PREDICTION OF LOWER BOUND FRACTURE TOUGHNESS IN THE TRANSITION TEMPERATURE REGION BY T_{33}-STRESS

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Table of Contents

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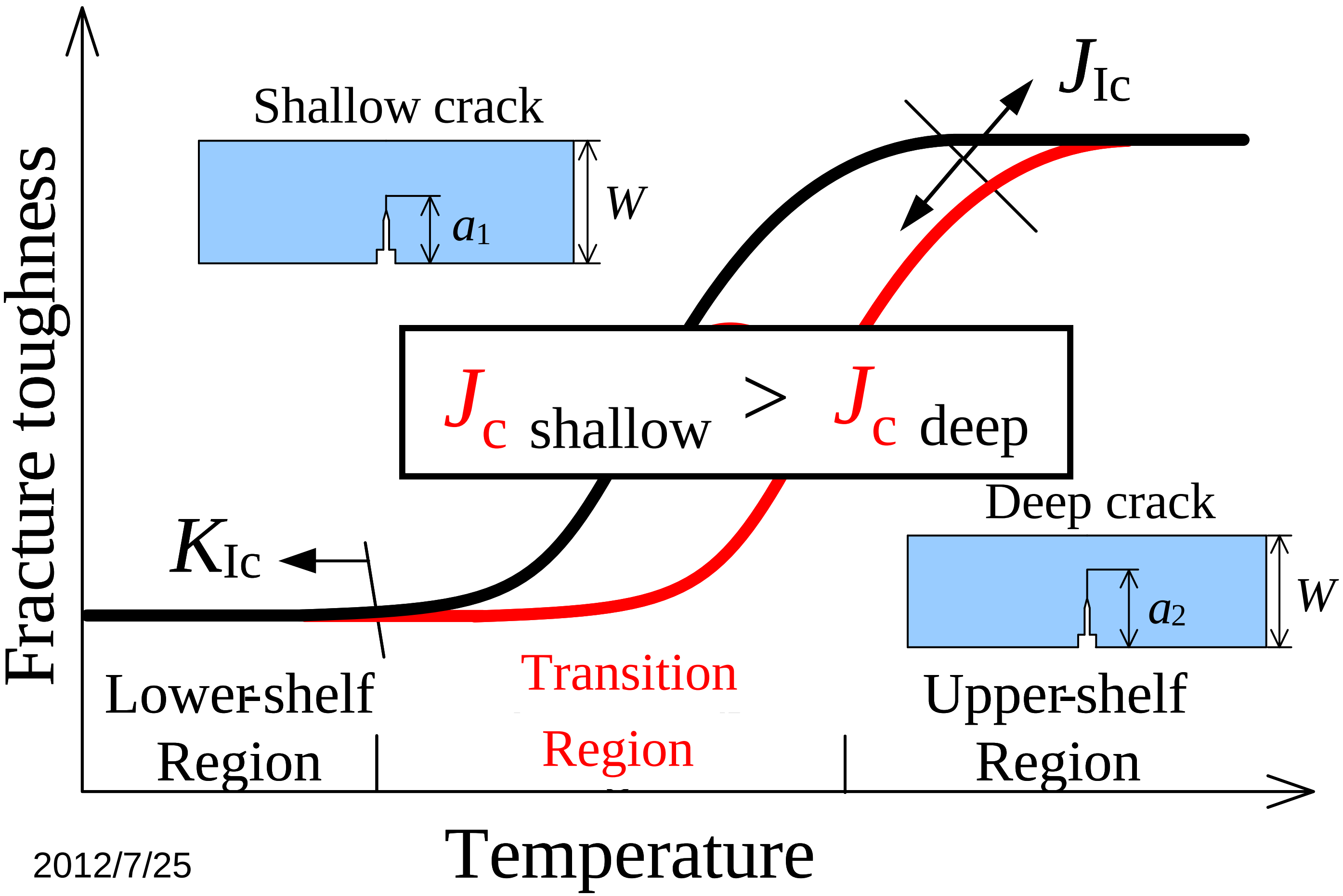
■ Background

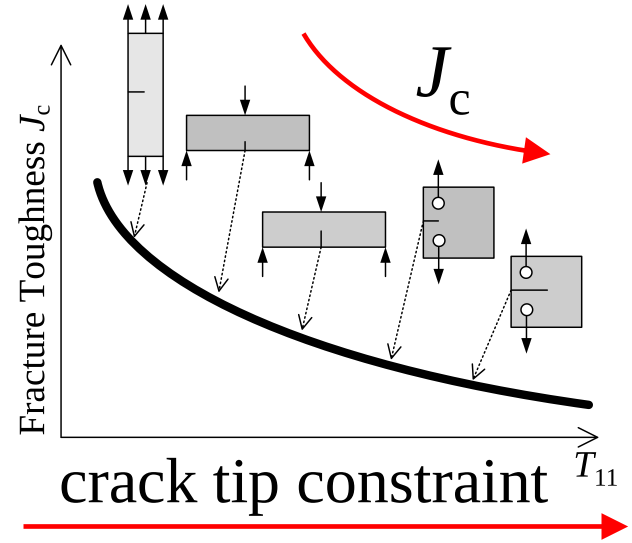
Background: Size effect on J_c

- Fracture toughness J_c: test specimen size effect



Background: Size effect on J_c

- "Planar" size effect on J_c
  - Differences in crack tip constraint
  - T-stress (Larsson & Carlsson, Rice)
  - Hancock et al., O'Dowd, ...
    - $T_{11} > 0$

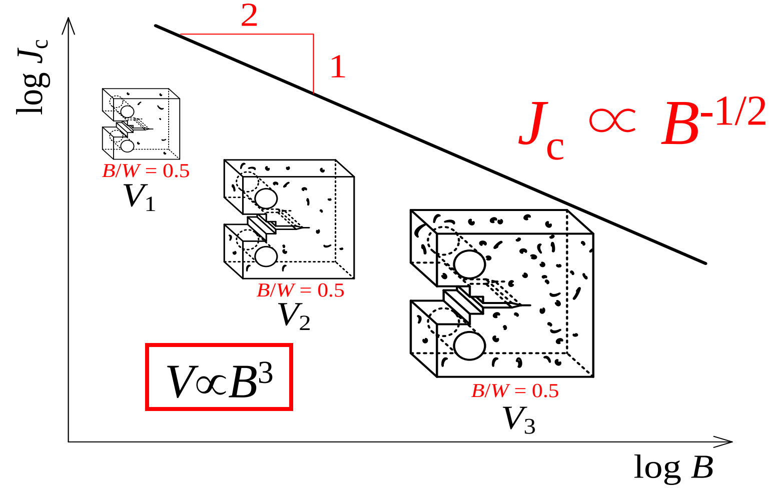


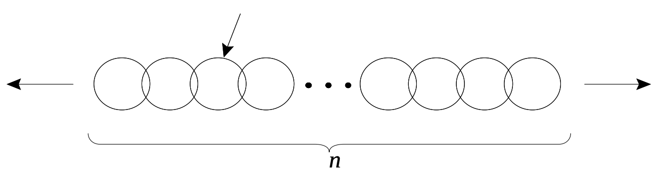
$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} = \frac{K_I}{\sqrt{2\pi r}} \begin{Bmatrix} \cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\ \cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\ \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \end{Bmatrix} + \begin{Bmatrix} T_{11} \\ 0 \\ 0 \end{Bmatrix}$$

- Mechanical issue

Test Specimen Thickness effect on J_c (1)

- Test Specimen Thickness (TST) effect on J_c
  - Wallin
    - $J_c \propto B^{-1/2}$
  - Anderson et al.
    - Weakest Link (WL) Model



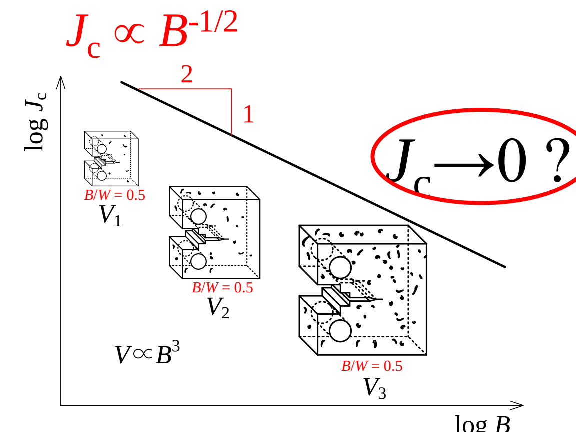


WL model

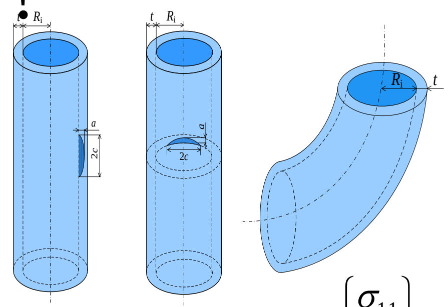
- Material issue

Test Specimen Thickness effect on J_c (2)

- **Contradiction**
  - $J_c \propto B^{-1/2}$: $J_c \rightarrow 0$ for $B \rightarrow \infty$
- TST effect on actual flaw
  - Not clear : definition of B ?



increasing B



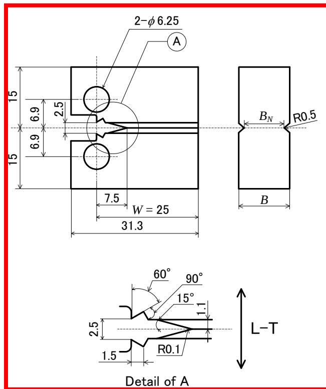
- Meshii et al.
  - Out-of-plane constraint issue
  - Mechanical parameter: T_{33}

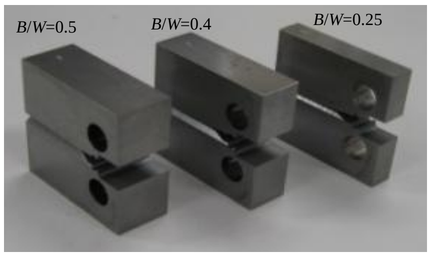
$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{Bmatrix} = \frac{K_I}{\sqrt{2\pi r}} \begin{Bmatrix} \cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\ \cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\ 2\nu\cos\frac{\theta}{2} \\ \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \\ 0 \\ 0 \end{Bmatrix} + \begin{Bmatrix} T_{11} \\ 0 \\ T_{33} \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

Previous Results for S55C (1)

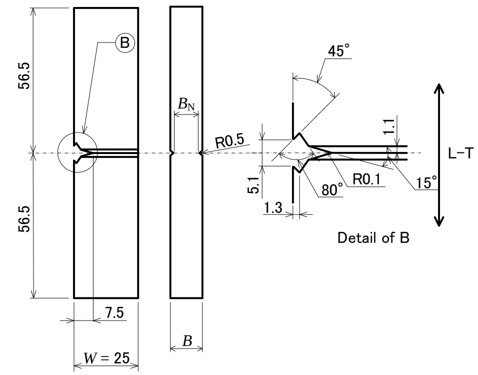
- Fracture toughness test
  - 0.55% carbon steel S55C at R.T.

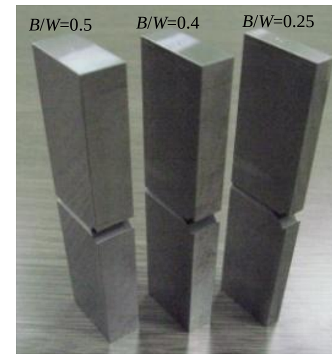
CT: B/W= 0.25 ~ 0.5



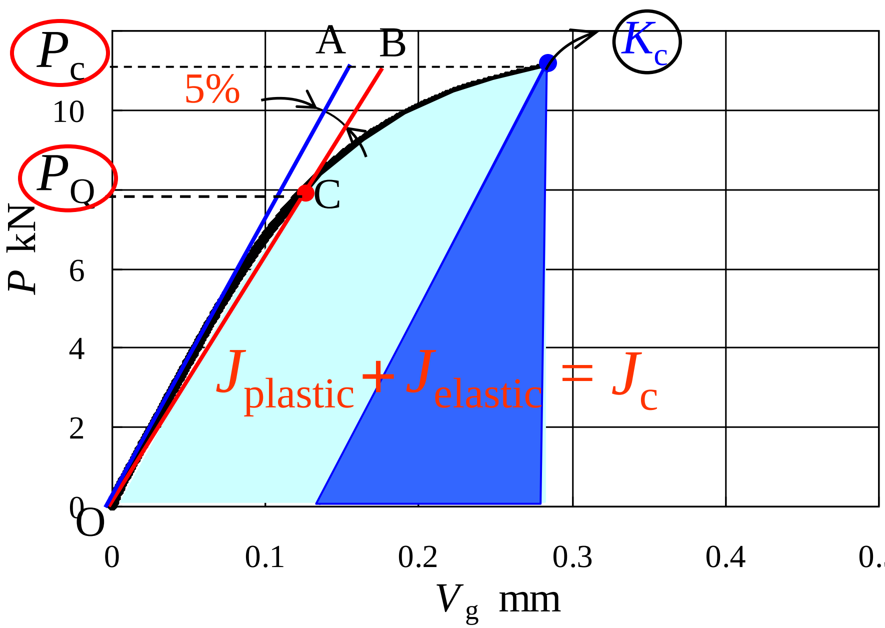


3PB: B/W= 0.25 ~ 0.5





- P–V_g curve
  - $P_c/P_Q > 1.1 \rightarrow K_{IC}$ invalid
  - J_c for P_c evaluated by E1820
  - K_c : K for P_c

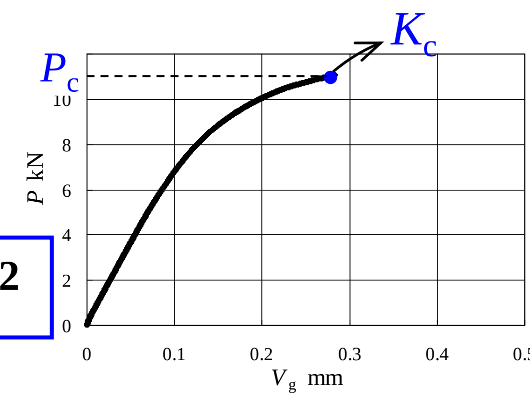


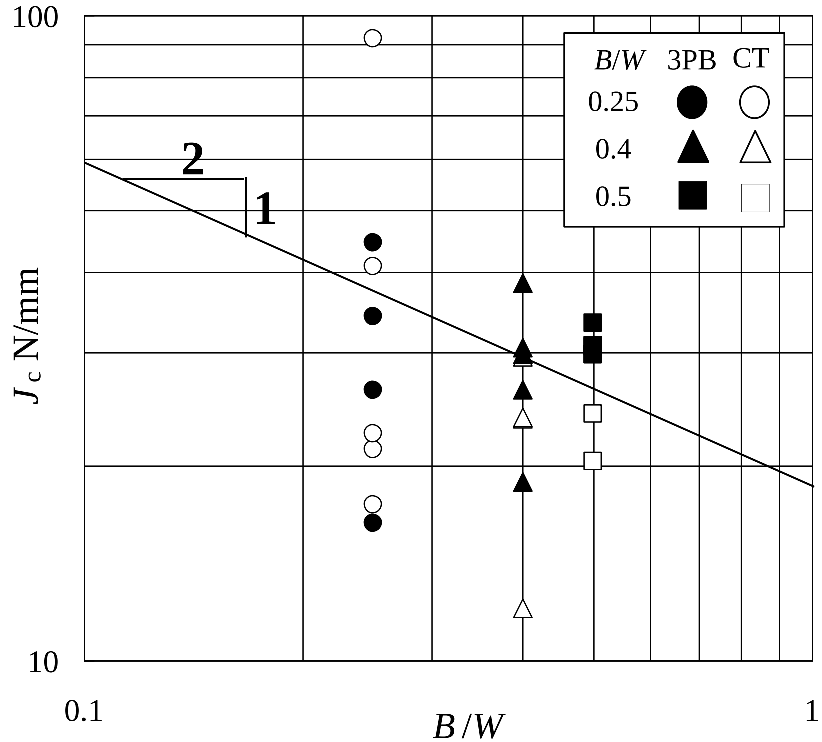
Previous Results for S55C (2)

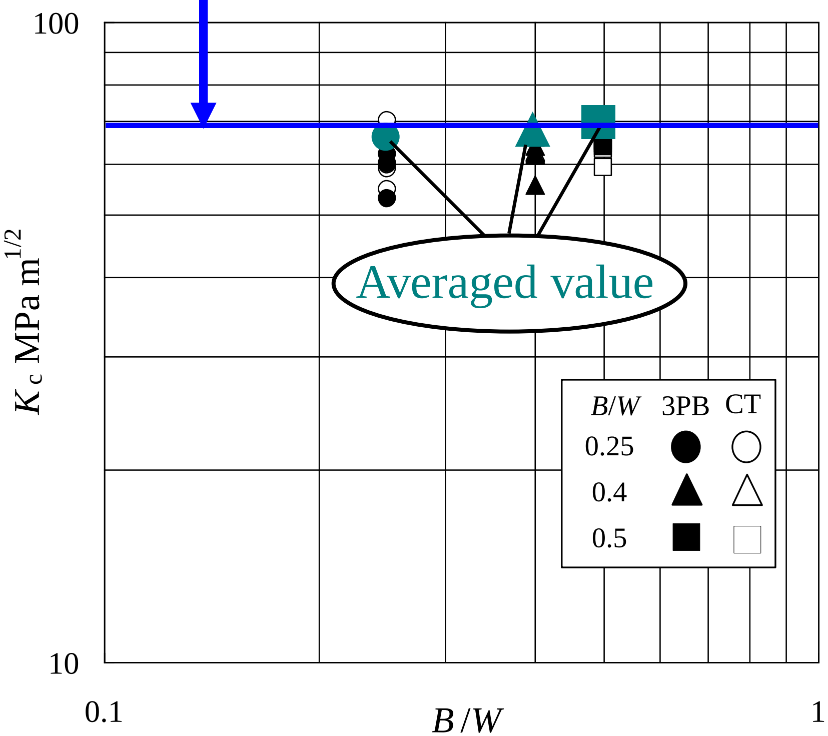
- Exp: (S55C*)

$J_c \propto B^{-1/2}$

$K_c = 66$ MPa m$^{1/2}$



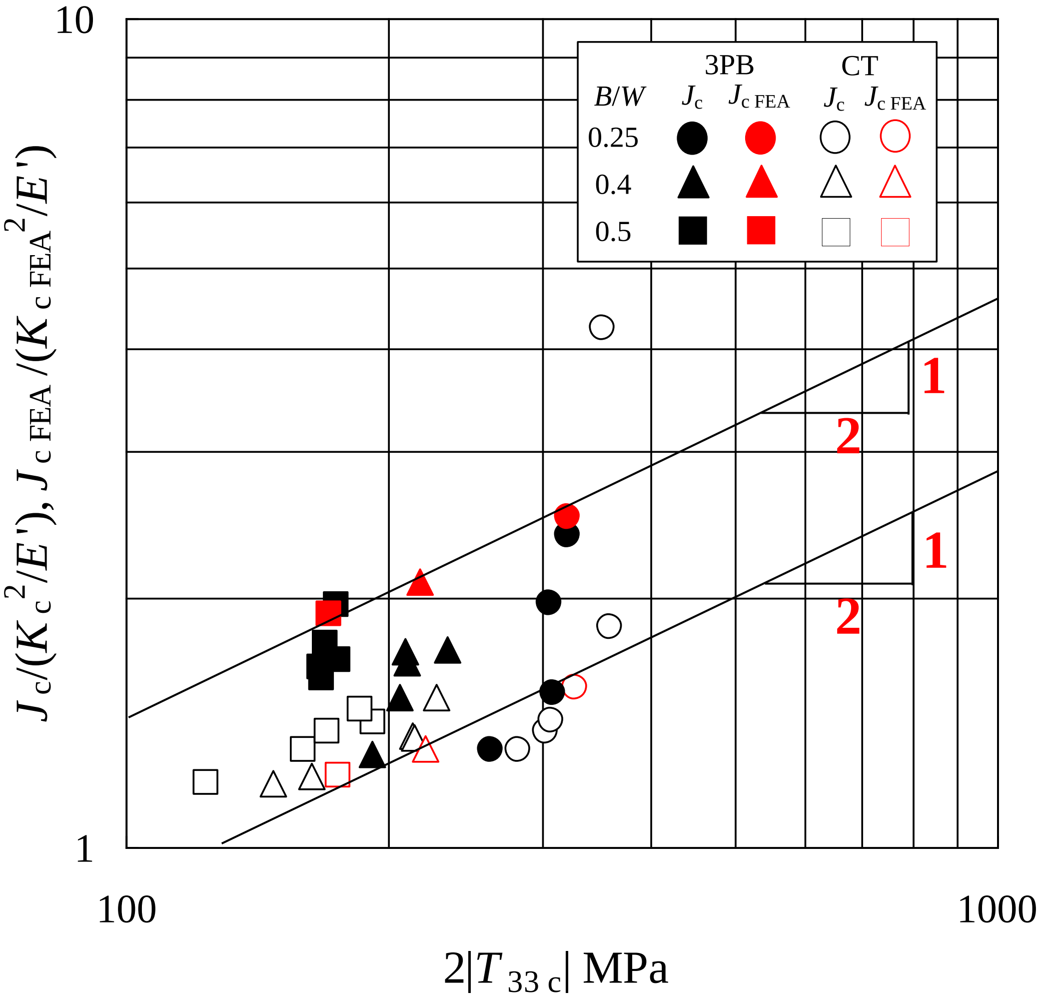




*Toshiyuki Meshii, Tomohiro Tanaka. Engineering Fracture Mechanics. 2010;77(5):867-877
*Tomohiro Tanaka, Toshiyuki Meshii. ASME Pressure Vessels and Piping Conference, 1-7 (2010).

Previous Results for S55C (3)

- Exp & FEA: (S55C*)



$J_c \propto |T_{33\,c}|^{1/2}$

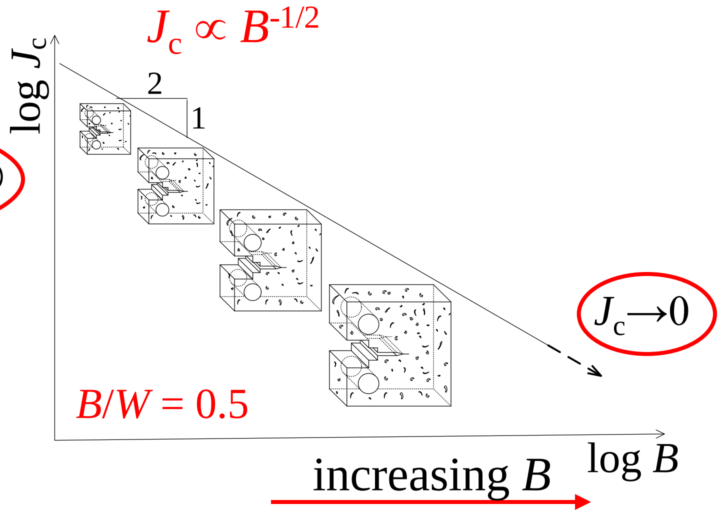
*Toshiyuki Meshii, Tomohiro Tanaka. Engineering Fracture Mechanics. 2010;77(5):867-877

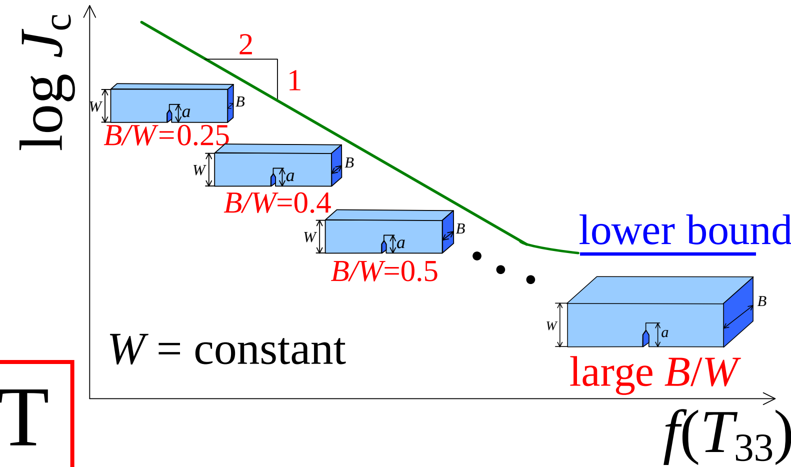
**Tomohiro Tanaka, Toshiyuki Meshii. ASME Pressure Vessels and Piping Conference, 1-7 (2010).

- Background
- Motivation
  - Predict lower bound J_c for TST

Motivation

- Anderson et al.
  - **Contradiction:** $J_c \rightarrow 0$ for $B \rightarrow \infty$
- Meshii et al.
  - Correlated with T_{33}: $J_c \propto |T_{33}|^{1/\gamma}$





Predict lower bound J_c for TST
& Solve the contradiction

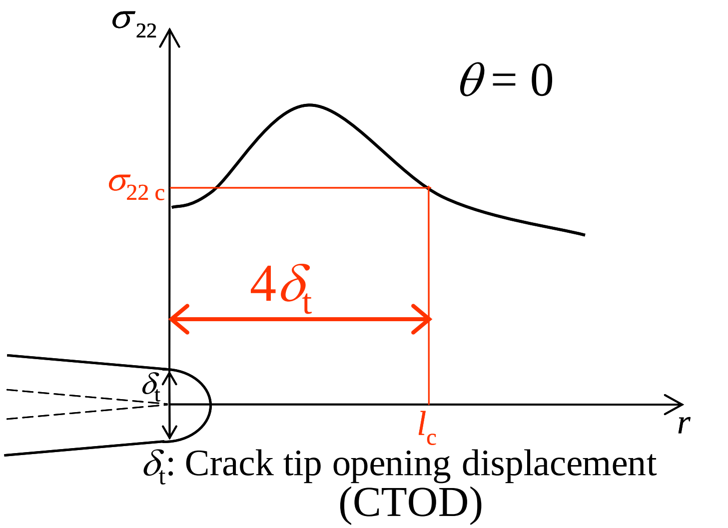
Failure Criterion

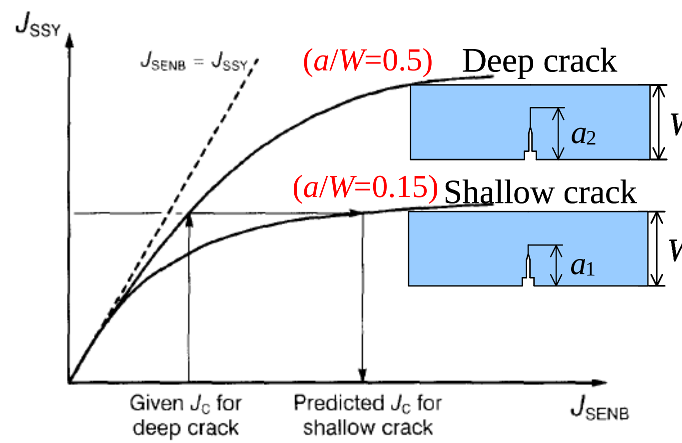
- **‘Planar’ Failure Criterion**
  - Ritchie et al.
  - Shih

  $\Big\}\ \sigma_{22} \geq \sigma_{22c}$ at l_c

  - Dodds et al.
    - Critical distance: $l_c=4\delta_t$
    - Quantified a/W effects on J_c

- Out-of-plane TST issue





- Background
- Motivation
  - Predict lower bound J_c for TST
- FEA
  - Derivation of failure criterion for S55C

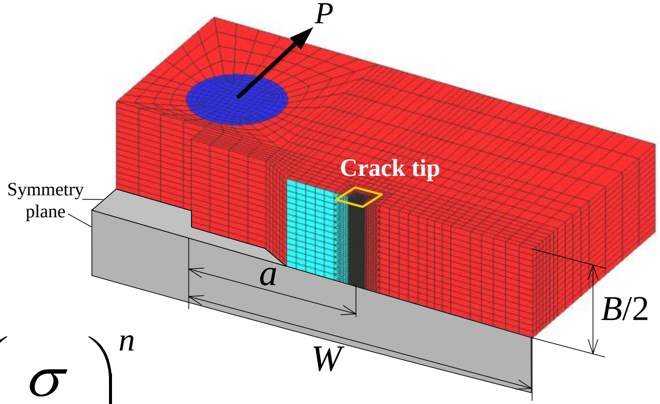
Elastic-Plastic FEA
Standard CT Specimen

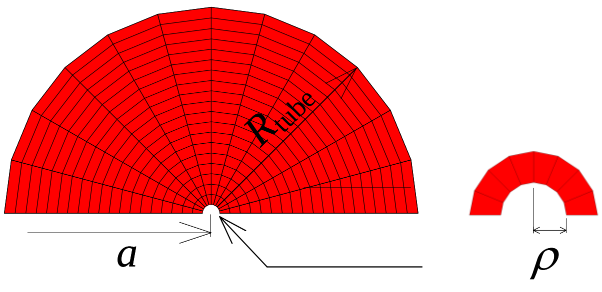
- Model
  - 1/4 symmetry (CT, B/W= 0.5, a/W=0.5)
  - Side groove: removing constraint
  - Circular hole ρ = 0.004 mm
- Material
  - J2-incremental plasticity
  - Ramberg-Osgood

    n = 6.9, α = 1.61, σ_0 = 428 MPa
    $$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n$$
- Maximum load
  - $K_{c\ S55C}$ = 66 MPa m$^{1/2}$ (30 load steps)
- Solver: WARP3D
  - Focused on thickness center value

Standard CT specimen

(W=25 mm, B/W= 0.5, a/W=0.5)

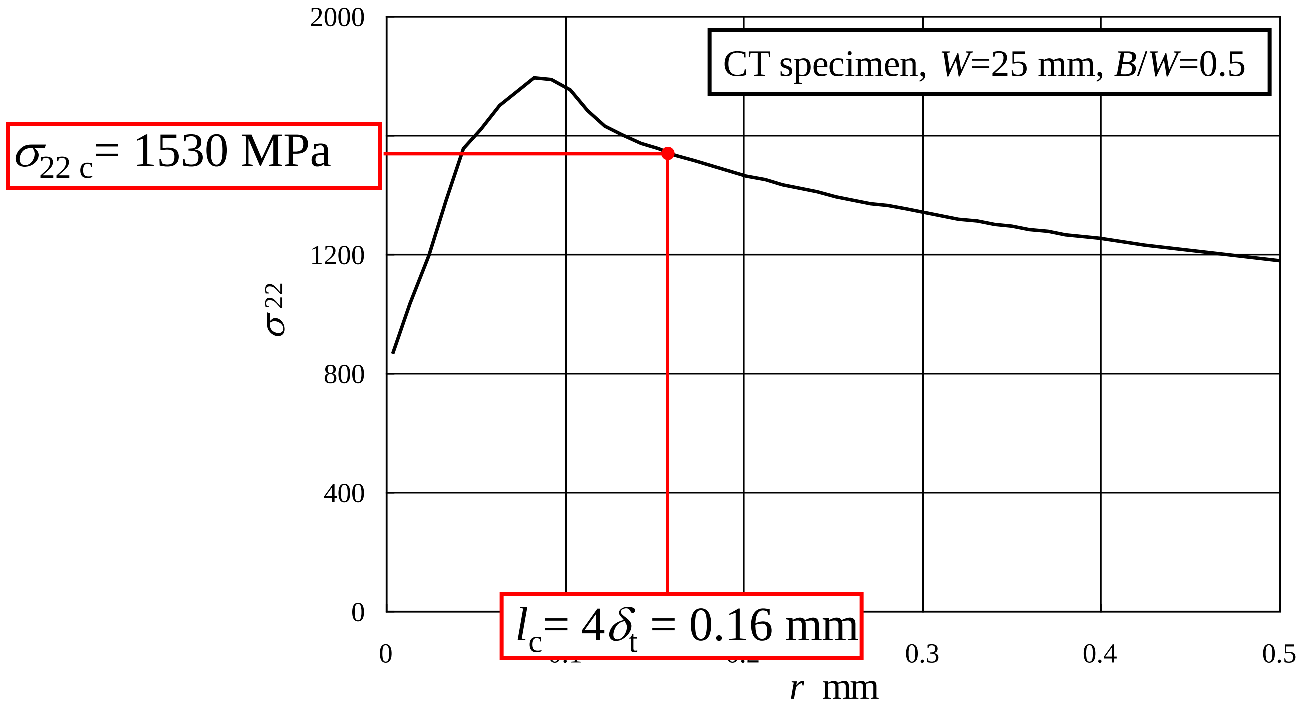




Derivation of Failure Criterion for S55C

- Standard CT specimen: $K_{c\ S55C} = 66$ MPa m$^{1/2}$

Thickness Center
- – Crack tip opening displacement δ_t: 0.04 mm
- – Crack opening stress σ_{22} (θ=0) distribution



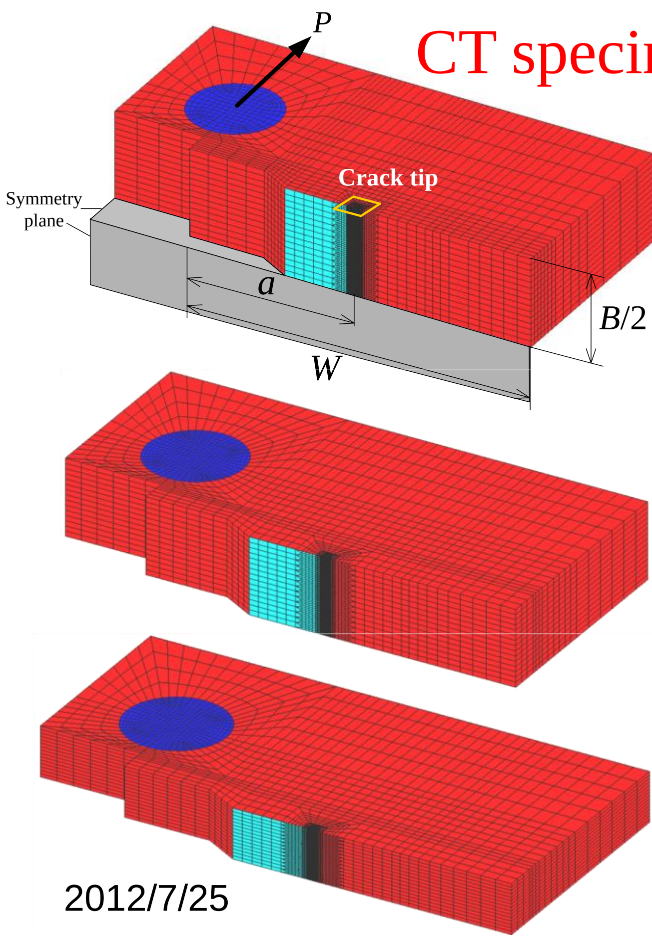
 Failure criterion: $\boxed{(l_c = 0.16 \text{ mm},\ \sigma_{22c} = 1530 \text{ MPa})}$

- Background
- Motivation
  - Predict lower bound J_c for TST
- FEA
  - Derivation of failure criterion for S55C
  - Validation of failure criterion to out-of-plane TST issue

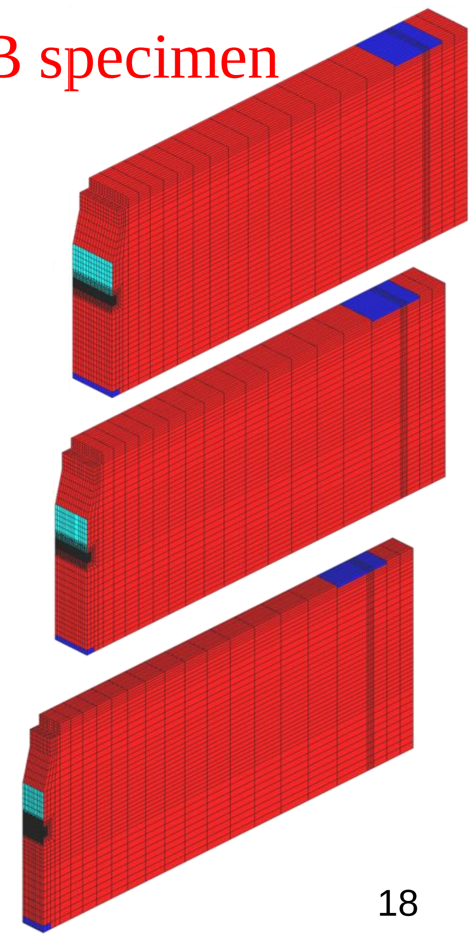
Validation of failure criterion for out-of-plane TST issue

- Elastic-plastic FEA for non-standard test specimen

CT specimen



3PB specimen



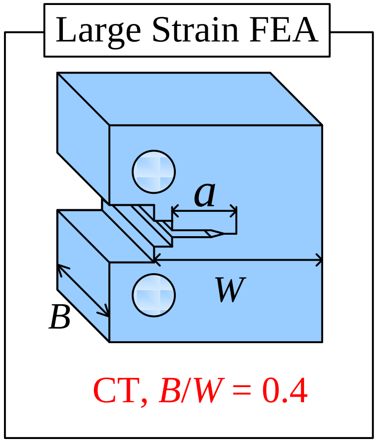
B/W=0.5

B/W=0.4

B/W=0.25

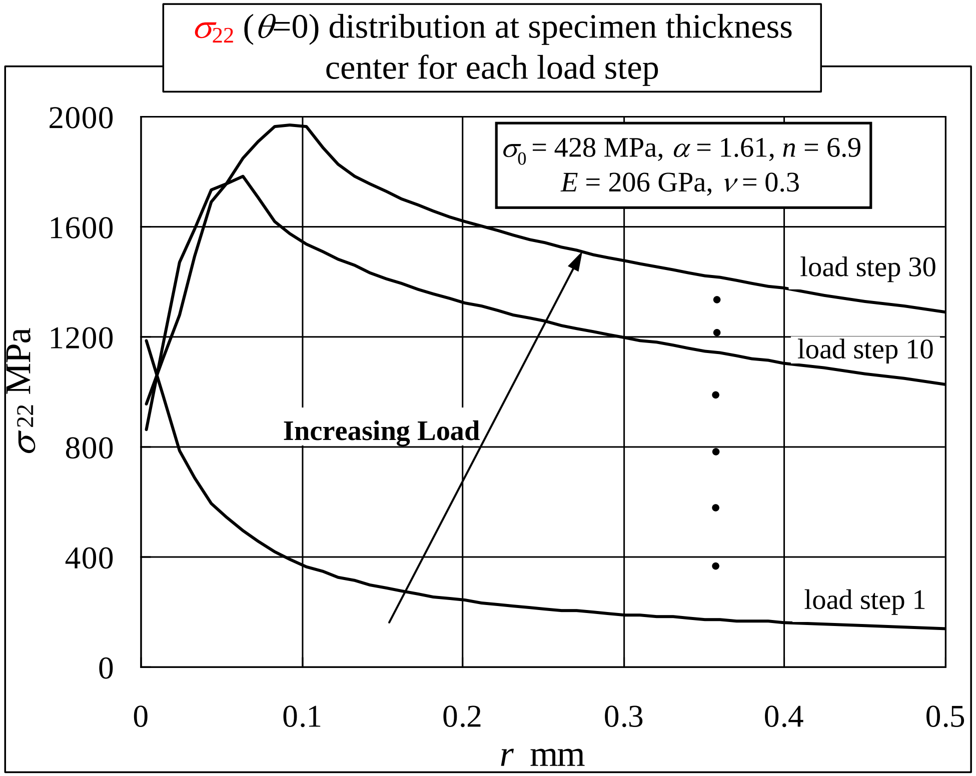
Validation of failure criterion for out-of-plane TST issue

■ Step 1: Large Stain FEA for 1/2TCT (B/W=0.4)



P_{max} @

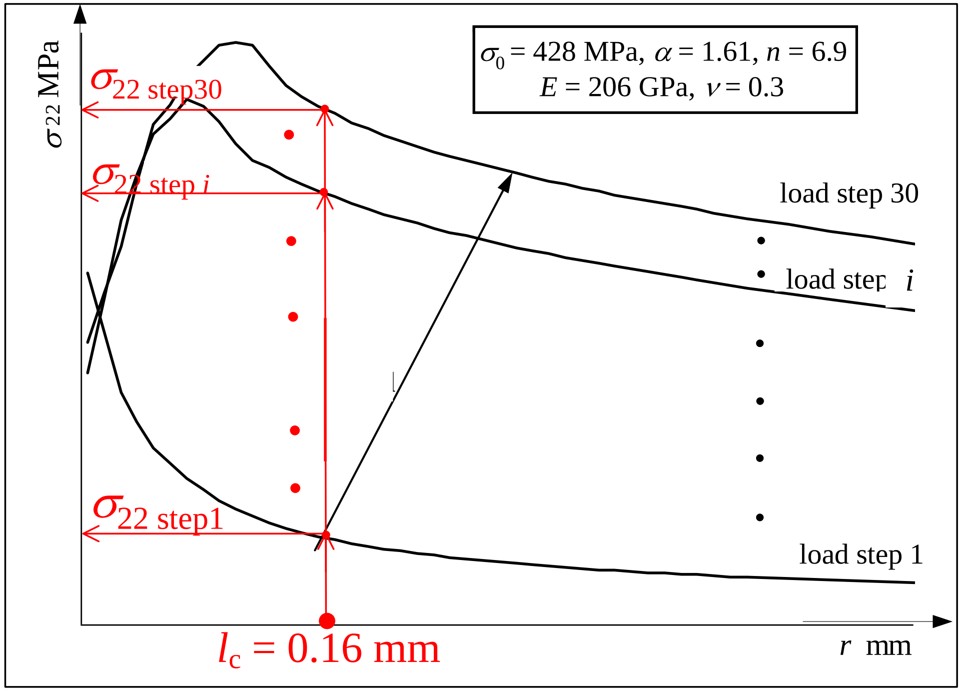
K_{max}=1.1 $K_{c\ S55C}$



Validation of failure criterion for out-of-plane TST issue

■ Step 2: Extract $\boldsymbol{\sigma}_{22}$ ($\theta = 0$) values at l_c = 0.16 mm

σ_{22} (θ=0) at the critical distance l_c = 0.16 mm



load step i	P_i/P_{max}	$\sigma_{22\,i}$ MPa (l_c=0.16 mm)
⋮	⋮	⋮
15	0.900	1529.0
16	0.908	1542.4
⋮	⋮	⋮

Validation of failure criterion for out-of-plane TST issue

■ Step 3: Derive fracture load: $\boldsymbol{P}_{\mathbf{c\ FEA}}$

load step i	P_i/P_{max}	$\sigma_{22\,i}$ MPa (l_c=0.16 mm)
15	0.900	1529.0
16	0.908	1542.4

$\boldsymbol{\sigma_{22\,c}=1530\ \mathrm{MPa}}$

Derivation of fracture load $P_{c\ FEA}$

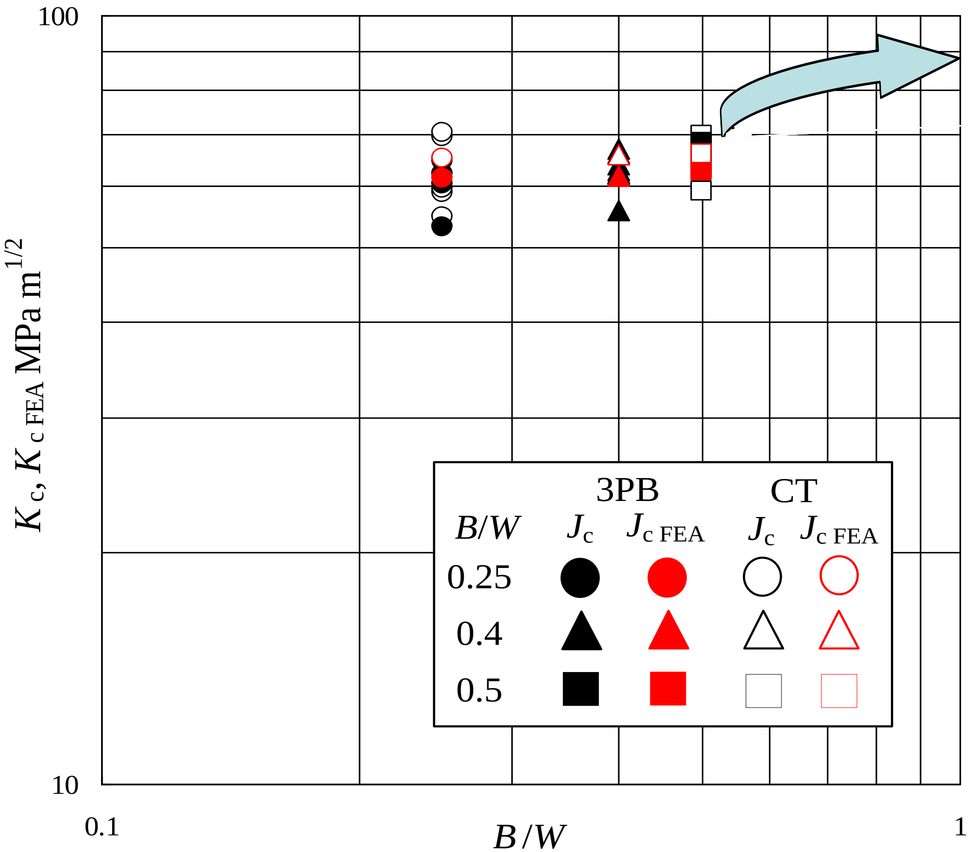
$$\boldsymbol{P}_{\mathbf{c\ FEA}}=\frac{P_{i+1}-P_i}{\sigma_{22\ i+1}-\sigma_{22\ i}}\bullet(\sigma_{22\ c}-\sigma_{22\ i})+P_i$$

■ Step 4: Estimate $\boldsymbol{K}_{\mathbf{c\ FEA}}$

$$K_{c\ FEA}=\frac{P_{c\ FEA}}{\sqrt{BB_N W}}f_{CT}\left(\frac{a}{W}\right)$$

Validation of failure criterion for out-of-plane TST issue

- Estimated $K_{c\ FEA}$ for other CT & 3PB specimens



$K_{c\ FEA}$: almost constant for TST

Failure criterion (l_c, σ_{22c})

applicable

Out-of-plane TST issue

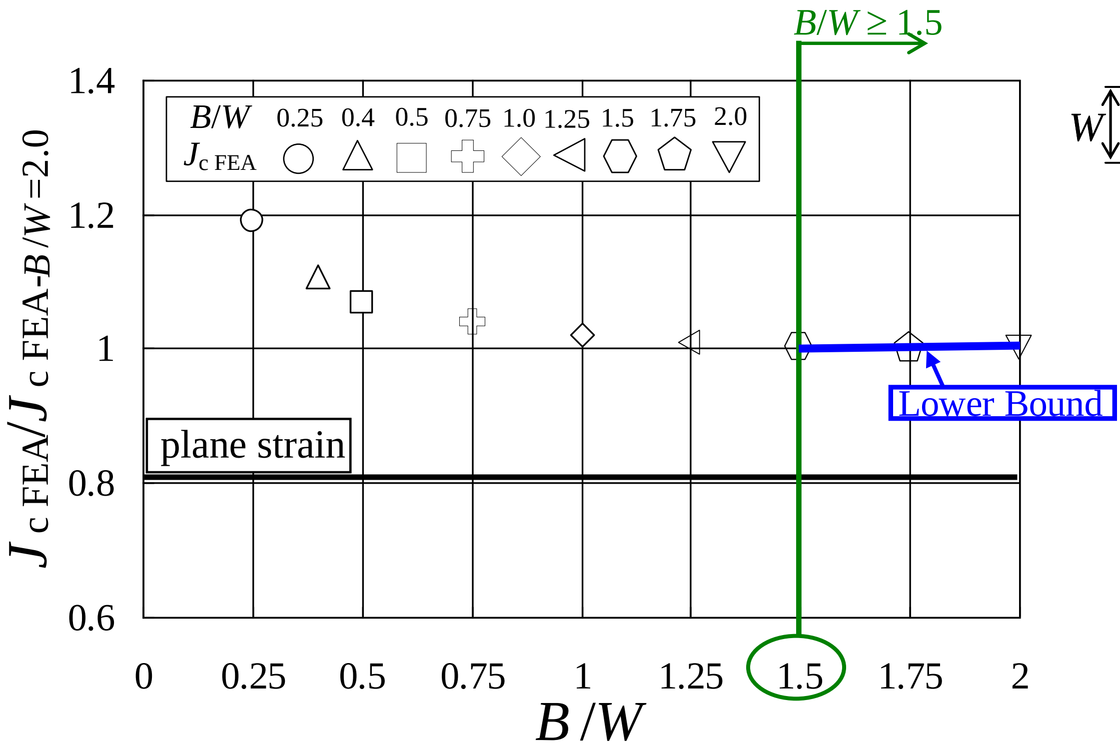
- Background
- Motivation
  - Predict lower bound J_c for TST
- FEA
  - Derivation of failure criterion for S55C
  - Validation of failure criterion to out-of-plane TST issue
  - Predict lower bound J_c for TST

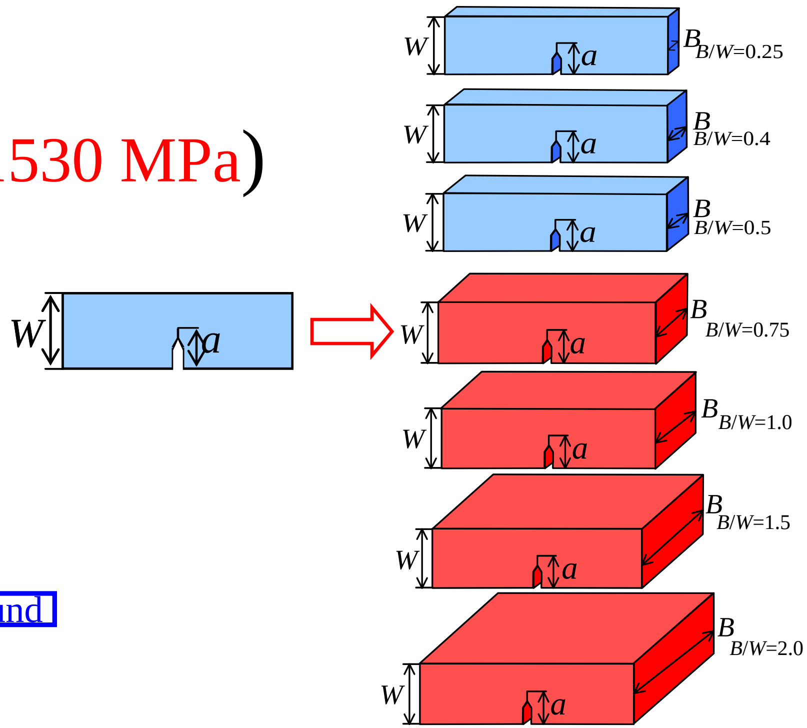
Prediction of Lower Bound J_c

- Non-standard 3PB specimen

  (B/W=0.25~0.5; 0.75~2.0)

- Failure criterion (l_c=0.16 mm, σ_{22c}=1530 MPa)





Lower bound J_c obtained for $B/W \geq 1.5$

- Background
- Motivation
  - Predict lower bound J_c for TST
- FEA
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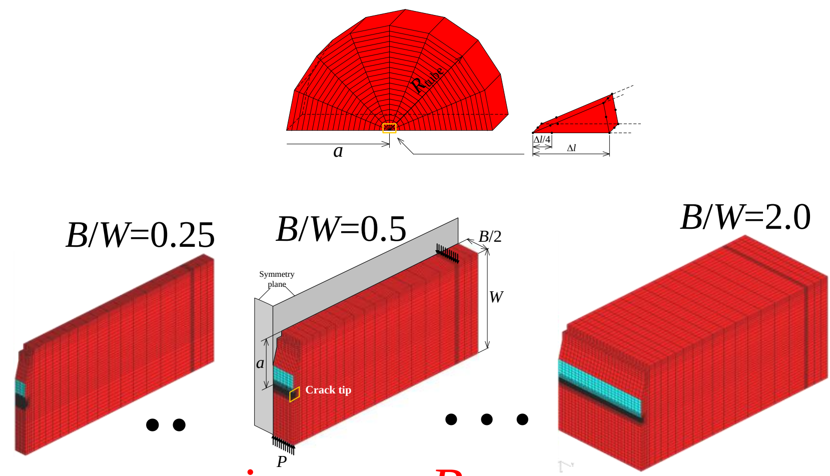
  - Validation of failure criterion to out-of-plane TST issue
  - Predict lower bound J_c for TST
  - Prediction of lower bound J_c with T_{33}-stress

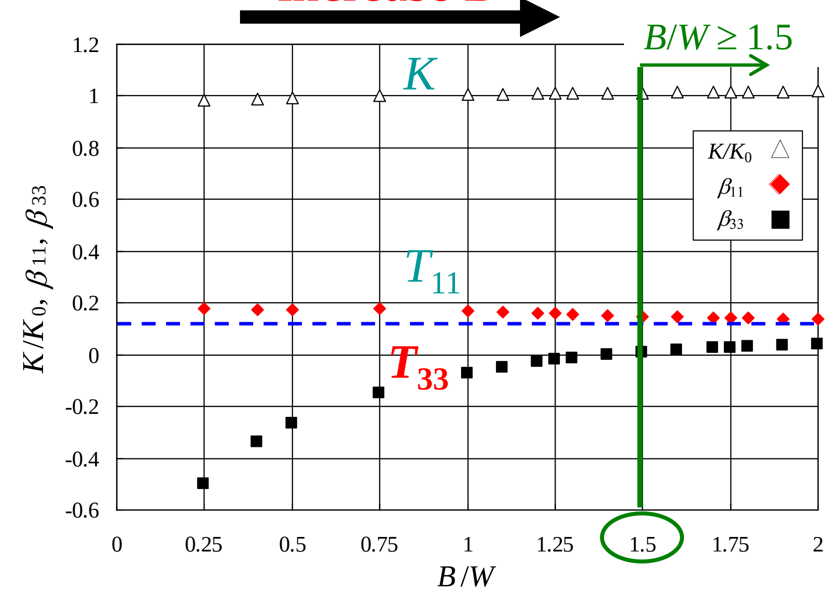
Prediction of Lower Bound J_c with T_{33}-stress

- Model
  - 1/4 symmetry
  - Side groove: removing constraint
  - W=25 mm, B/W=0.25~2.0
  - Singular element: $\Delta l/a$=0.0016
- Load: K_0 =1 MPa m$^{1/2}$
- Values at specimen center
  - K,T_{11}: little change
  - T_{33}: significant change
  - T_{33} : a bound value for $B/W \geq 1.5$

$$\beta_{kk} = \frac{T_{kk}\sqrt{\pi a}}{K_0} \quad (k = 1, 3)$$

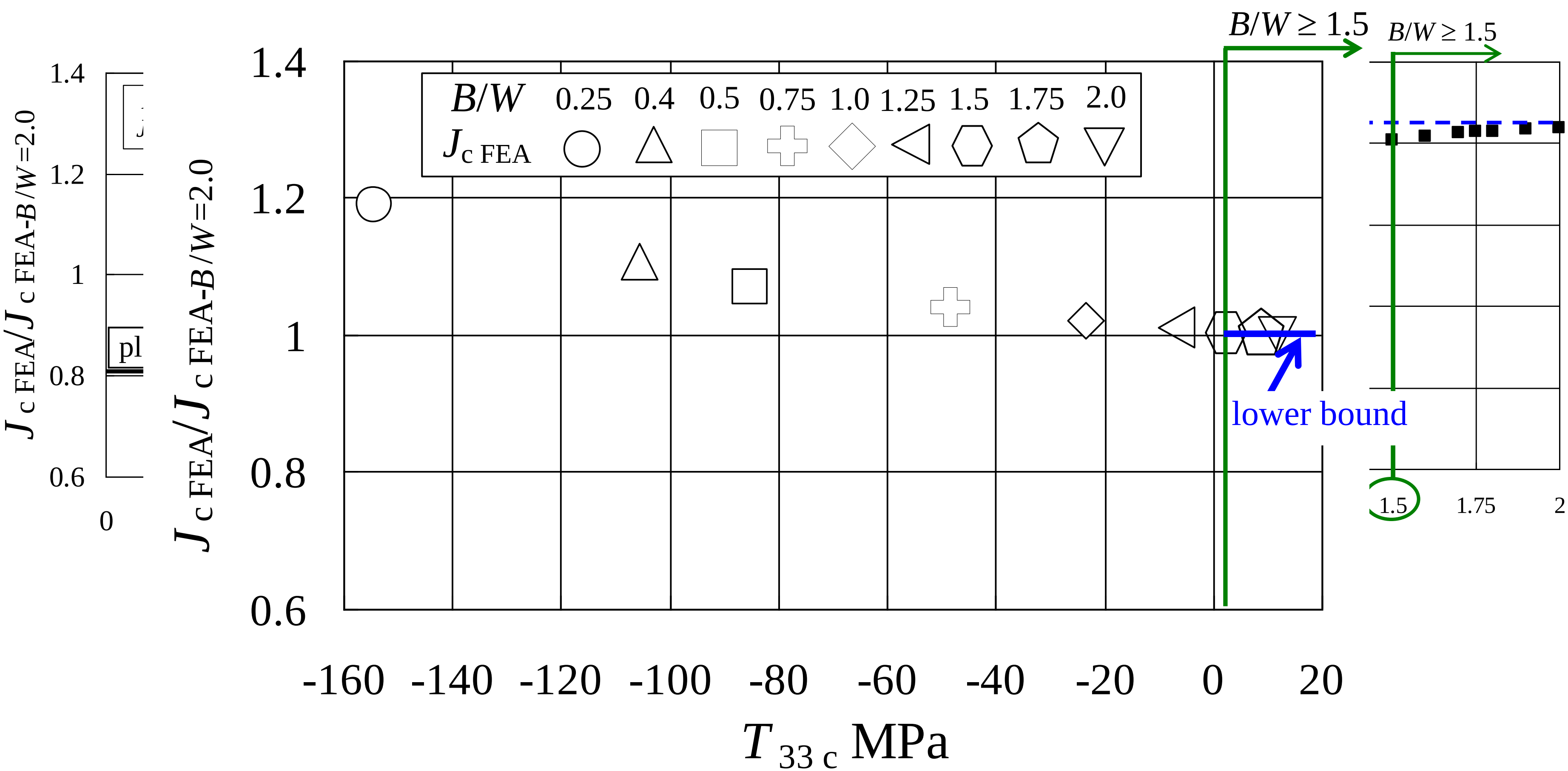


increase B



Prediction of Lower Bound J_c with T_{33}-stress

- Lower bound : Predicted by T_{33}-stress
- $J_{c\ FEA}$ & T_{33} : $J_{c\ FEA}$ values for $B/W \geq 1.5$



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  - Predict lower bound J_c for TST
  - Prediction of lower bound J_c with T_{33}-stress
- **Summary and Future Plans**

Summary & Future Plans

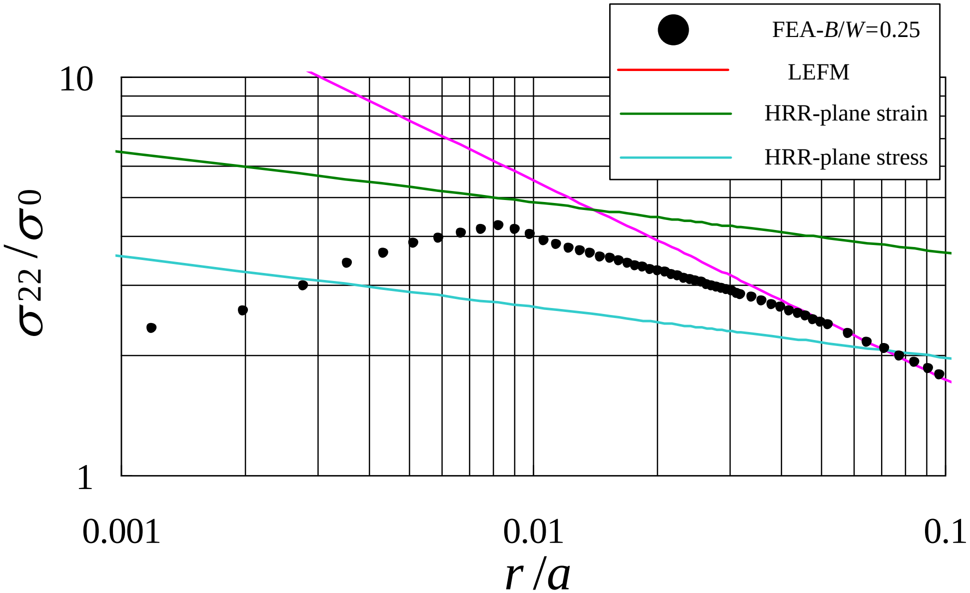
- The ‘planar’ failure criterion
  – Applicable for out-of-plane TST issue
- Lower bound J_c for S55C: $B/W \geq 1.5$
- Lower bound J_c could be predicted by T_{33}-stress

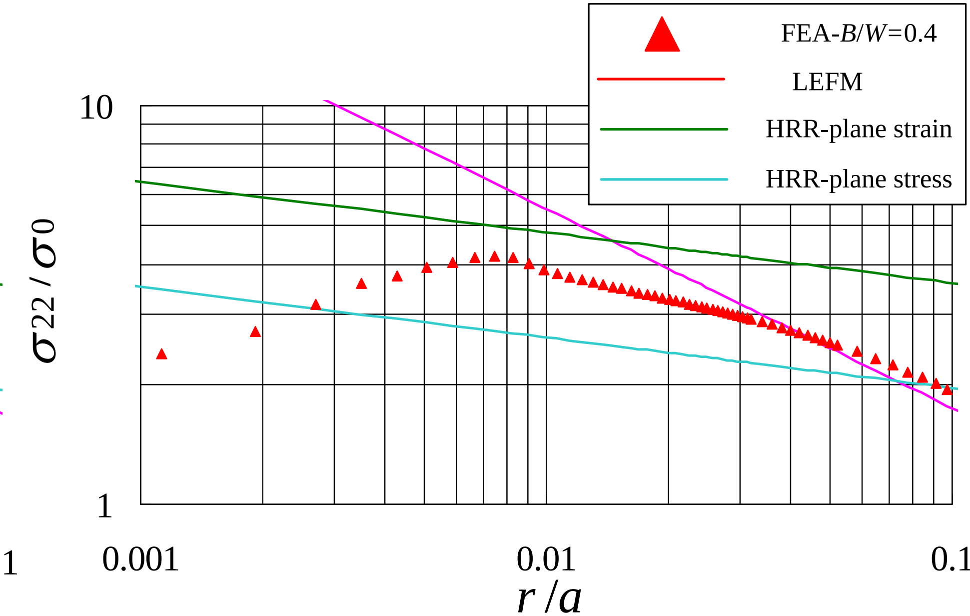
Next study plan…

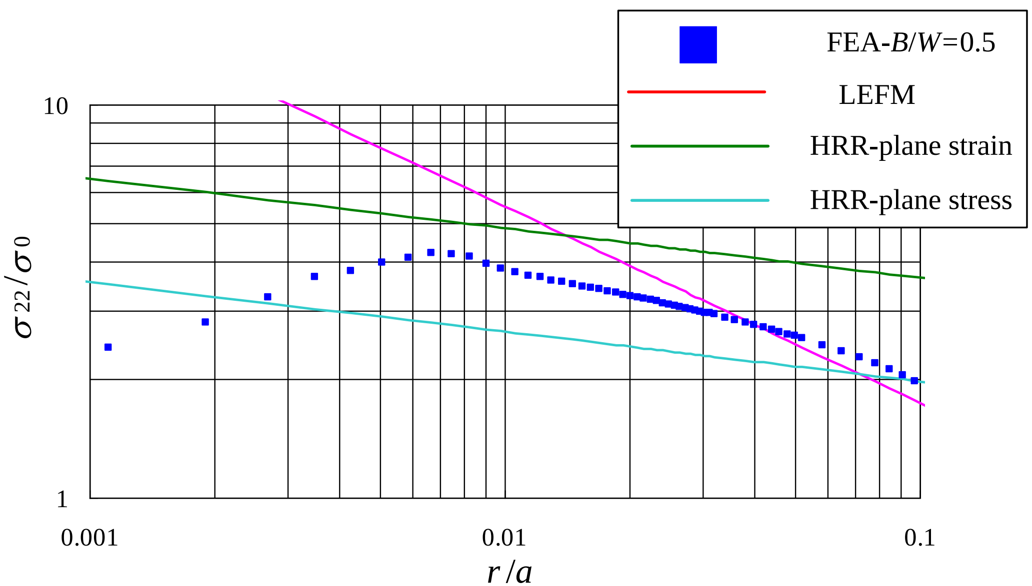
– Validate the lower bound J_c by fracture toughness test
– Numerical study for different materials and test specimens
– Correlate test specimen J_c with actual flaw

σ_{22} distribution ($\theta = 0$) at K_c=66 MPa m$^{1/2}$

CT-W=25 mm-B/W=0.25～0.5

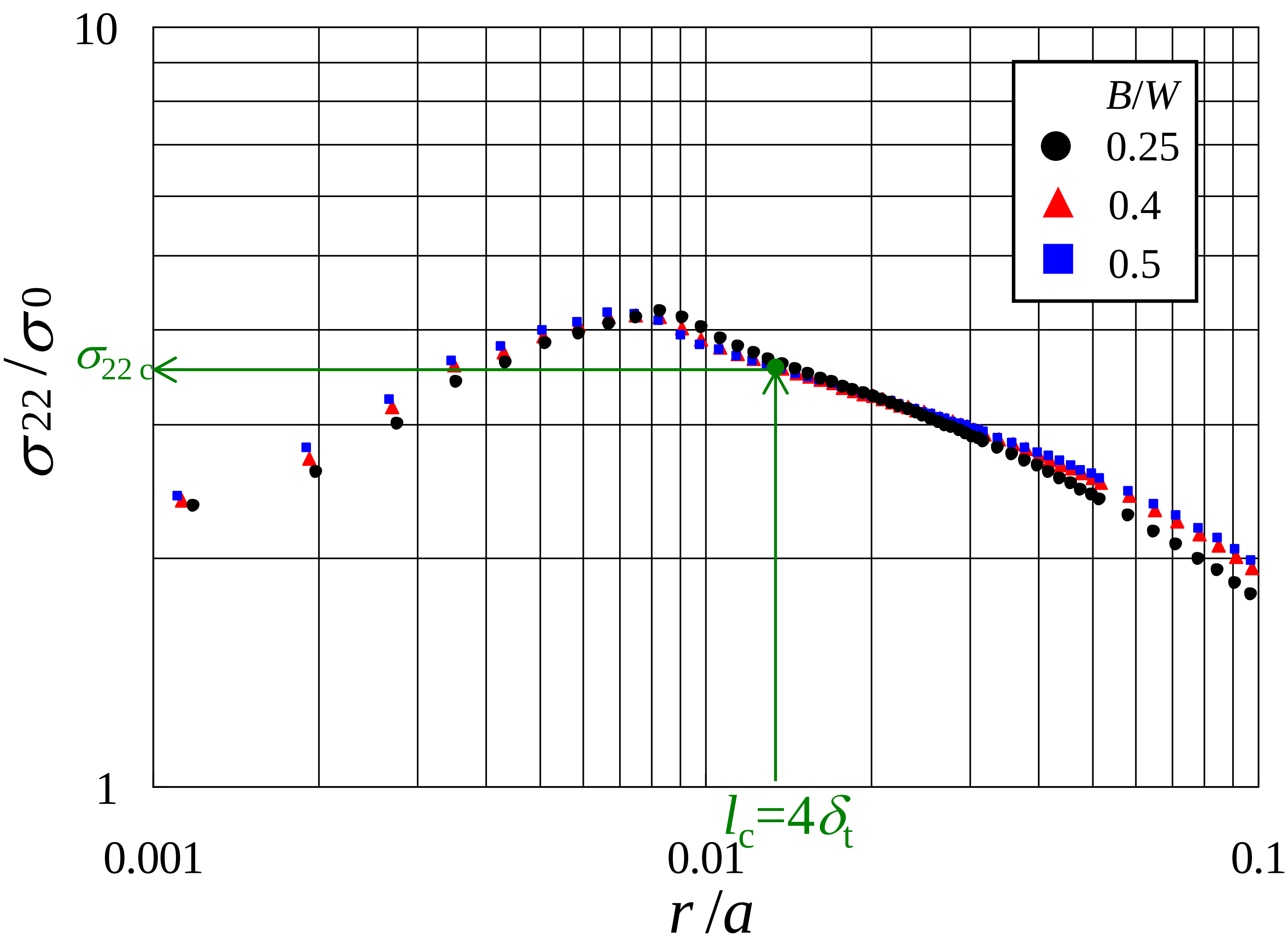






σ_{22} distribution ($\theta = 0$) at $K_{c\ S55C}$=66 MPa m$^{1/2}$

CT-W=25 mm-B/W=0.25～0.5

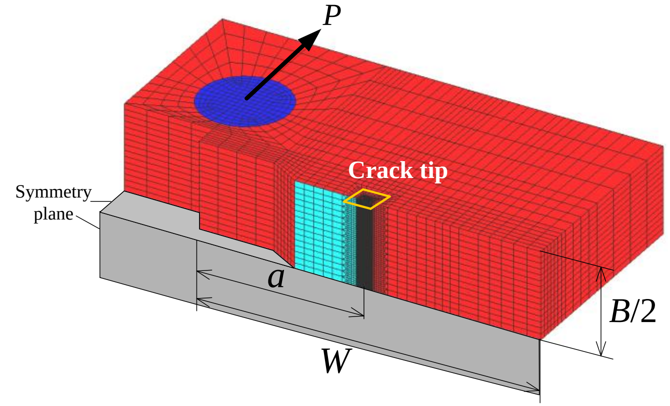


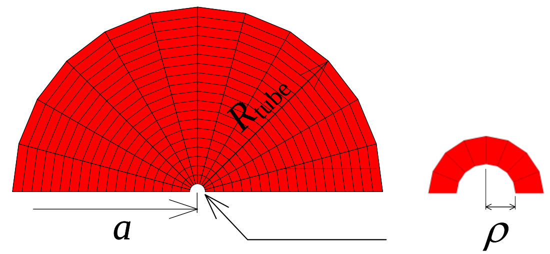
(l_c=0.16 mm, σ_{22c}=1530 MPa)

CT-W=25 mm-B/W=0.5-a/W=0.5

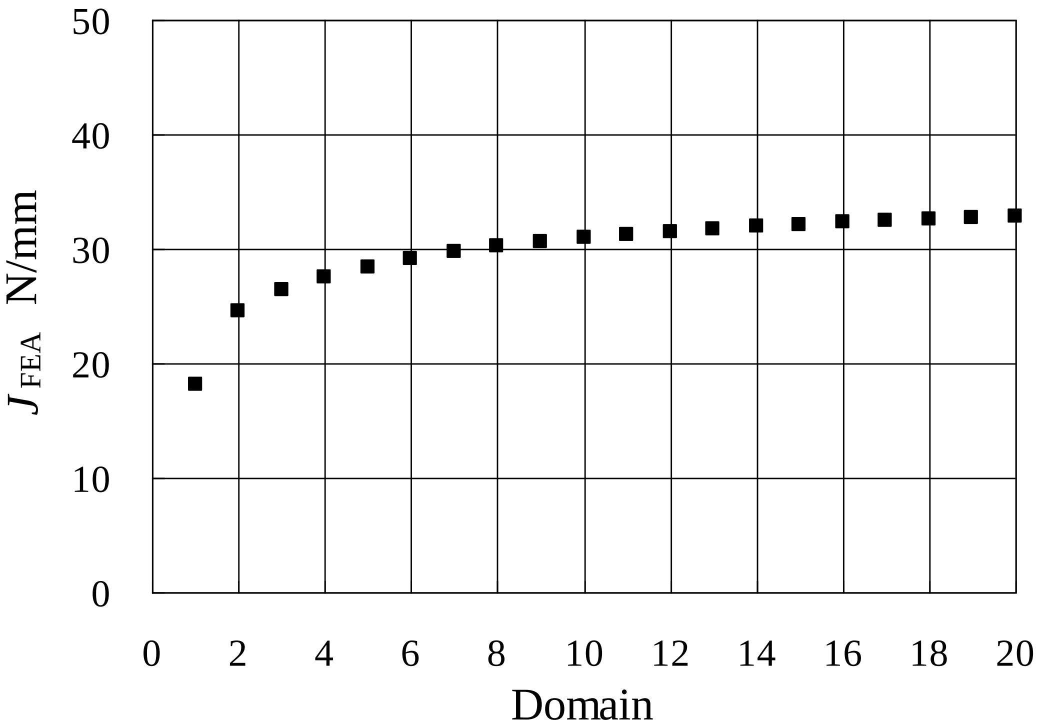
S55C: σ_0= 428 MPa, α =1.61, n=6.9, E=206 GPa

$K_{c\ \ S55C}$ = 66 MPa m$^{1/2}$





J values at thickness center:



CT-W=25 mm-B/W=0.5-a/W=0.5

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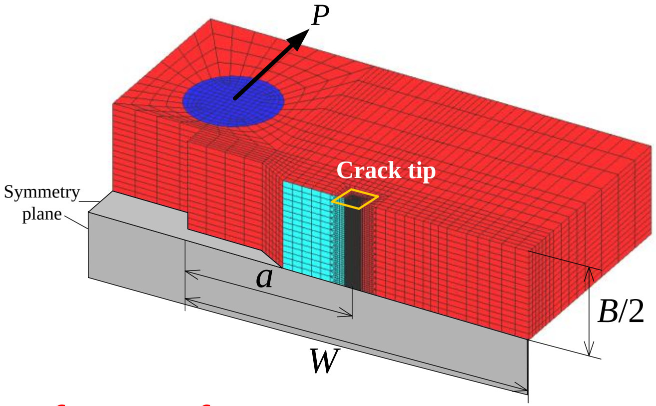
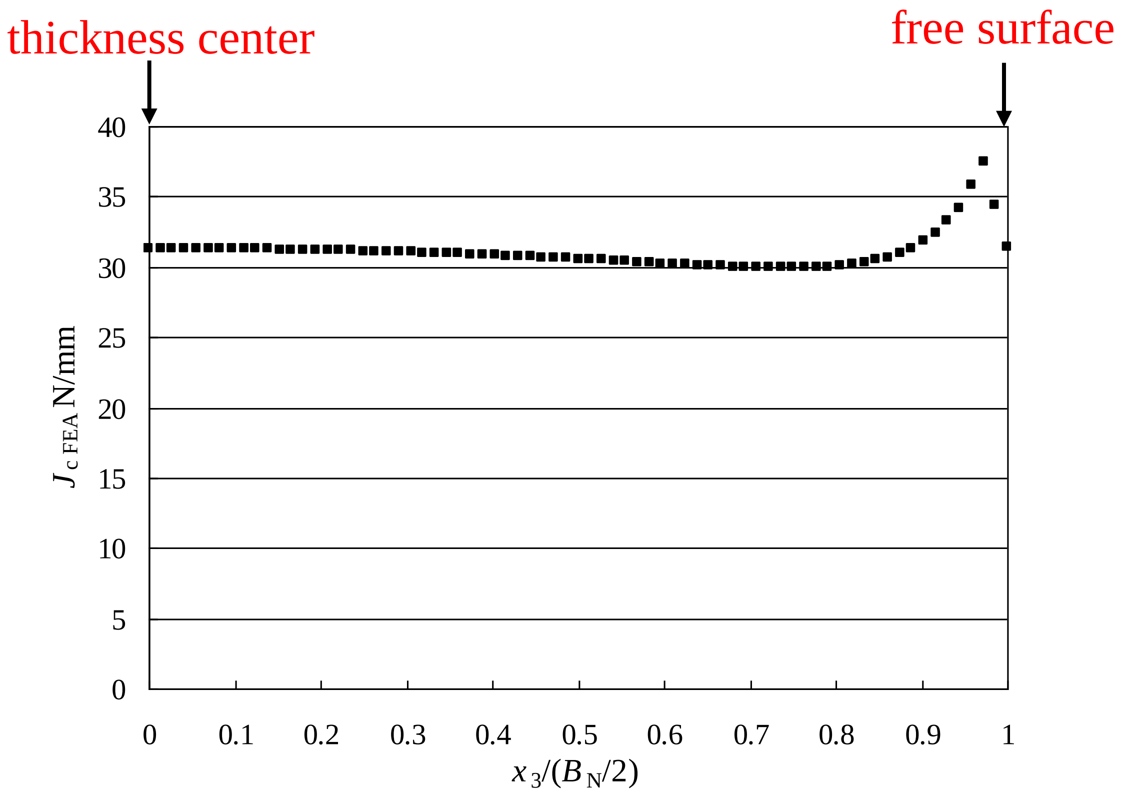


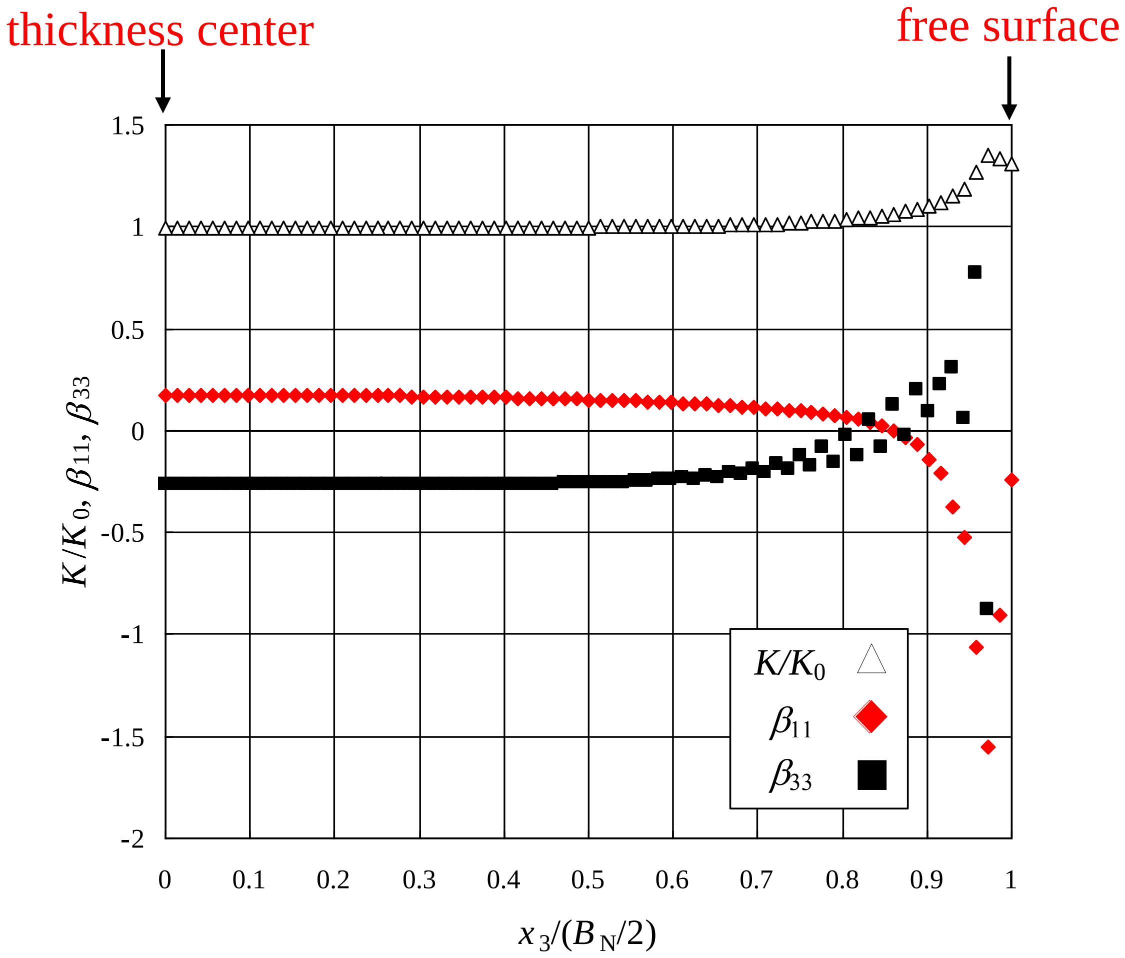
J values in thickness direction:



3PB-W=25 mm-B/W=0.5-a/W=0.5

E=206 GPa, ν=0.3

Elastic FEA results in thickness direction:

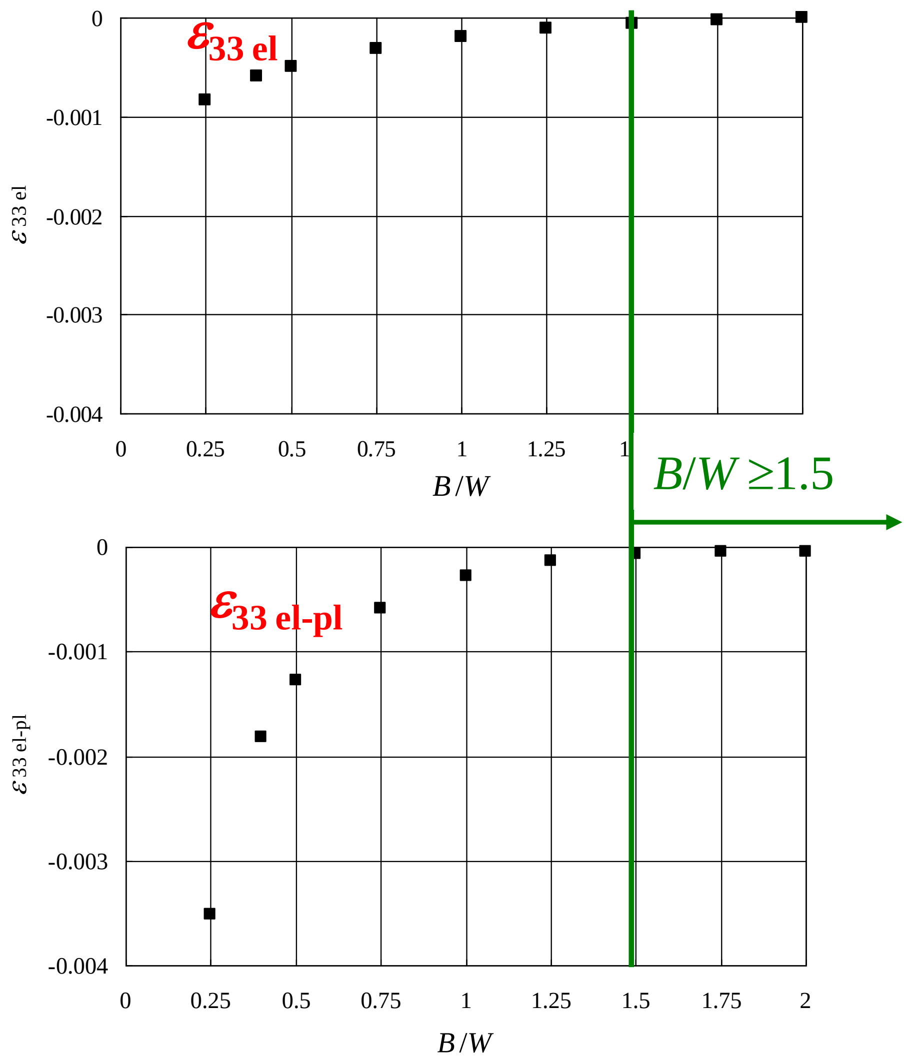


Q: Why TST effect on J_c could be expressed by T_{33}-stress ?

A: Out-of-plane ε_{33} at specimen thickness center

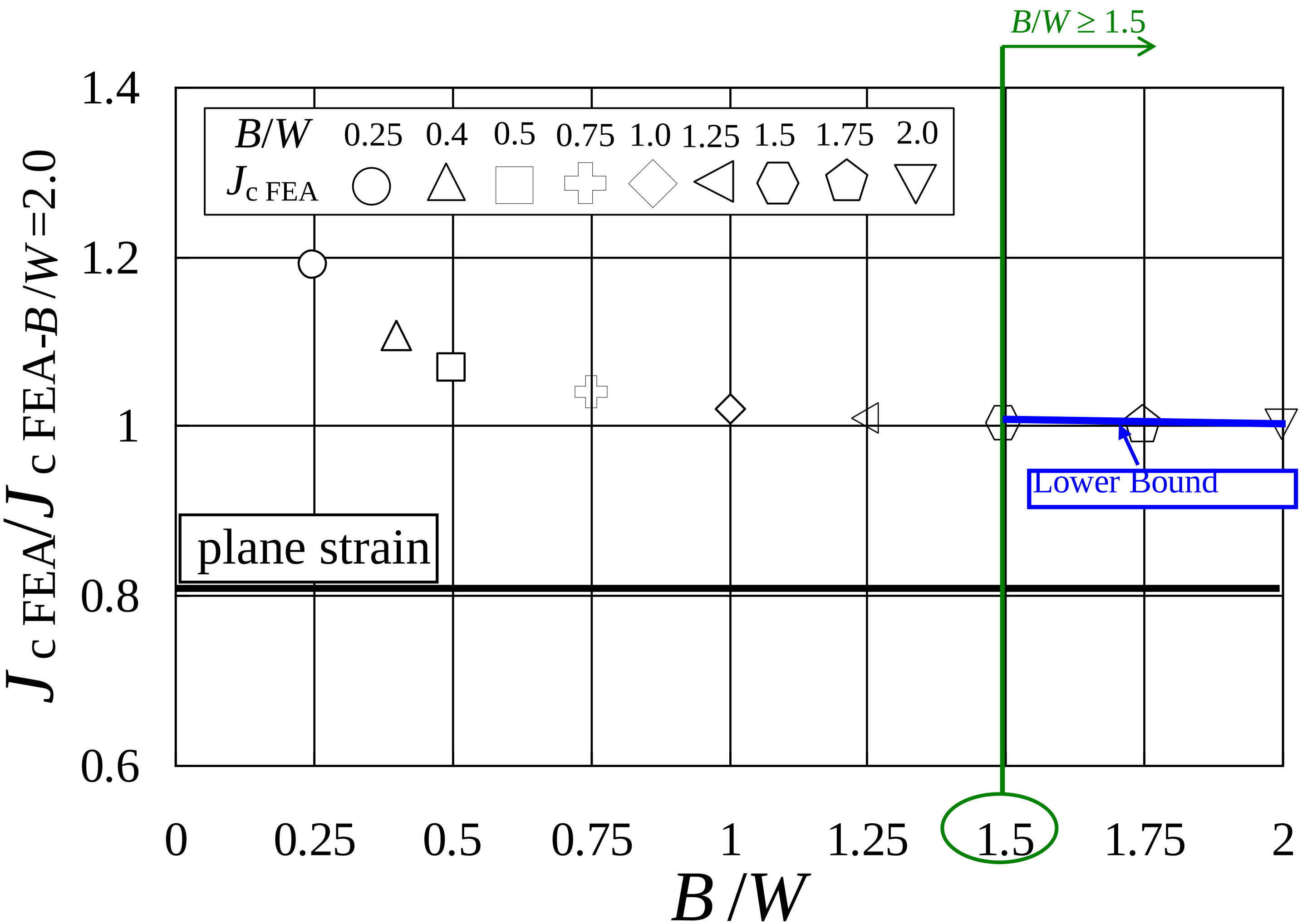
Elastic:

Elastic-plastic:



Q: Why the normalized lower bound $J_{c\ FEA}$ is not equal to plane strain J.

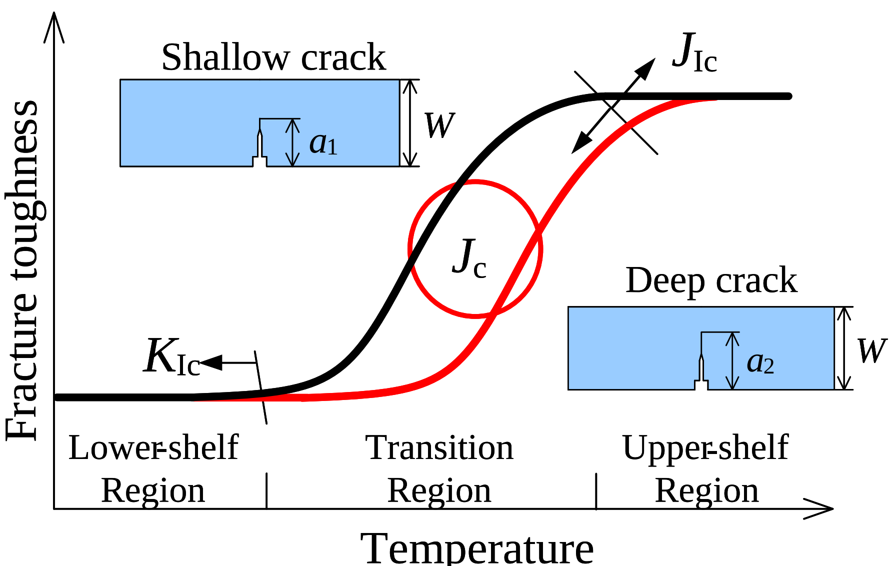
A: Full plastic 2D J solution according to the method by EPRI, in this work, we conducted 3D FEA for 3PB specimen.

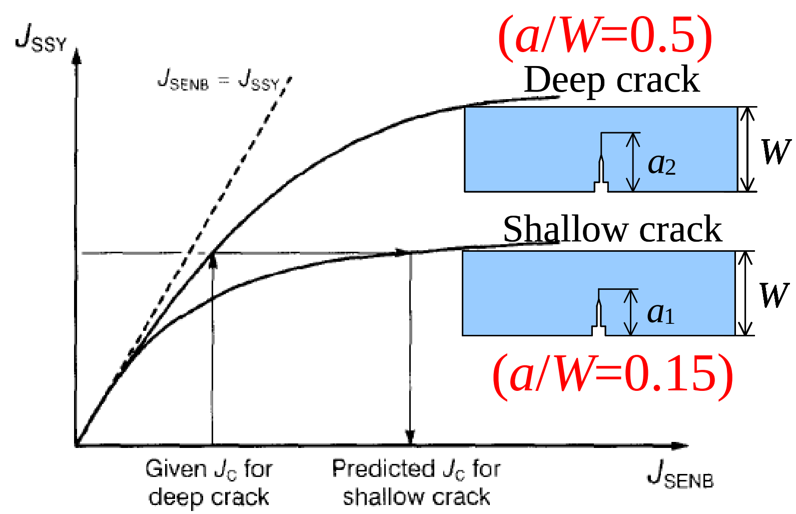


Q: How do you distinguish between shallow cracked specimen and deep cracked specimen ?

A: By now, no standard could be follow.

However, In Dodds et. al's works, they defined $a/W = 0.15$ (shallow crack) and $a/W=0.5$ (deep crack).





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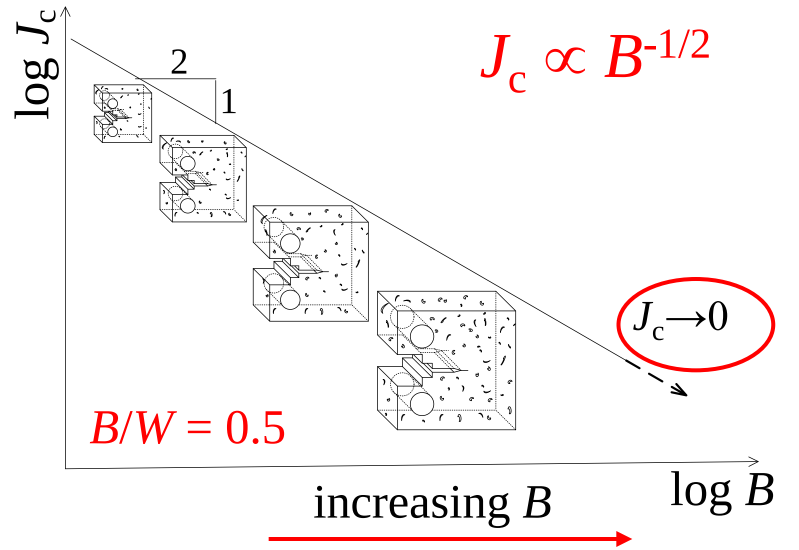
Q: What is the new point of view in your works ?

A:

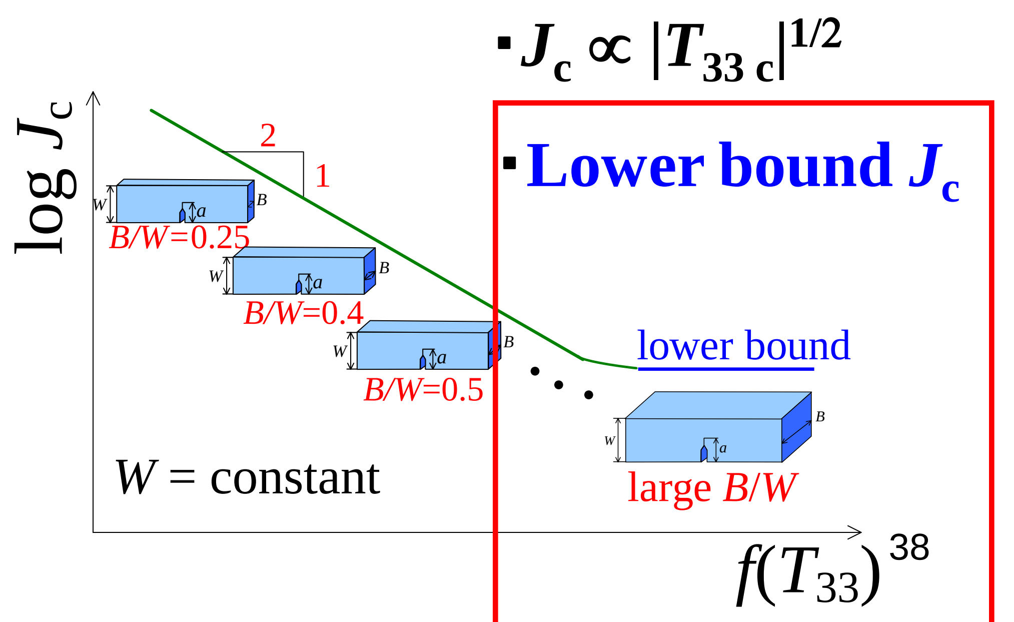
Anderson et al. :

material issue



Meshii et al. :

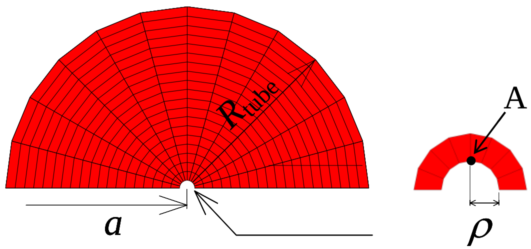
mechanical issue

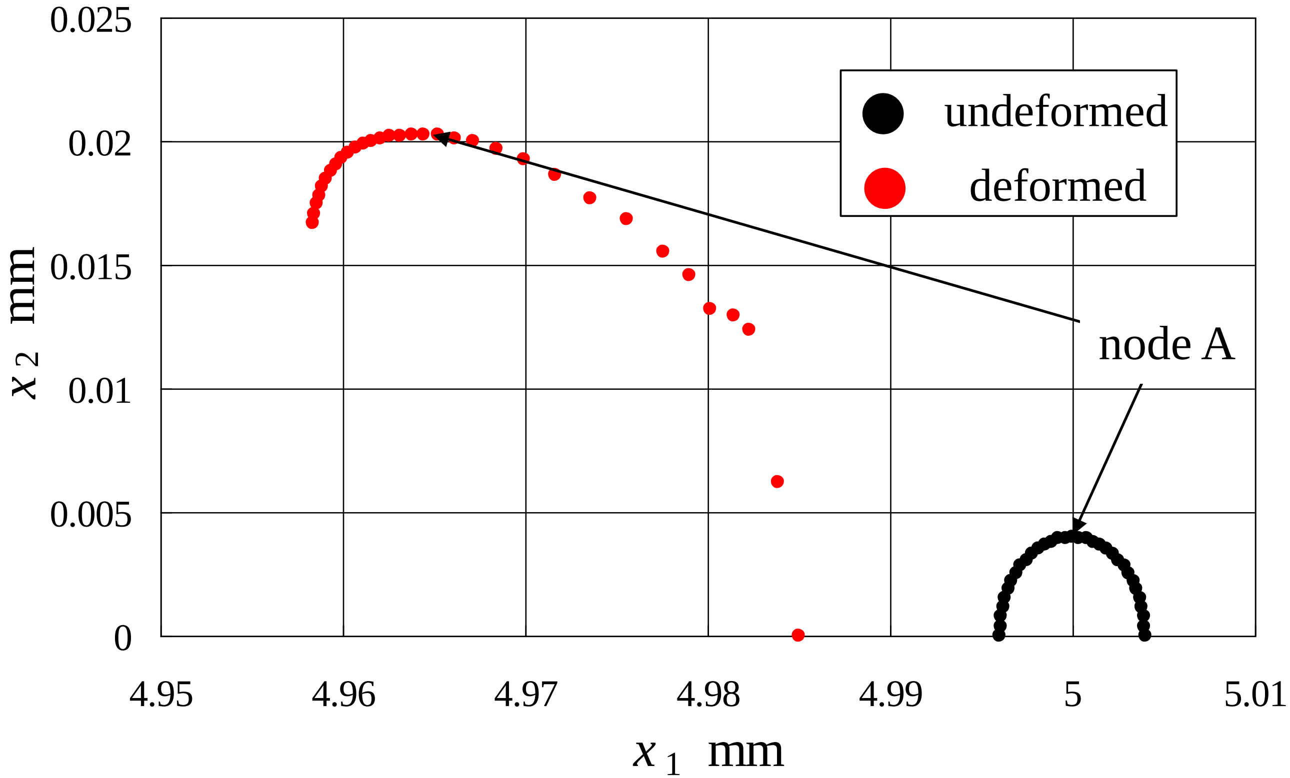


Q: In elastic-plastic FEA, how did you define the keyhole size ρ at the crack tip ?

A: McMeeking & Parks : CTOD $\geq 5\rho$. In this work, CTOD/$\rho \geq 10\rho$

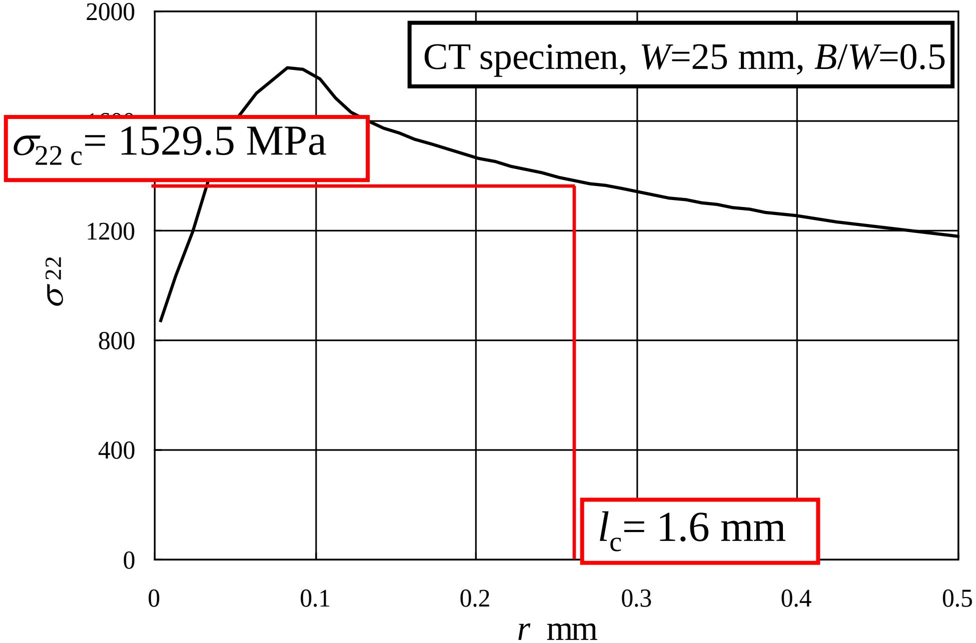
δ_t: Crack tip opening displacement; CTOD

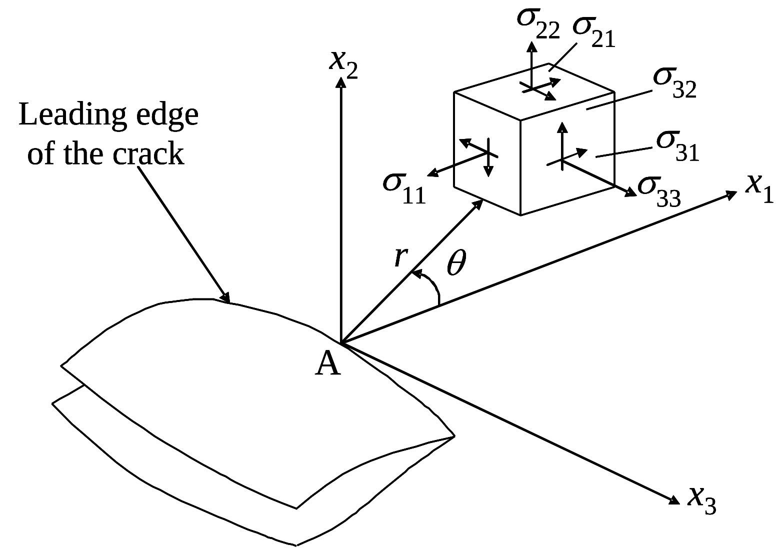




Q: The σ_{22c} value of the failure criterion obtained in this work is very large.

A: For three dimensional cracks, considering triaxial stress state, the equivalent Mises stress was below the true tensile stress σ_B.





$$\sigma_{Mises} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

$$\sigma_{\mathrm{Mises}} < \sigma_{\mathrm{B}}$$