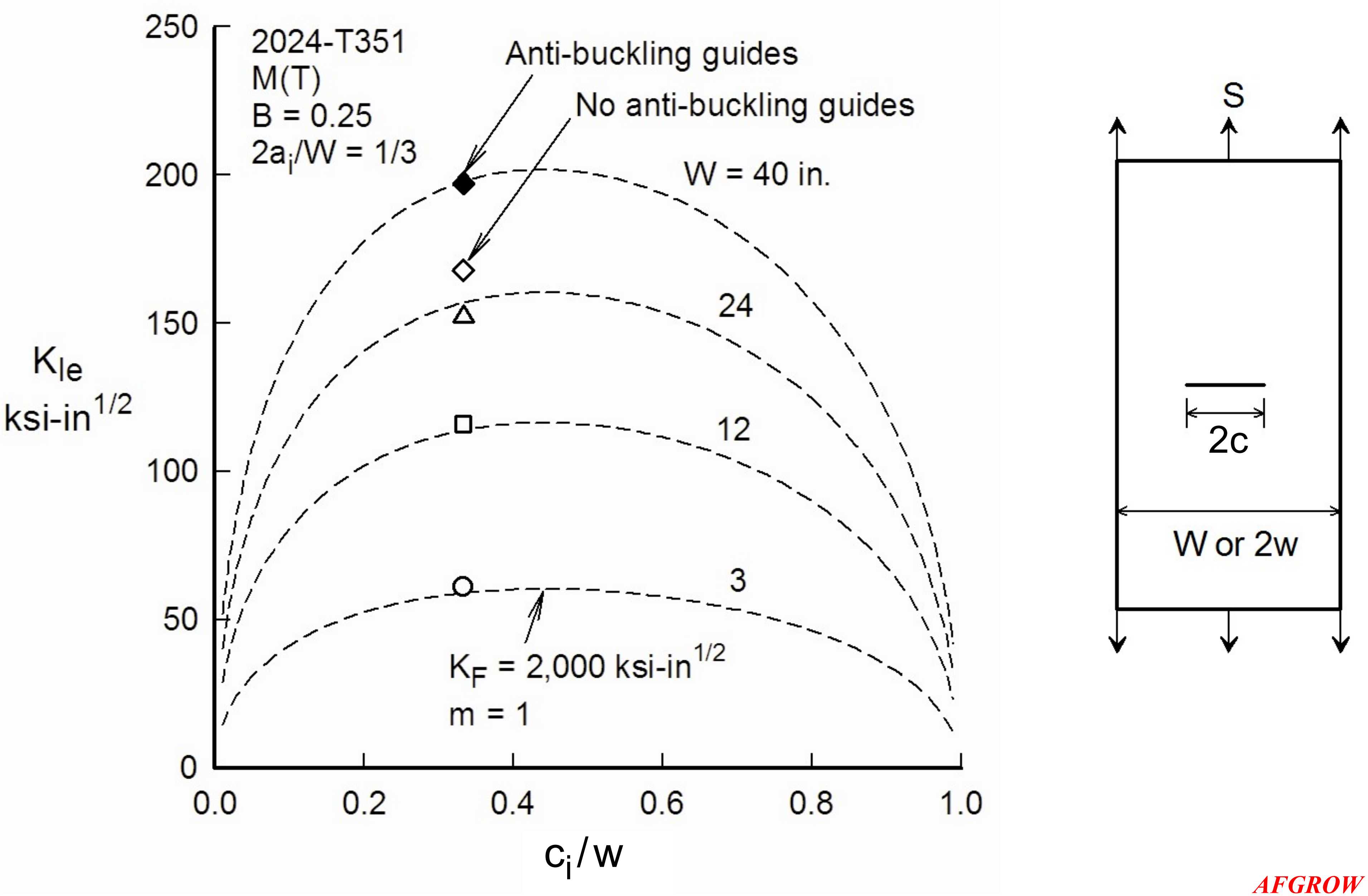
Fracture of 7075-T6 Thin Sheet M(T) Specimens for Two Widths





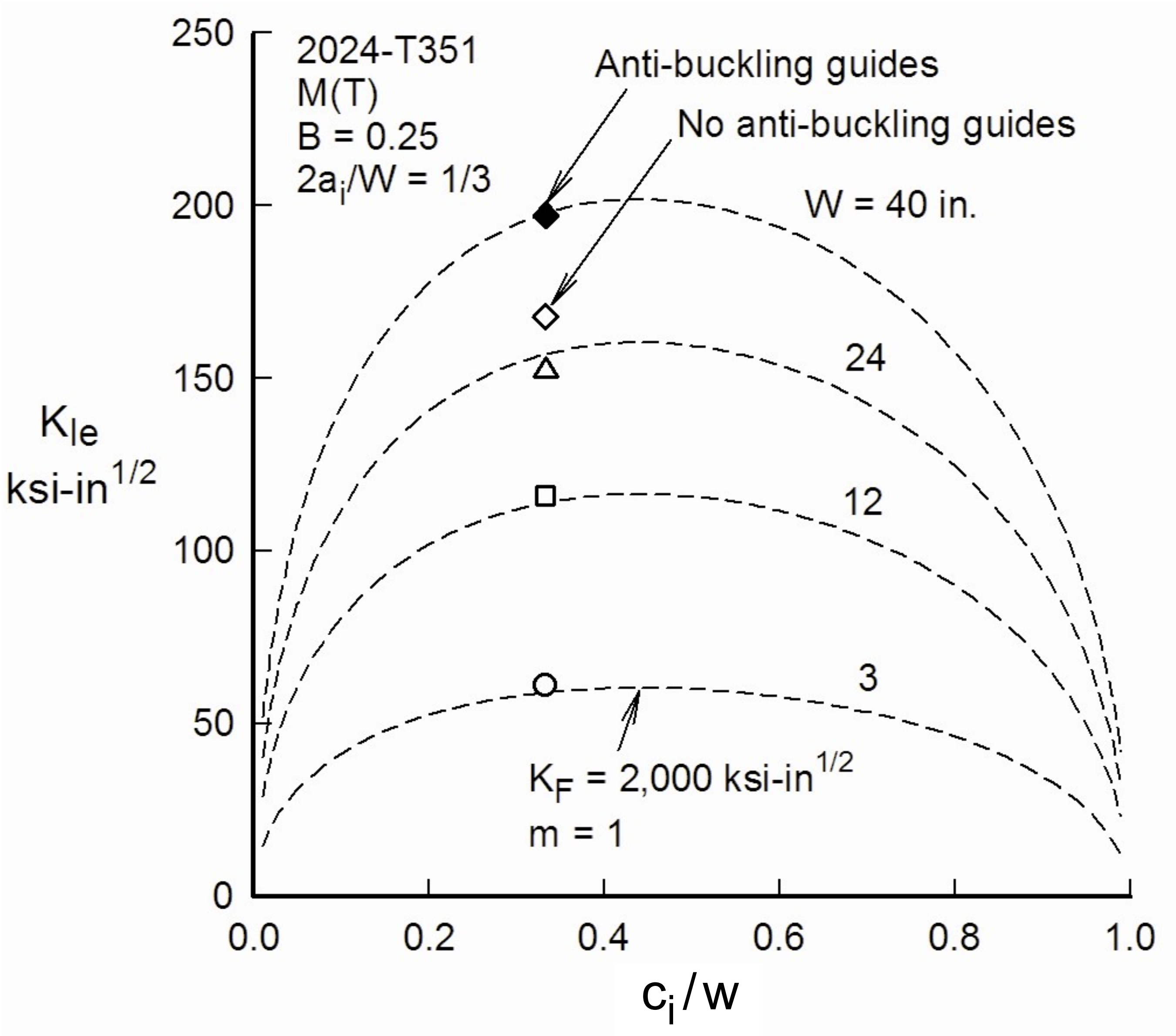
Fracture of 2024-T351 Small- and Large-M(T) Specimens

(Note: All tests and analyses have $S_n > \sigma_{ys}$)



Fracture of 2024-T351 Small- and Large-M(T) Specimens (2)

(Note: All tests and analyses have $S_n > \sigma_{ys}$)



TPFC:

Tension $S_n > \sigma_{ys}$

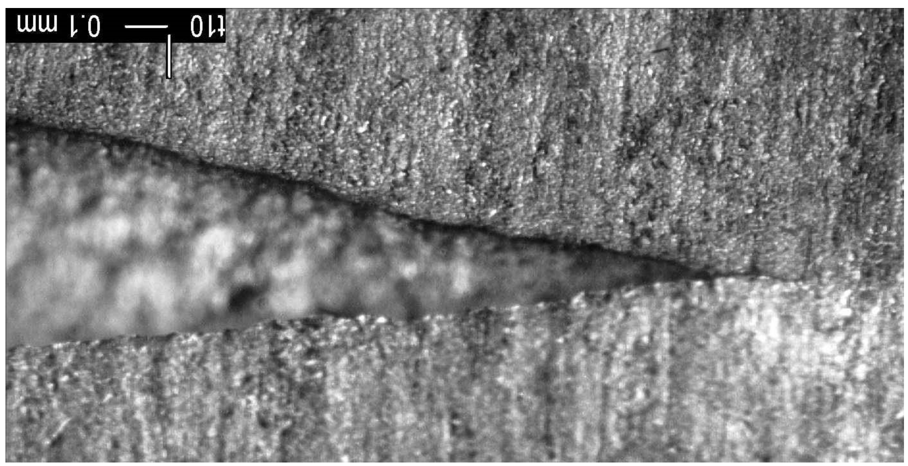
$$S_n = \frac{\sigma_u}{1 + K_{Ie}/K_F}$$

$K_F \rightarrow \infty$

$S_n \rightarrow \sigma_u$

Stress failure criterion!

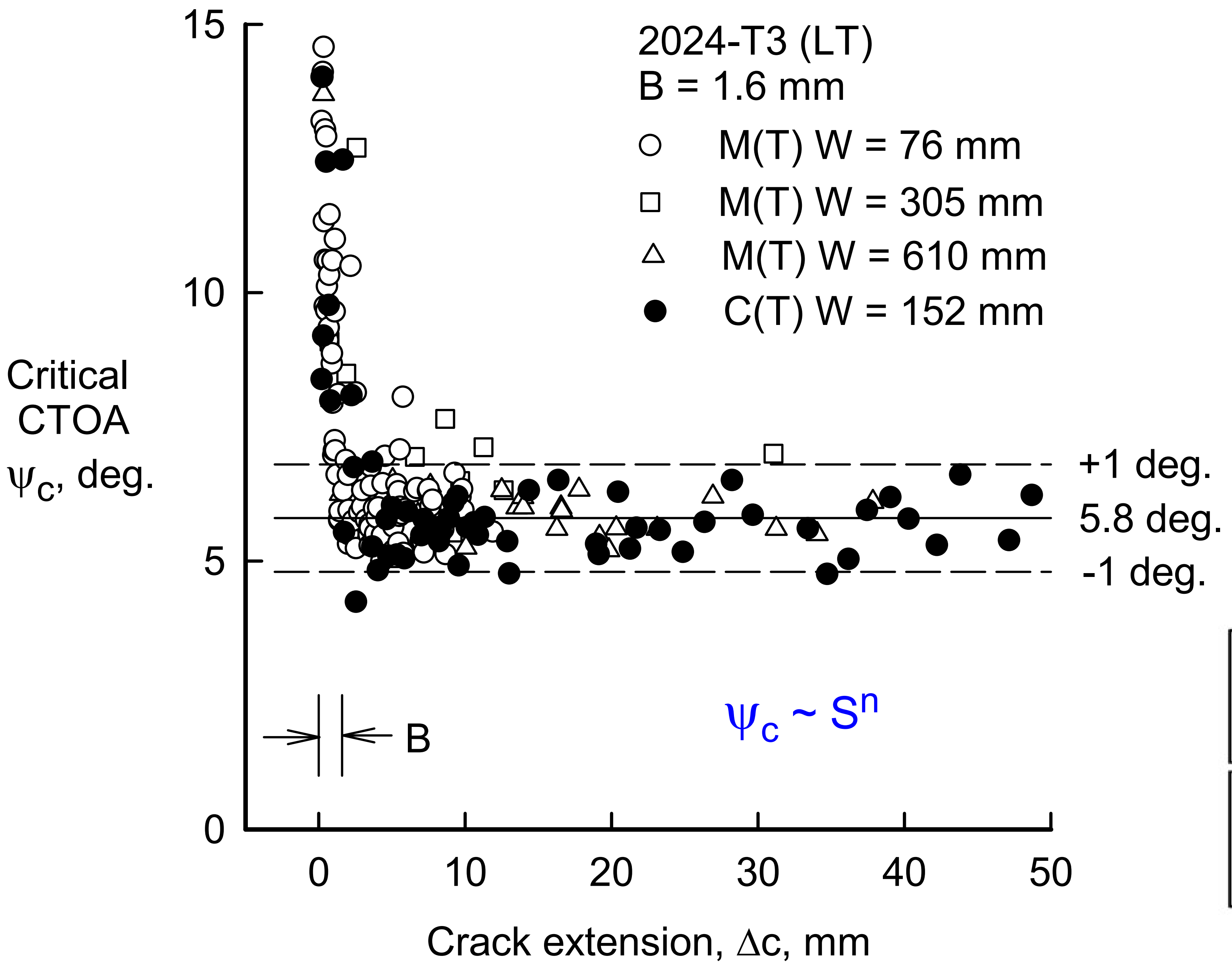
Fracture Simulations using Elastic-Plastic Finite-Element Analyses and Critical CTOA

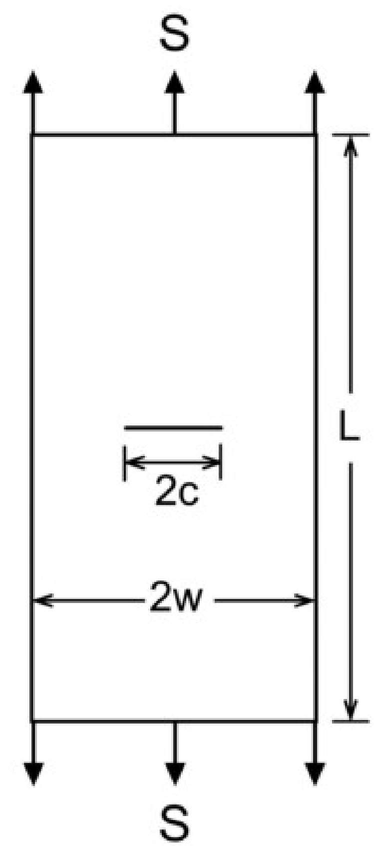


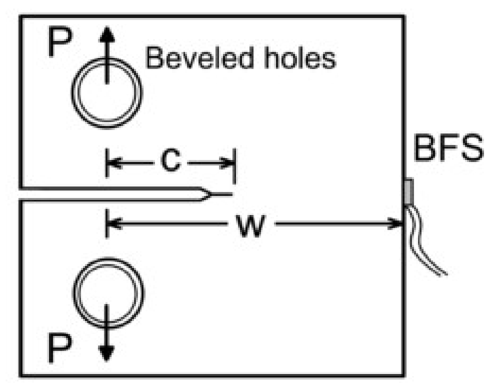
Prof. C.T. Sun (1995)
Purdue University
Mild steel

Measured Critical Crack-Tip-Opening Angles (CTOA)

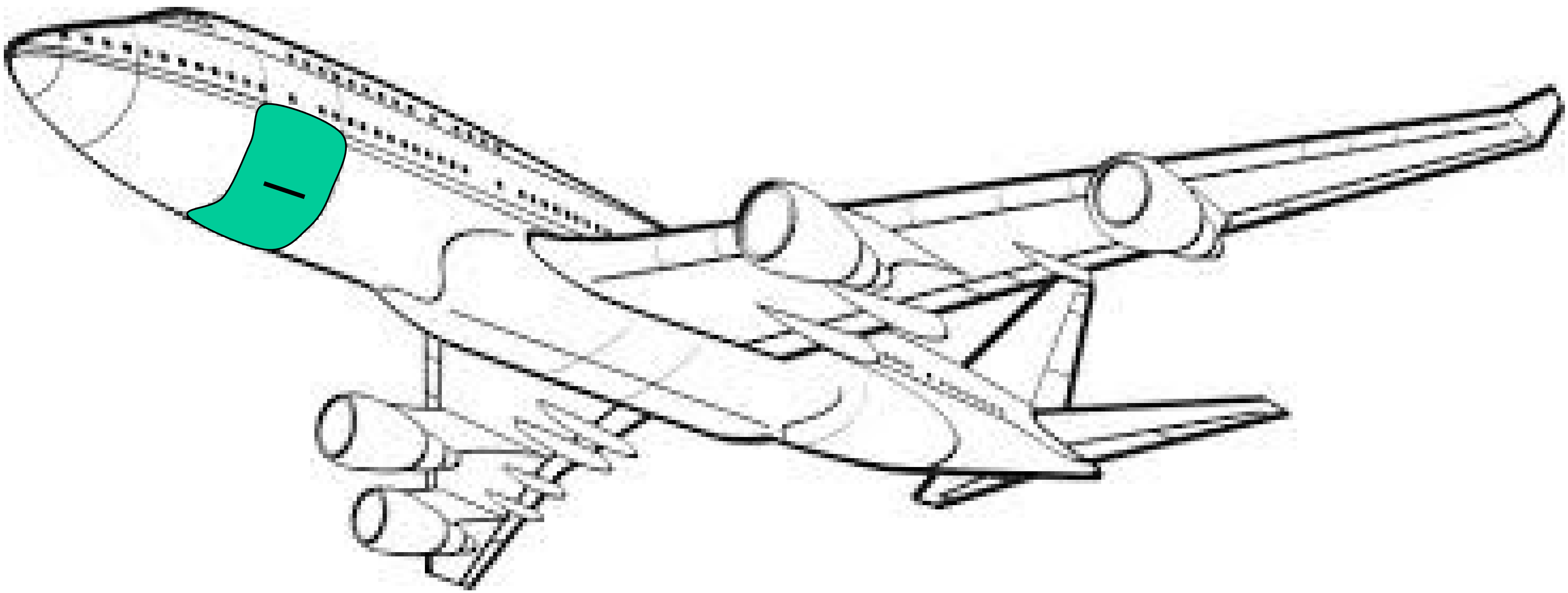
Newman and Dawicke (1993)







Why are "large" cracked panels important?



STAGS and
^
Hsu et al., "Residual Strength Analysis using CTOA Criteria for Fuselage Structures containing Multiple-Site Damage, Engineering Fracture Mechanics, Vol. 70, 2003.

Predicted internal pressure to fail damaged DC-9 fuselage at WPAFB was within 4% of the test pressure at failure

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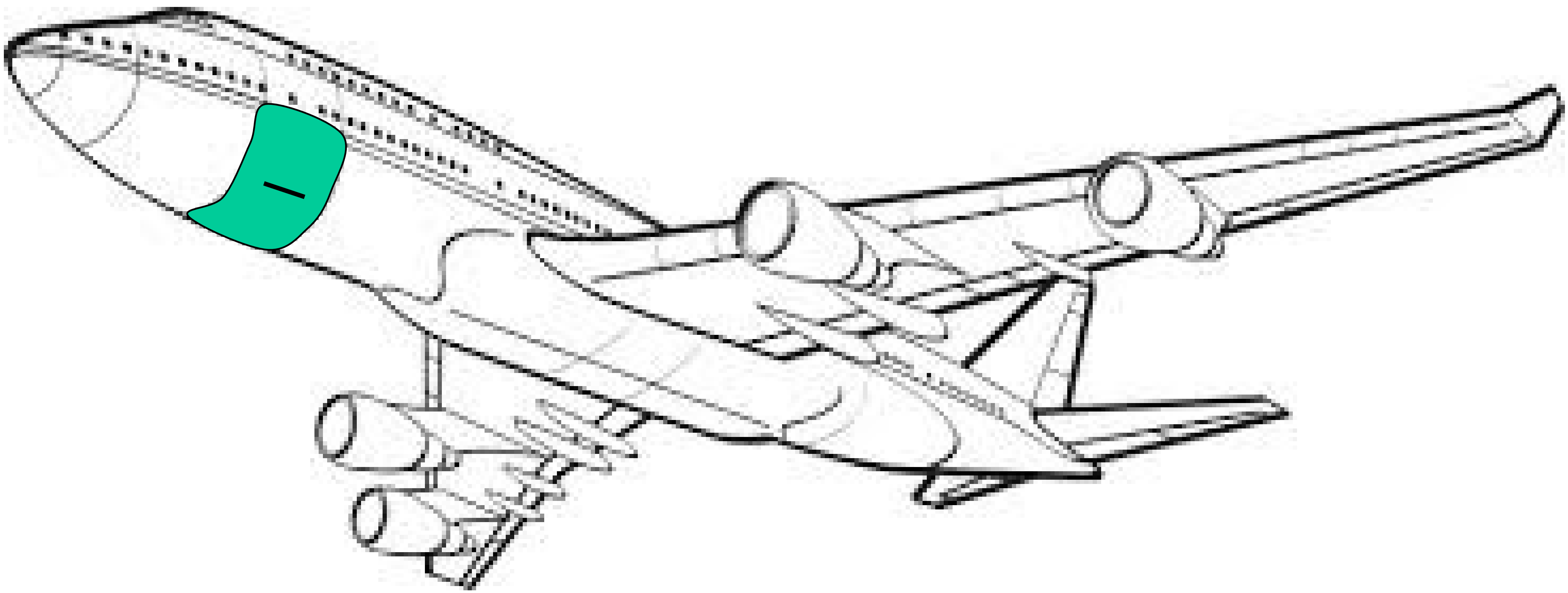

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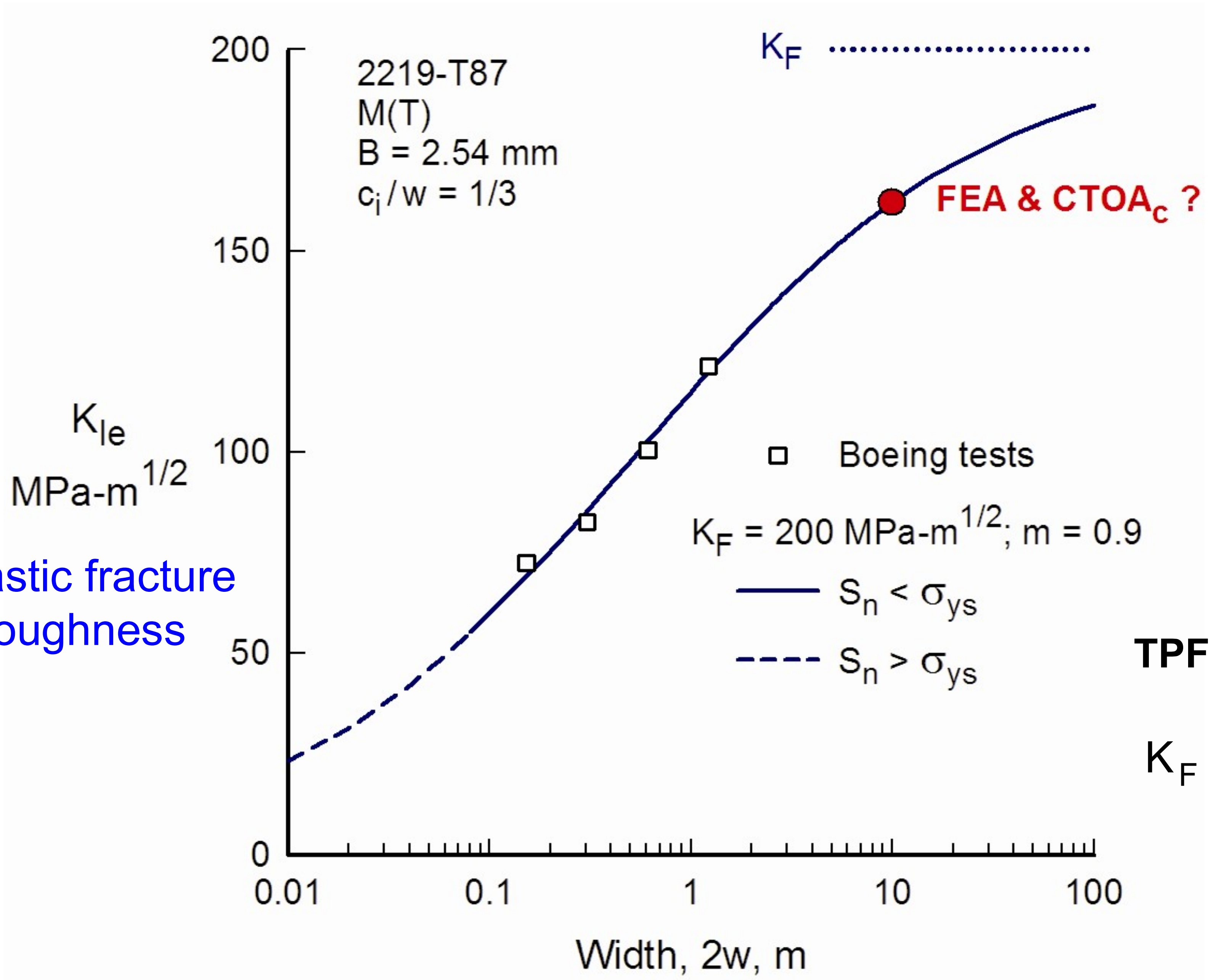
Predicted internal pressure to fail damaged DC-9 fuselage at WPAFB was within 4% of the test pressure at failure, **before the test was ever conducted !!!**

Experimental and Analytical Relationship between K_{Ie} and Specimen Width at Constant c_i/w Ratio



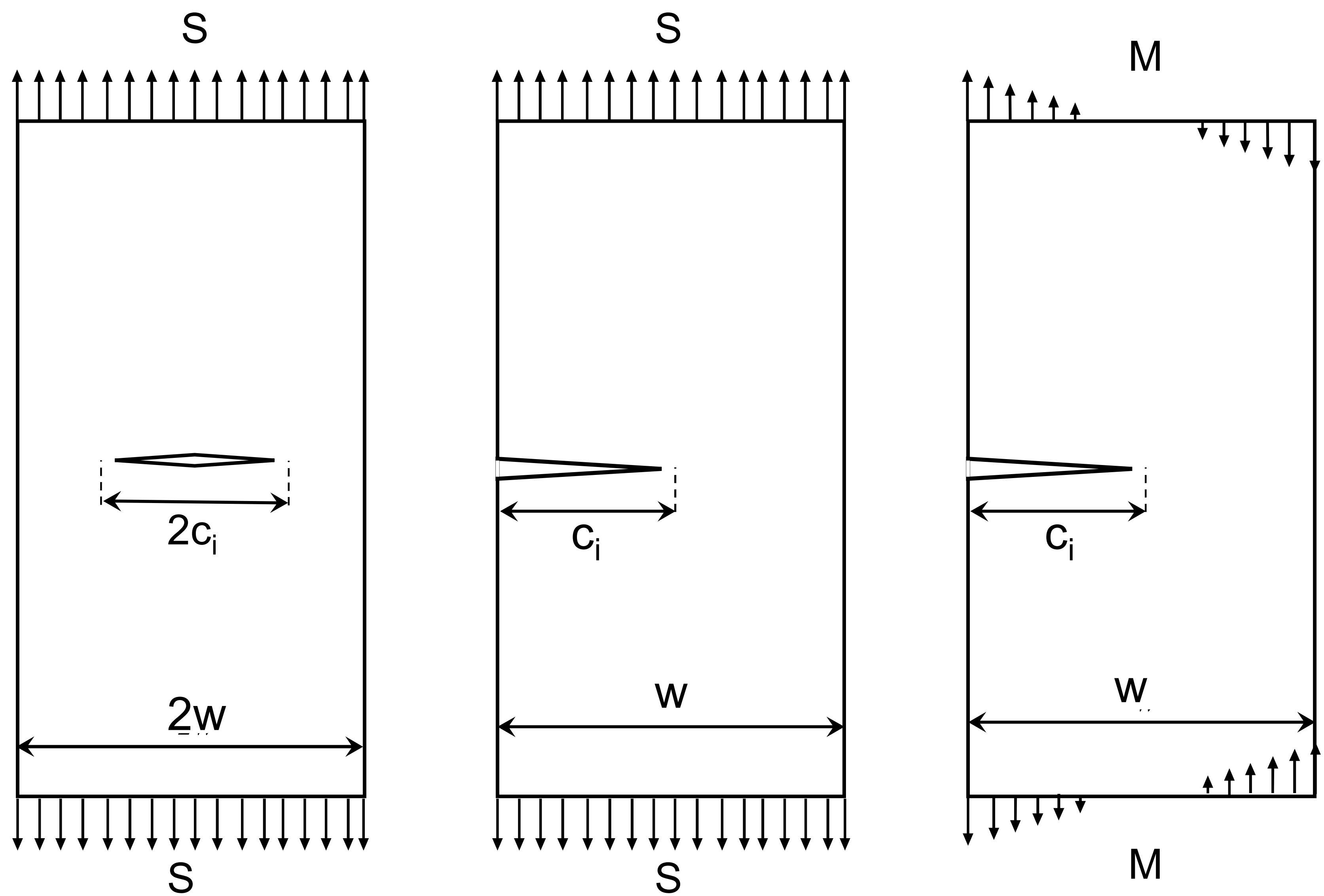
Elastic fracture toughness

TPFC (1973):

$$K_F = \frac{K_{Ie}}{1 - m\,(S_n/\sigma_u)}$$

$$S_n < \sigma_{ys}$$

Crack Configurations Analyzed

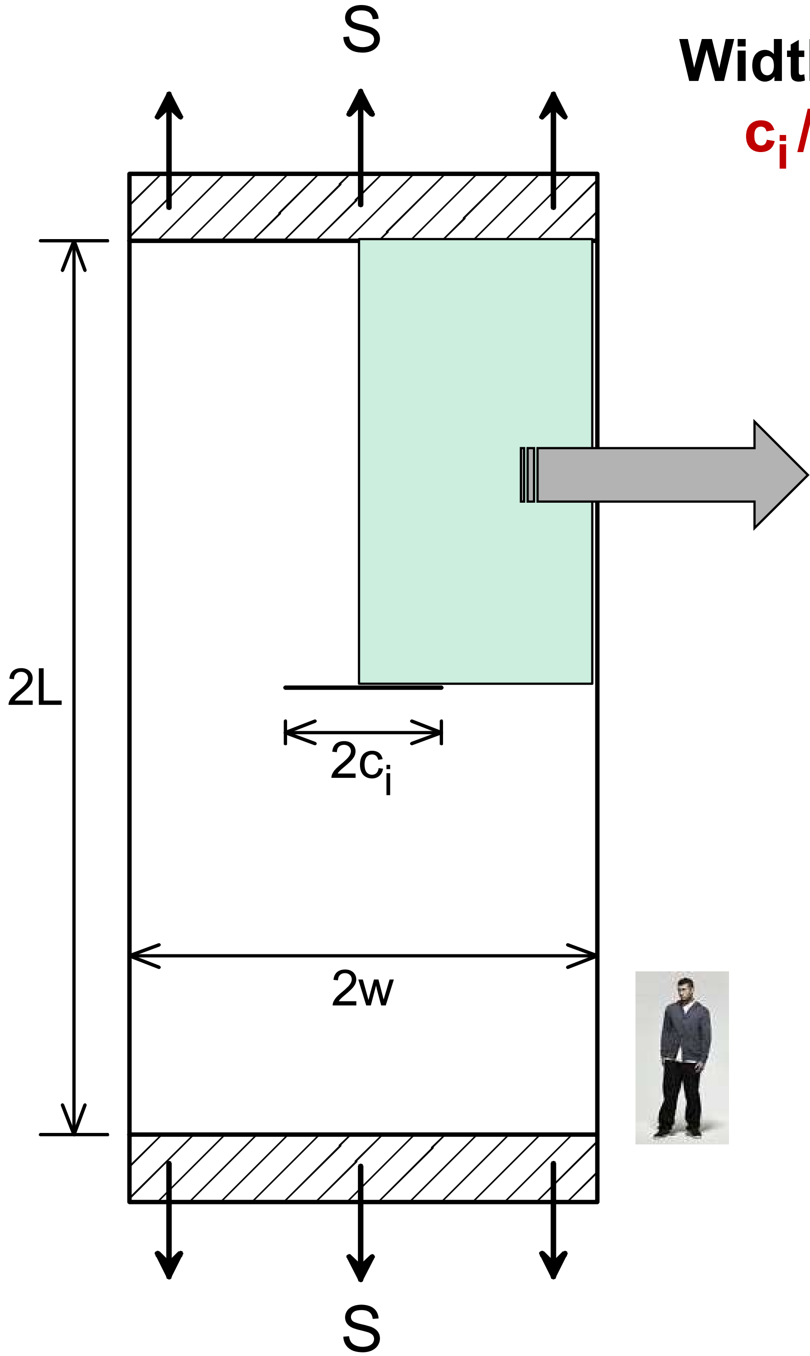


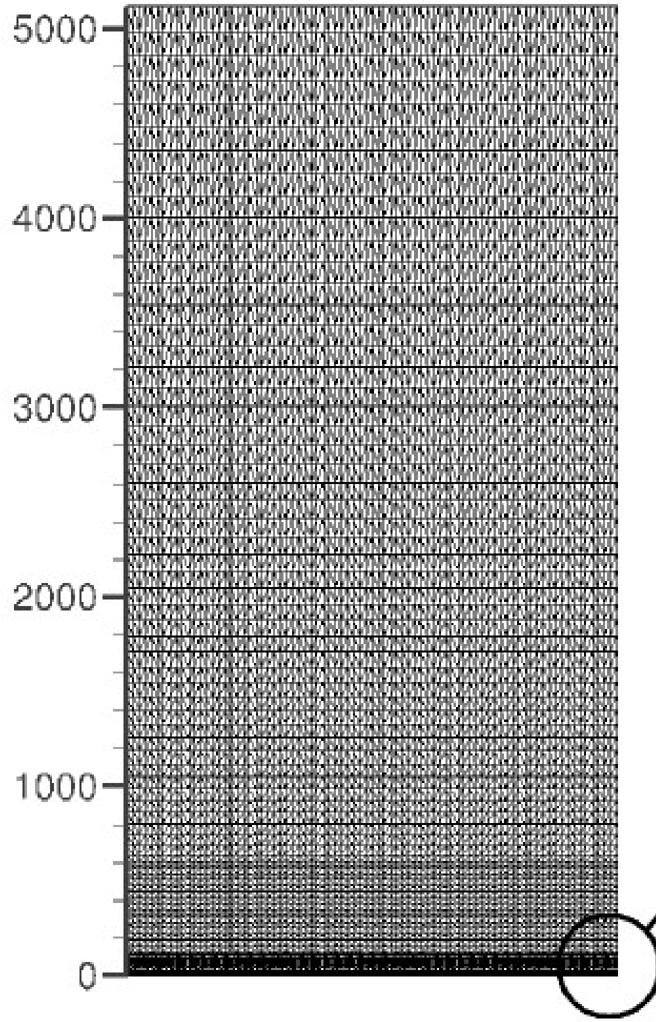
(a) Middle tension (b) Single-edge tension (c) Single-edge bending

Largest M(T) Specimen Model and Normal Size Man

Width = 2w = 60 to 4,880 mm (2.4 in. to 16 ft)

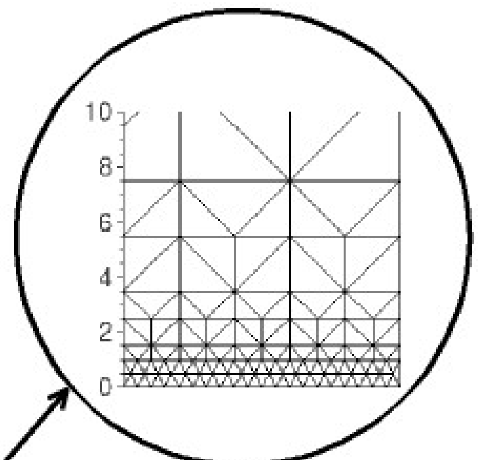
c_i / w = 0.05 to 0.95





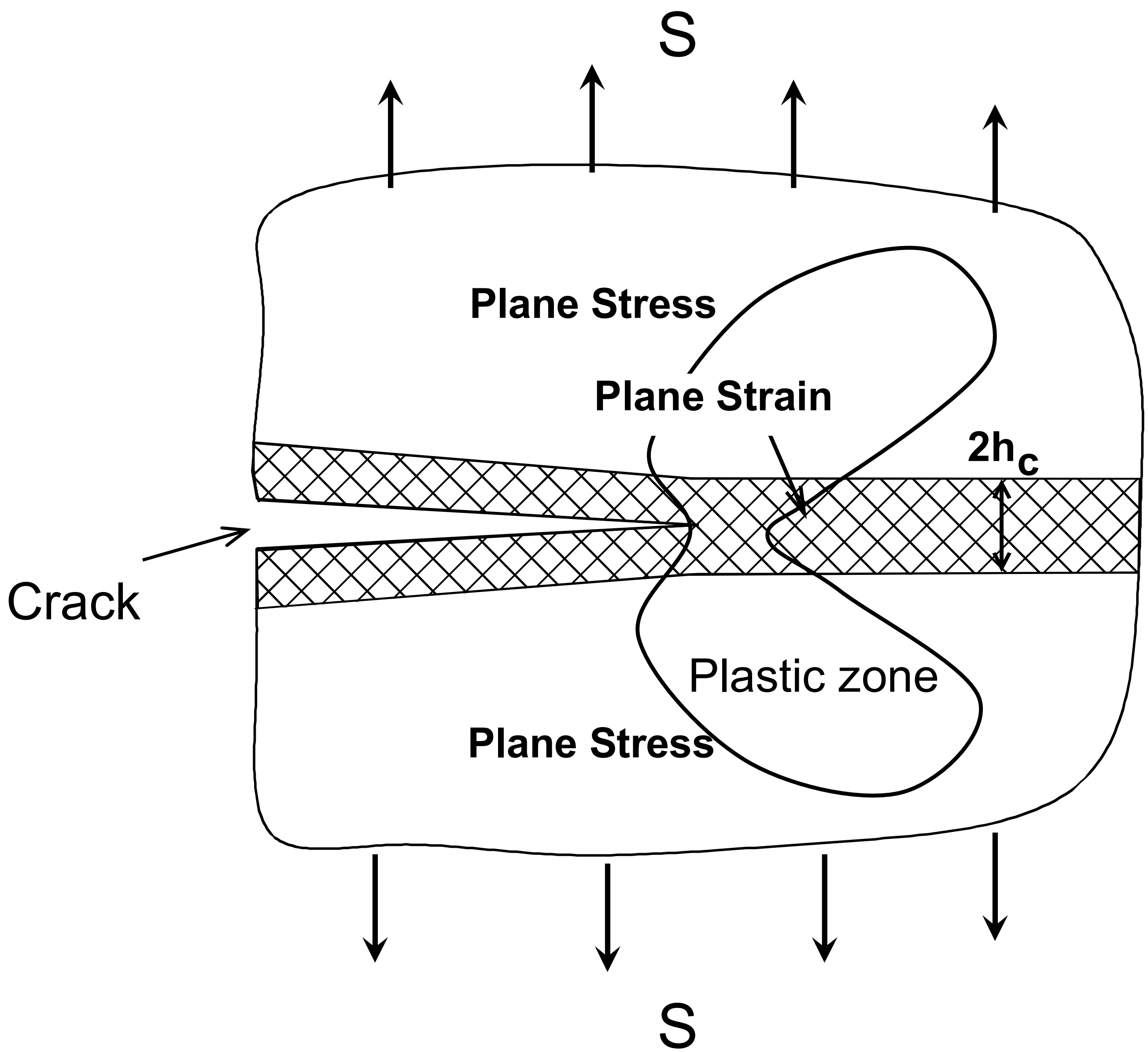
(a) One-quarter model

ZIP2D:
~ 57000 elements
~ 31000 nodes



(b) Local mesh pattern

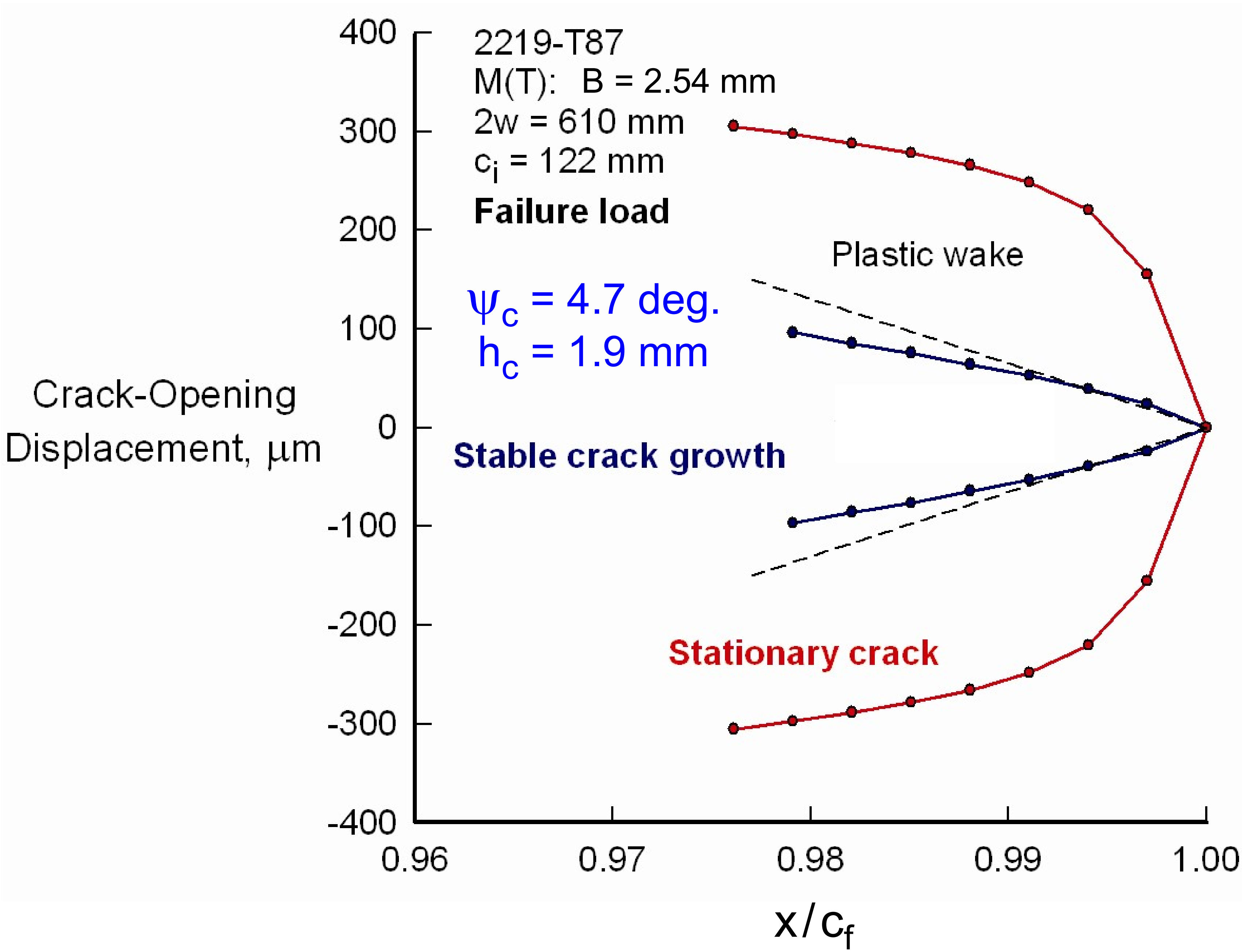
Plane-Strain Core in Plane-Stress Finite-Element Models



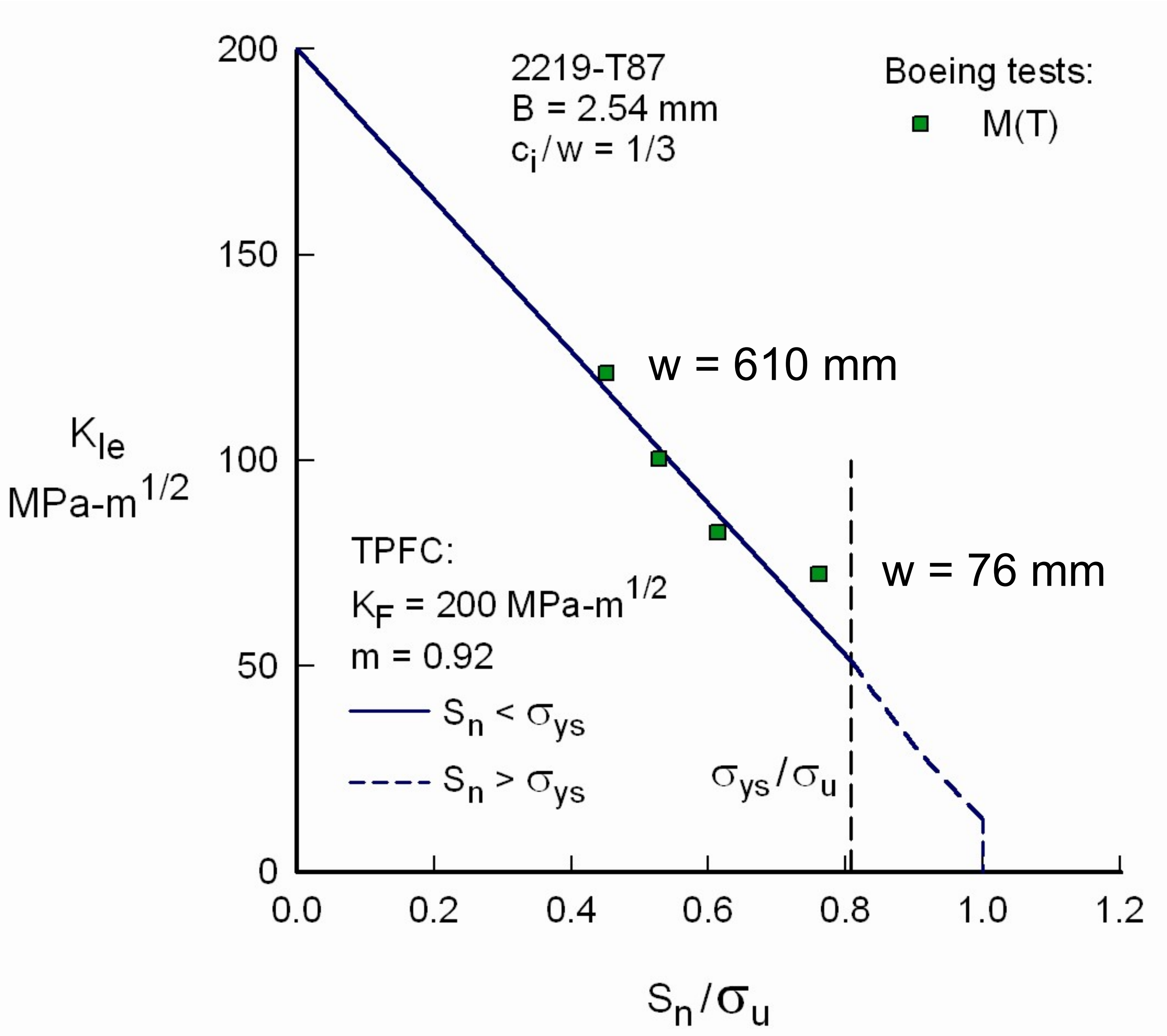
<u>Finite-element codes:</u>

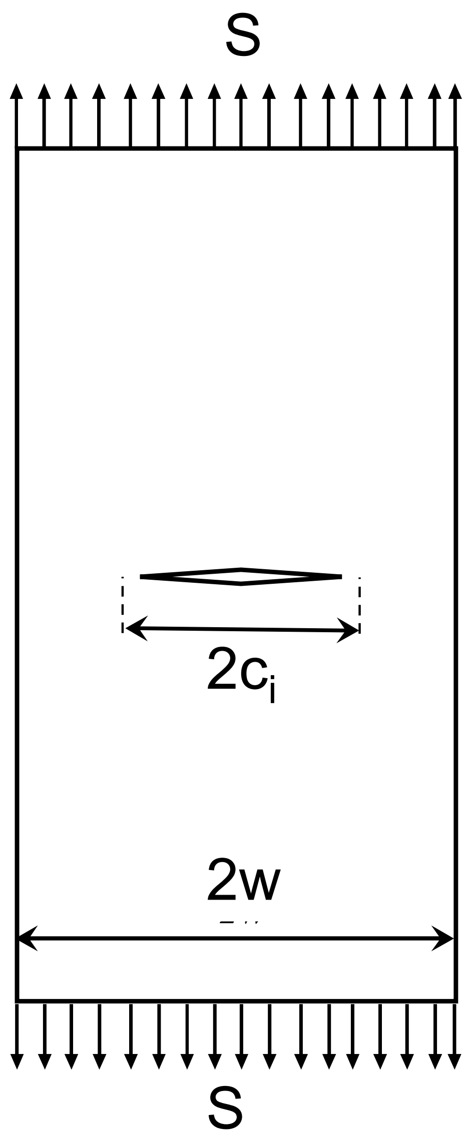
- **ZIP2D**
- **STAGS**
- **FEA – C.T. Sun (Purdue Univ.)**

Crack-Opening Displacements for Stationary and Stably Tearing Crack



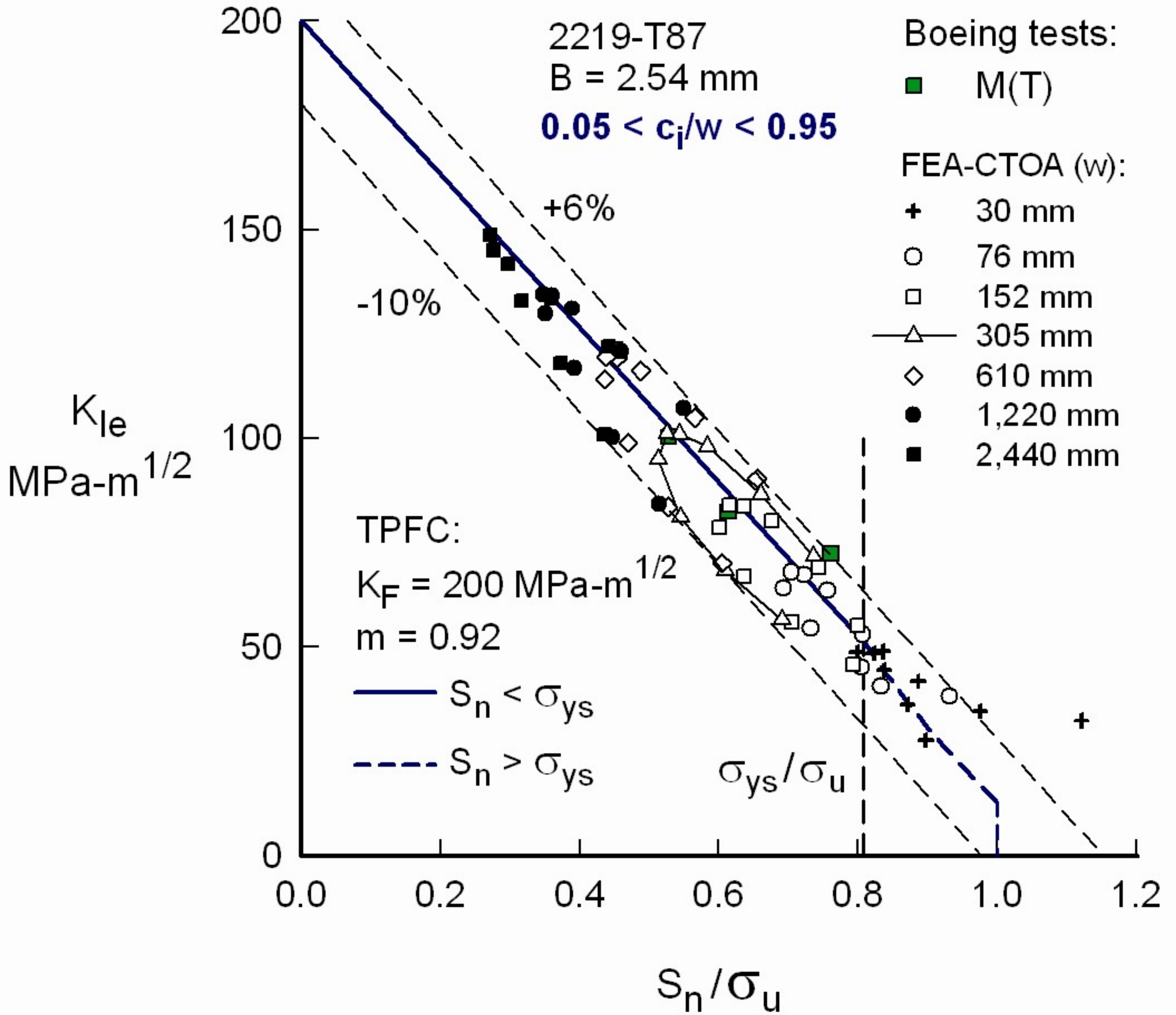
Two-Parameter Fracture Criterion (TPFC) Analysis on 2219-T87 Aluminum Alloy M(T) Specimens

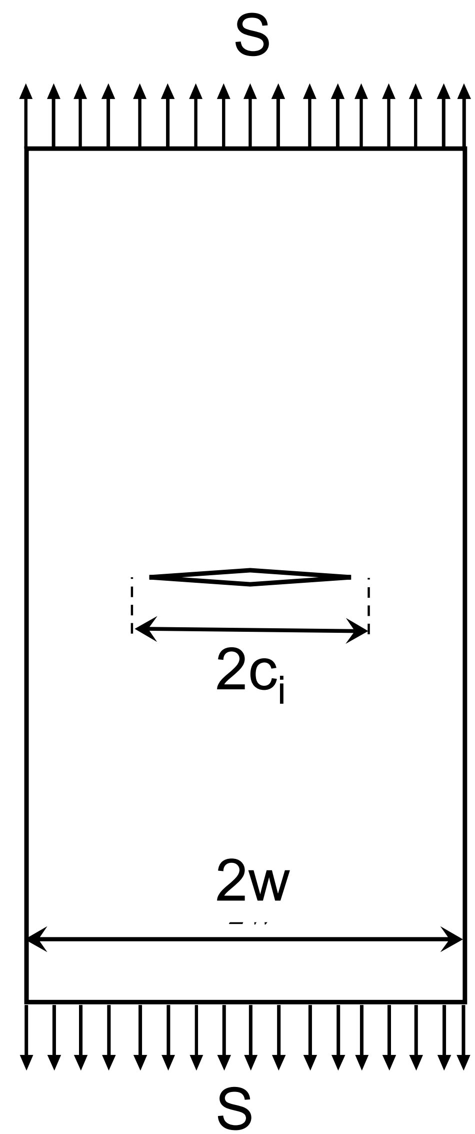




Elastic Stress-Intensity Factor at Failure for Wide Range of *Middle-Crack Tension* Specimens

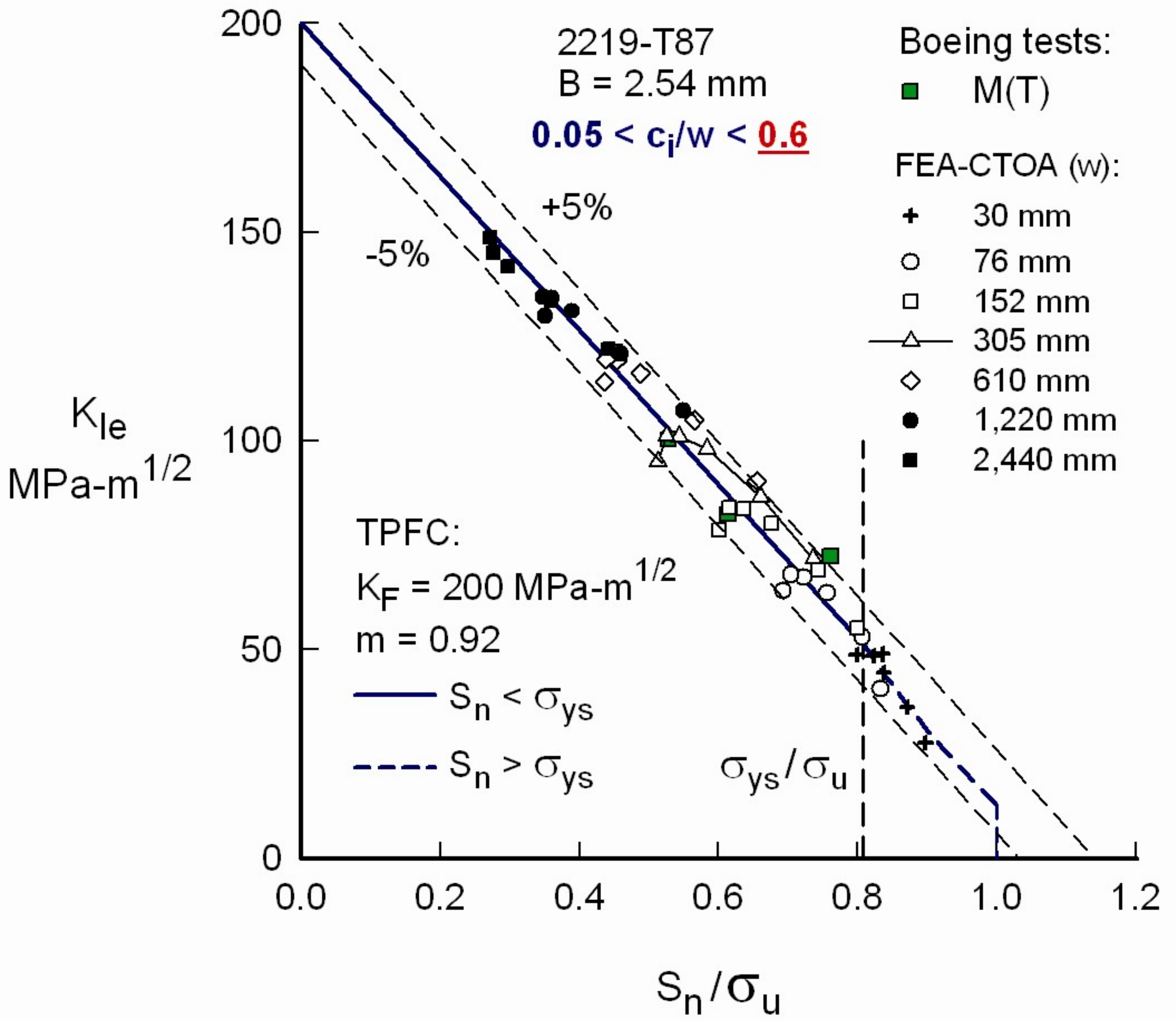
Mahtabi et.al. (2015)

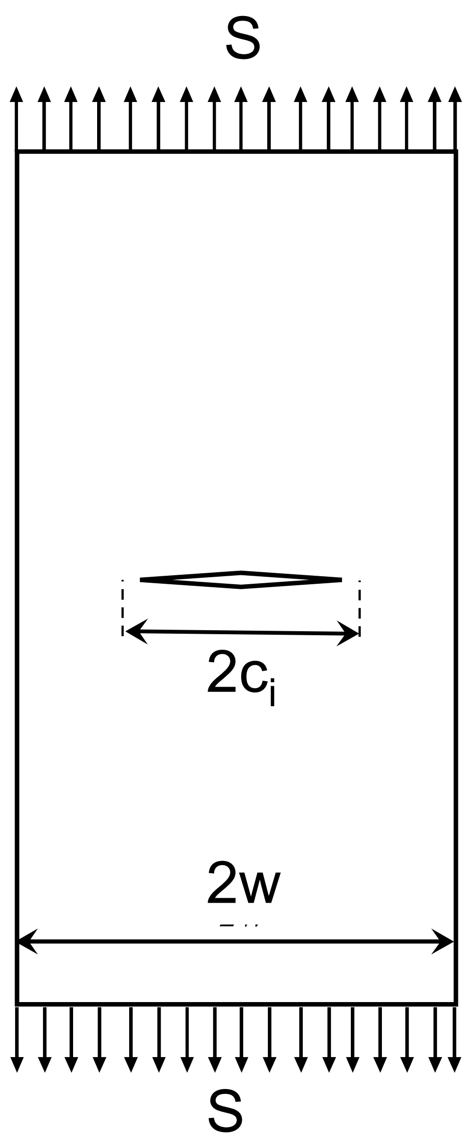




Elastic Stress-Intensity Factor at Failure for Limited Range of *Middle-Crack Tension* Specimens (2)

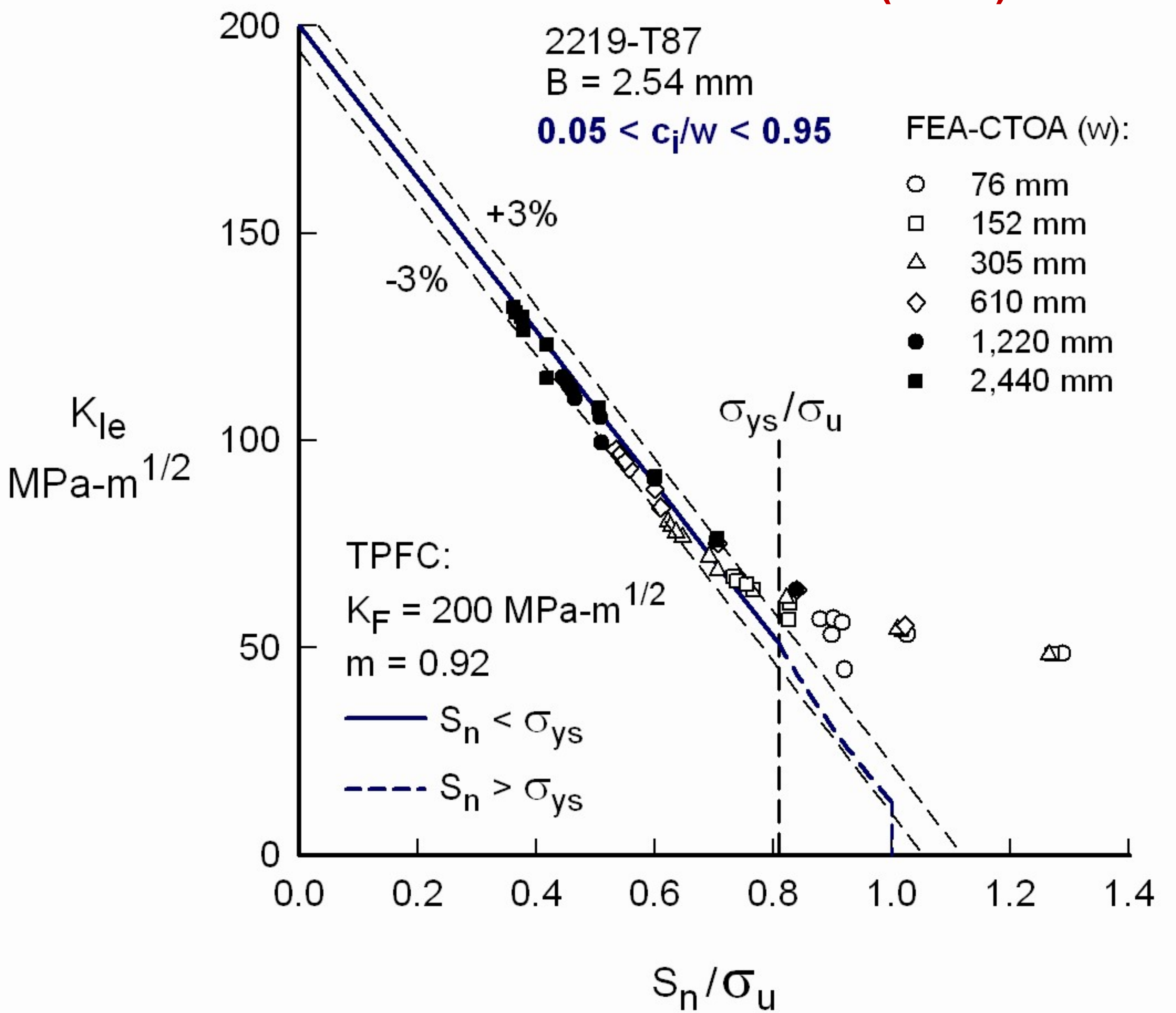
Mahtabi et.al. (2015)

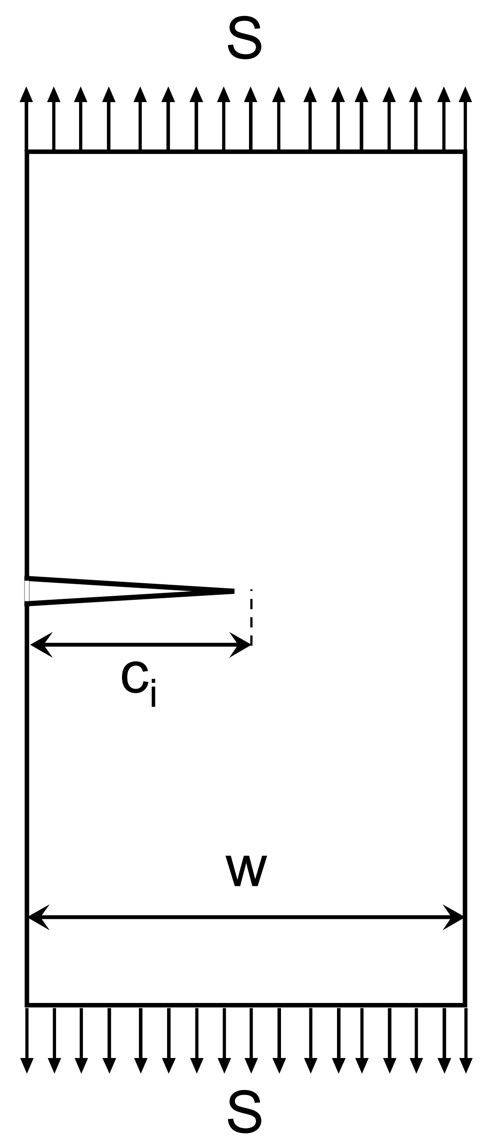




Elastic Stress-Intensity Factor at Failure for Wide Range of *Single-Edge-Crack Tension* Specimens

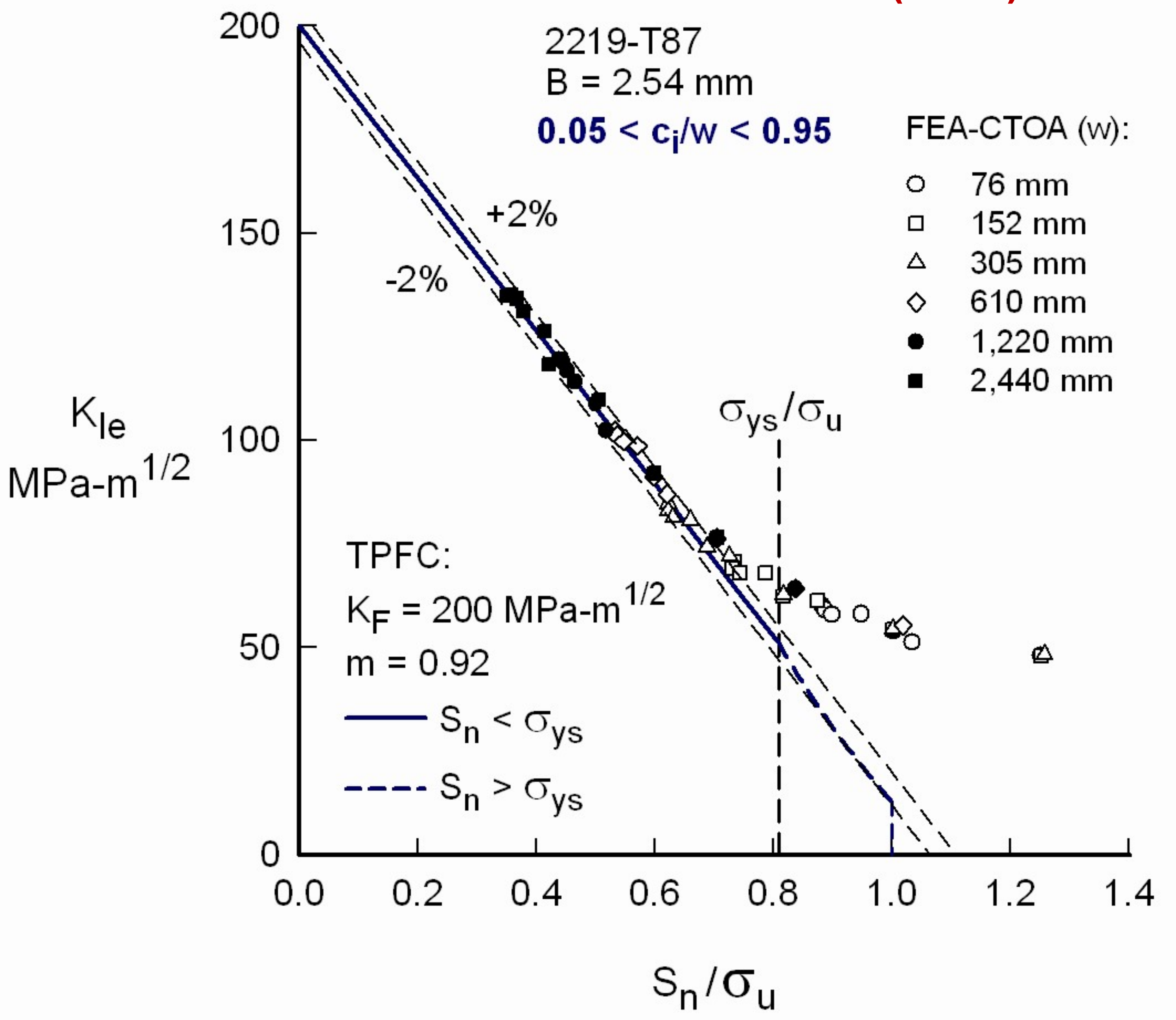
Mahtabi et.al. (2015)

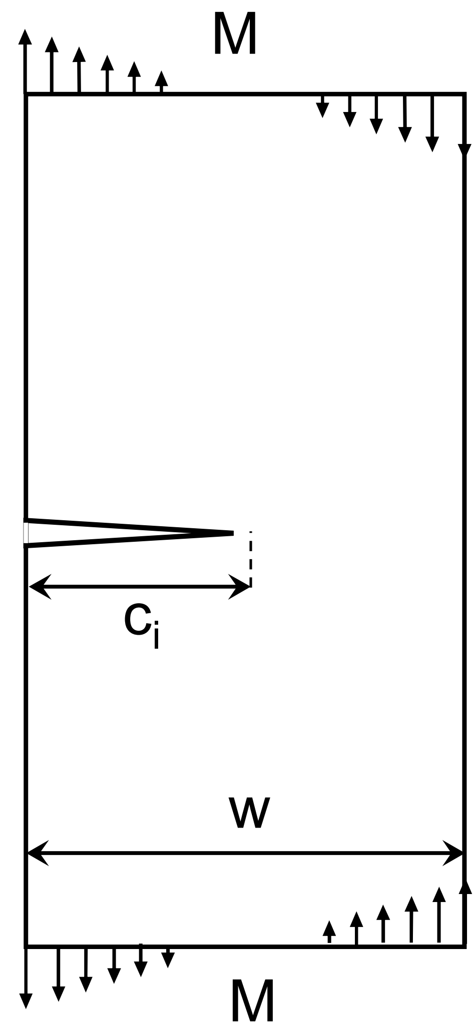




Elastic Stress-Intensity Factor at Failure for Wide Range of *Single-Edge-Crack Bend* Specimens

Mahtabi et.al. (2015)

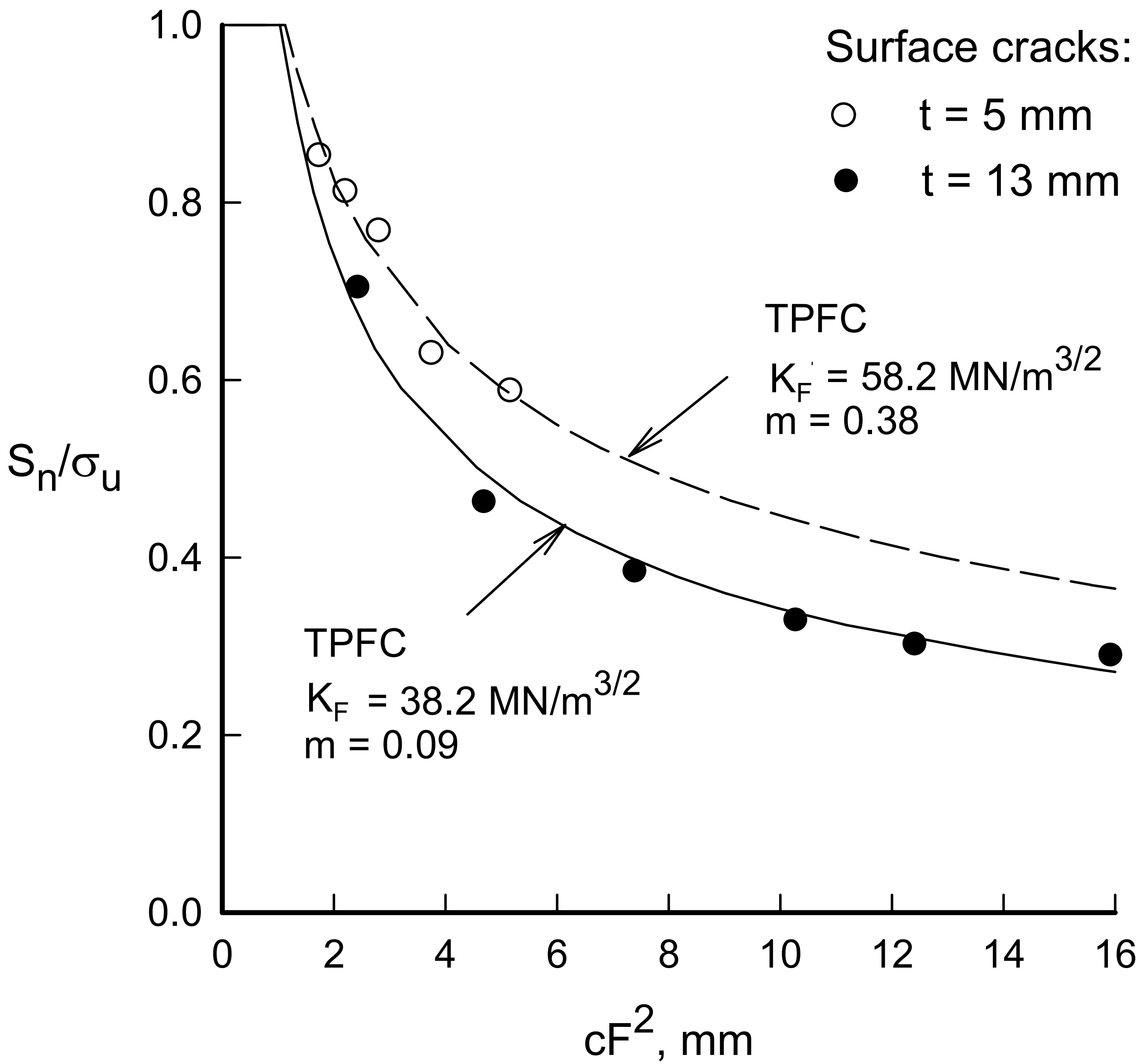


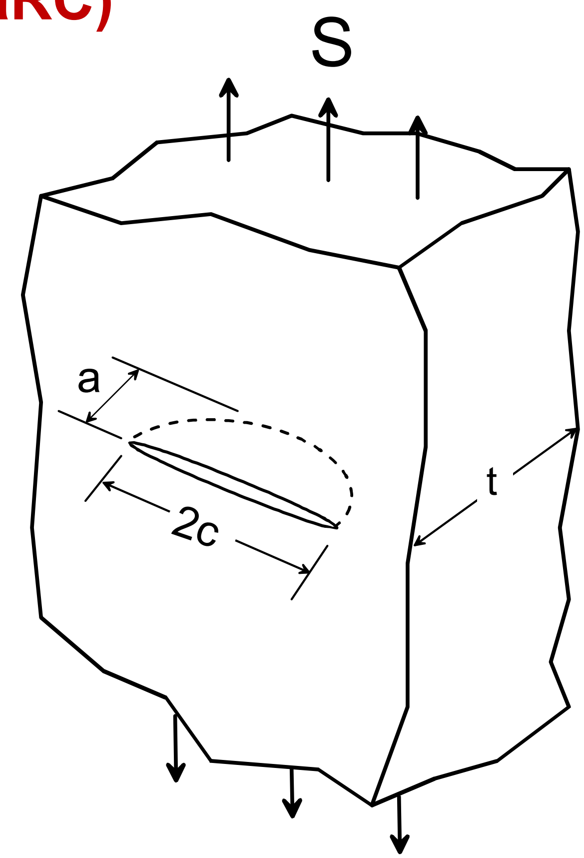


Surface-Crack Tests and TPFC Analyses

Residual Strength Analyses of Surface Cracks

7075-T651 Aluminum Alloy (NASA LaRC)



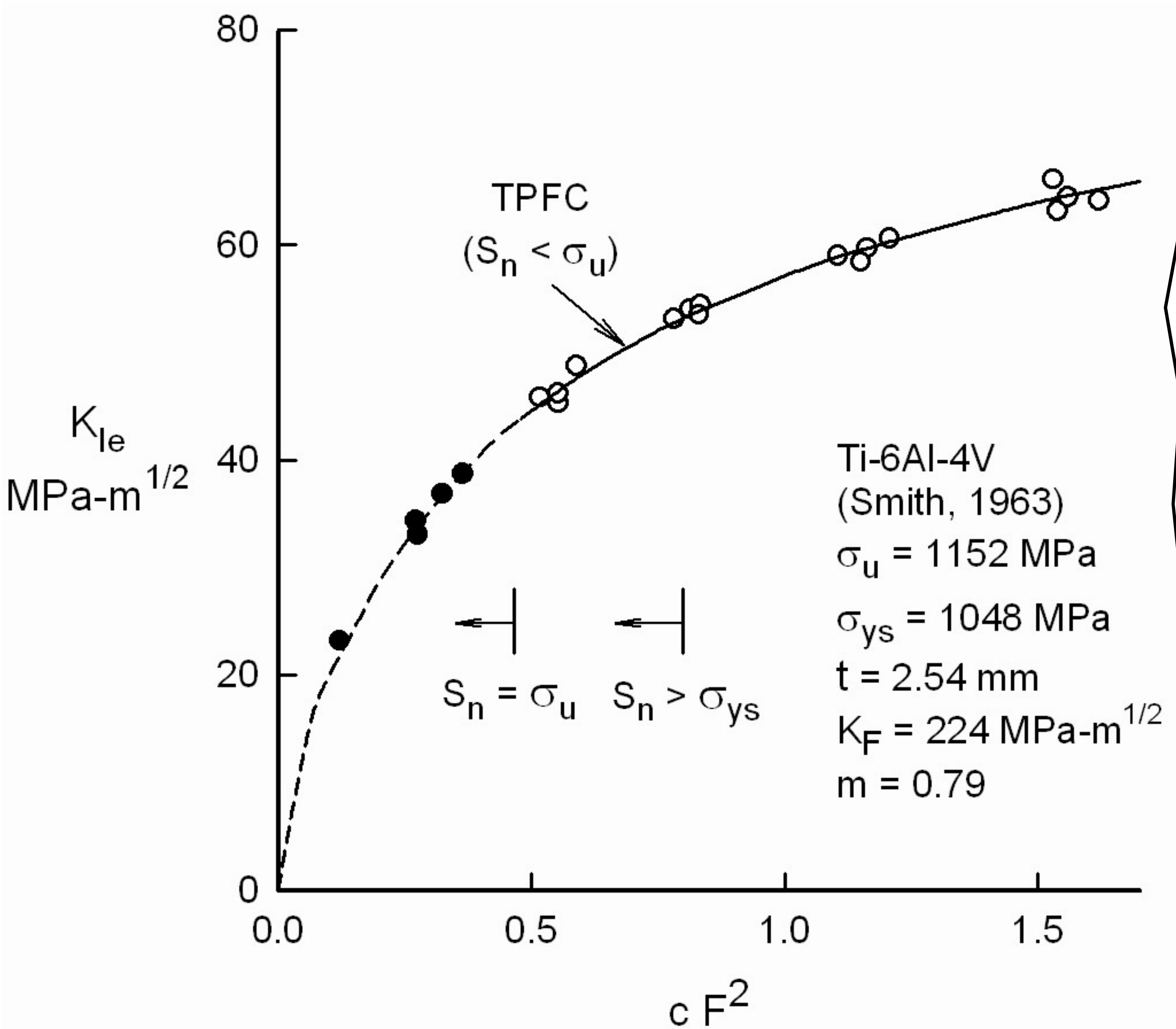


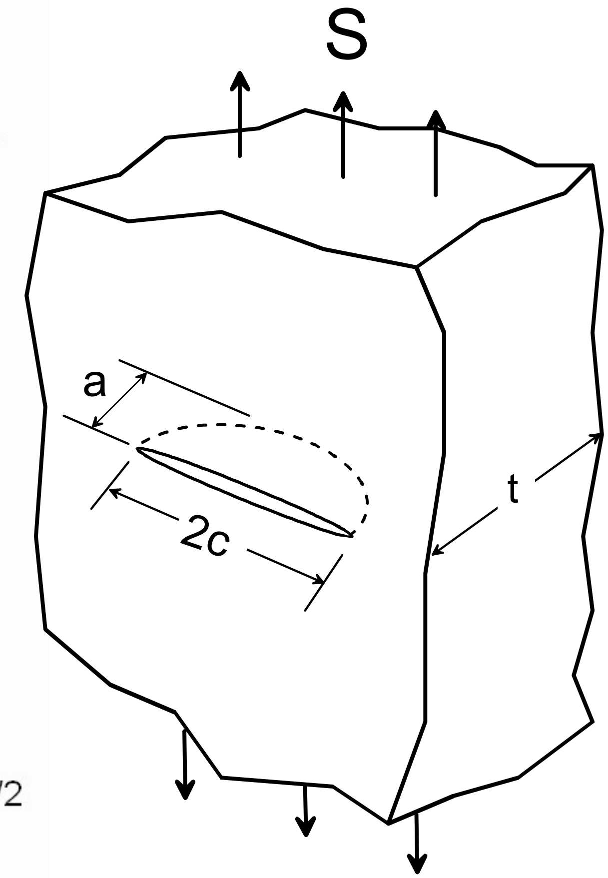
$K_{Ie} = S\sqrt{(\pi c)}\ F(a,c,w,t)$

ϕ_c = 30 deg

Elastic K_{Ie} at Failure is Uniquely Related to cF^2

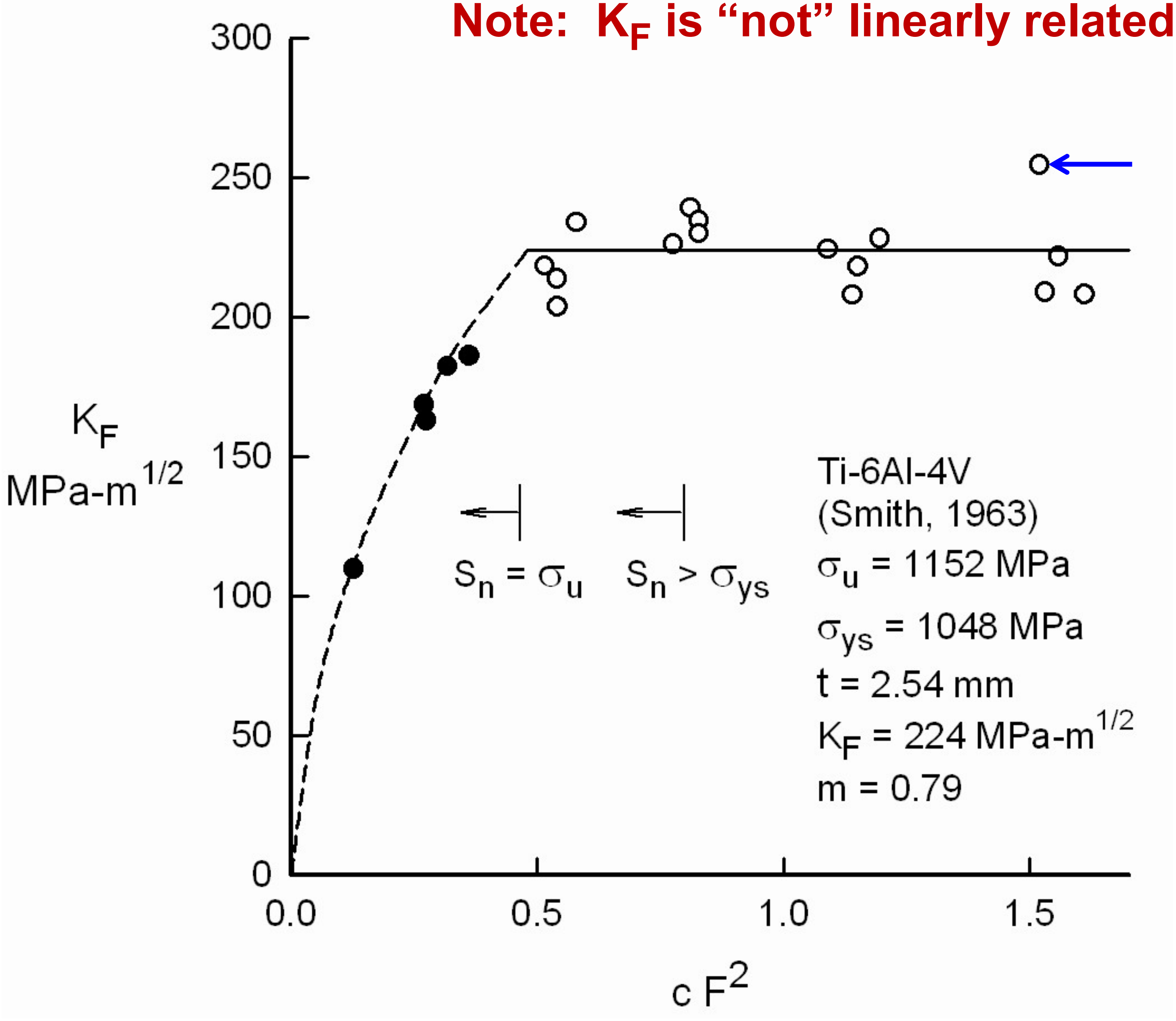
Wide range in a/c and a/t values!





Fracture Toughness, K_F, is Constant for $S_n < \sigma_{ys}$

Note: K_F is "not" linearly related to load!



< 3% error in predicted load using TPFC

Concluding Remarks

- **Relationship between K_{Ie} (elastic stress-intensity factor at failure) and S_n (net-section stress) is "linear".**

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- **More work required on TPFC for bend-type loading ($S_n > \sigma_{ys}$).**

Future Recommendations

1. **ASTM E-740 – Surface-Crack Standard – Does *NOT* have a fracture toughness assessment, but something like the TPFC needs to be added. Method is simple and very accurate for residual-strength analyses of *surface cracks*. (ASTM E-2899 is only for "initiation" toughness and *NOT* residual strength.)**

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2. **ASTM E-08 needs a simple fracture toughness standard for *through cracks* in low-constraint, high toughness materials that works for both *tension and bending* crack configurations.**

Thank You, Thank You Very Much !

Questions ?