Triaxial Residual Stress Effects in Fracture

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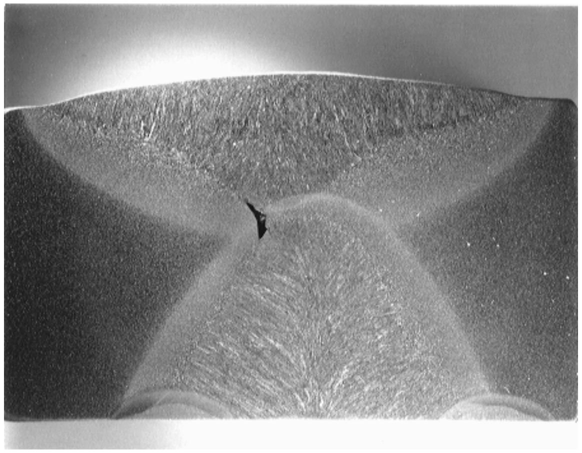
Weld Fracture



- Defects provide location for fracture initiation
- Residual stress impacts fracture process
  - Opening stress
  - Driving Force
- Non-linear interaction of applied and residual stress at the crack-tip
  - Crack-tip yielding in metals
  - Residual stress (RS) can impact constraint

Outline

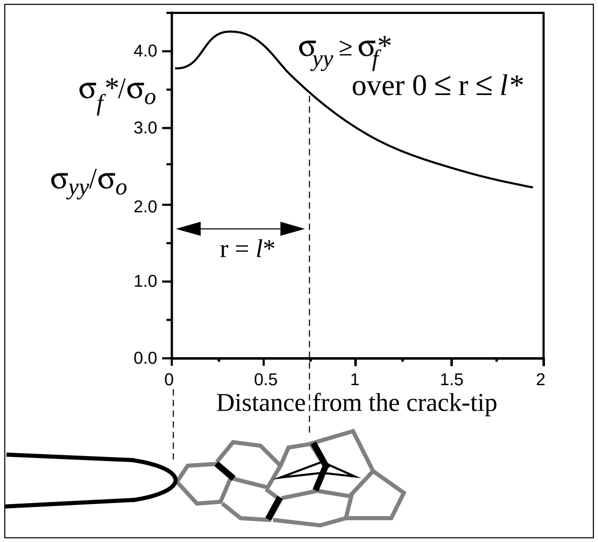
- Predicting RS effects in fracture
    - Computational framework
    - Micromechanical fracture models
    - *J*-*Q* theory
- Example applications
    - Brittle fracture in welded pressure shell
        - Computation only
    - Ductile fracture in locally-compressed bend bars
        - Experiment and computation
- Discussion

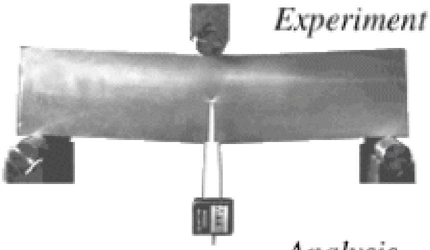
Computational Framework

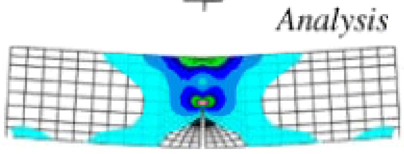
- Elastic-plastic finite element modeling
    - Incremental, J_2 plasticity and finite strain
    - Resolve stress and strain close to the crack-tip
- Employ micromechanical damage models
    - Continuum material response assumed
    - Crack-tip state used directly to predict fracture
- Include residual stresses
    - Eigenstrain
    - Direct process simulation
- Interpret results using *J-Q* theory
    - Quantify driving force *and* constraint effects

Brittle Micromechanical Model

- RKR model for cleavage
  - Critical stress for fracture, σ_f^*
  - Microstructural length scale, l^*
- FEM provides crack-tip stress
- Calibration of σ_f^* and l^*
  - Testing and computation
- Micromechanics defines fracture
  - J_c and Q known from computation

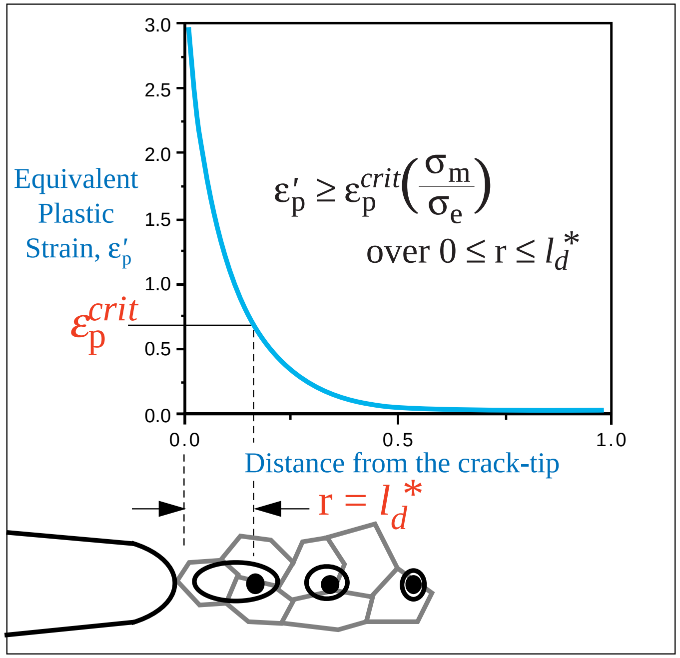






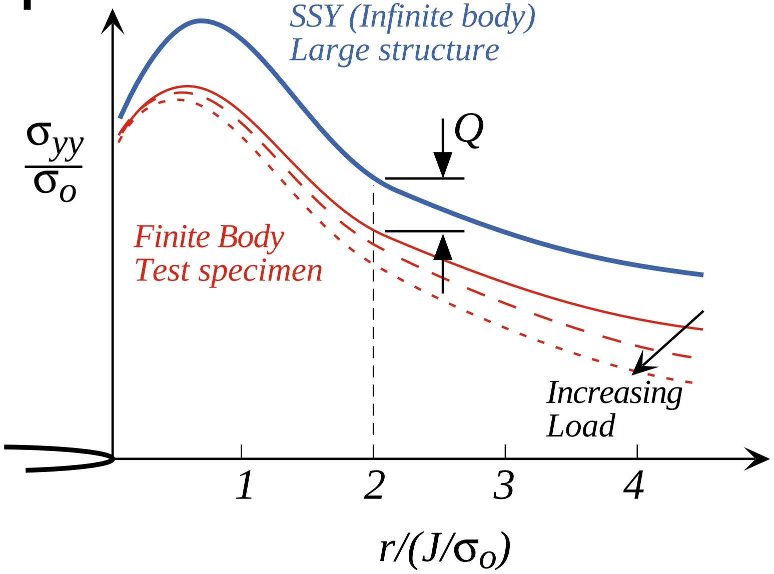
Ductile Micromechanical Model

- Stress-modified critical strain (SMCS)
  - Plastic strain to failure ε_p^{crit}
    - Void growth driven by ε'_p
    - Depends on triaxiality (σ_m/σ_e)
  - Length scale, l_d^*
- FEM provides crack-tip stress and plastic strain
- Calibration
  - Notched tensiles give $\varepsilon_p^{crit}(\sigma_m/\sigma_e)$
  - Fracture specimens give l_d^*



J-*Q* Theory

- Crack-tip stresses are *not* predicted by *J* if constraint varies from SSY
- Constraint altered by:
  - Size
  - Loading mode
  - Crack geometry
- Define the parameter *Q*
  - Difference in opening stress @ same *J* and x = n(J/σ_o); n = 2 to 5
  - Usually negative
- *J* and *Q* together describe crack-tip stress



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  - *J-Q* theory
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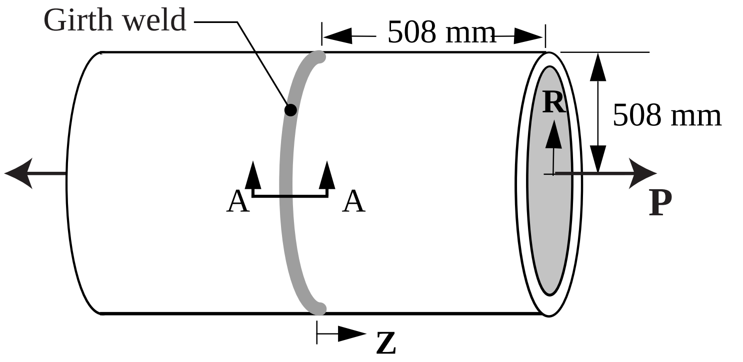
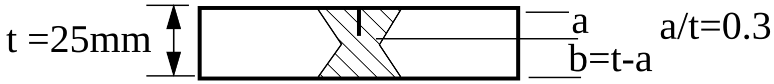
Example: Fracture of a Welded Shell

- Large diameter, thin-walled structure ($R_o/t = 20$)
  - Mild steel (A516-70)
    - Yield: $\sigma_o = 300$ MPa
  - Two-sided girth weld
  - Axial load
- External girth flaw $a/t = 0.3$
- Cleavage fracture
  - RKR micromechanical model: $\sigma_f^* = 3.5\sigma_y$ and $l^* = 3$ grain diameters
- Analyze with and without RS

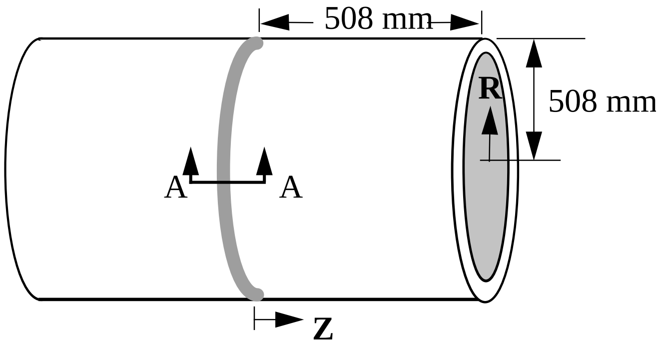


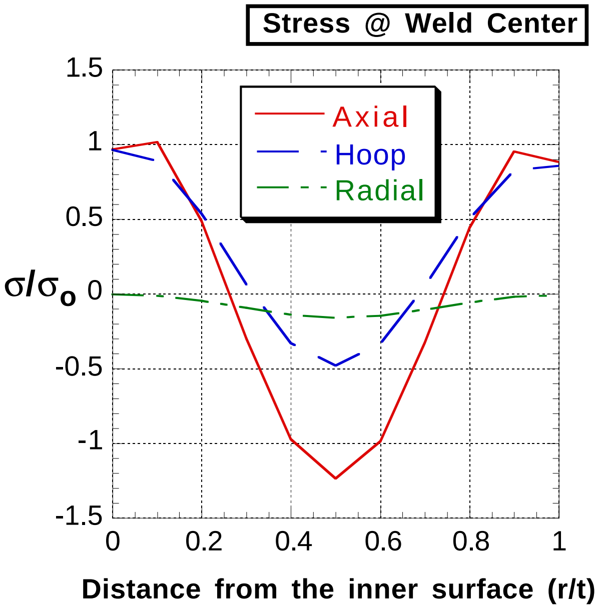


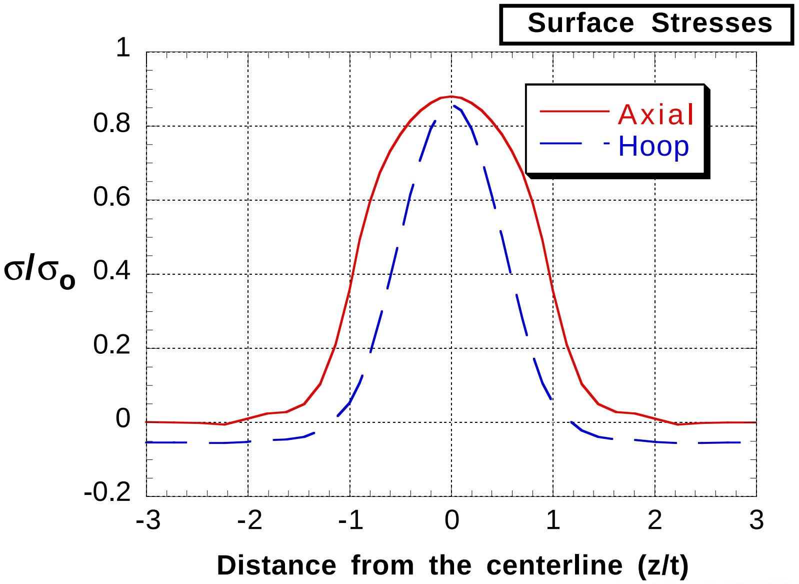
Section A-A

Residual Stress in Welded Shell

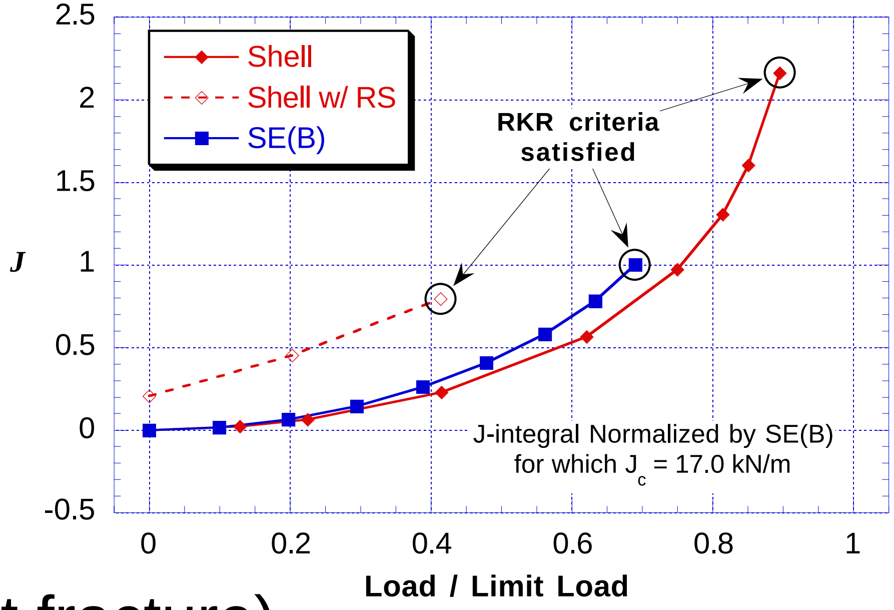
- Residual stress assumed independent of θ
- Stress computed by imposing eigenstrain





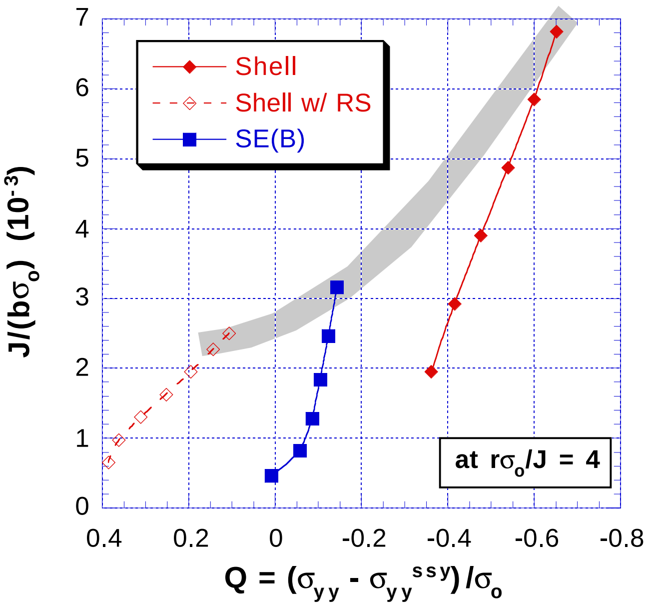


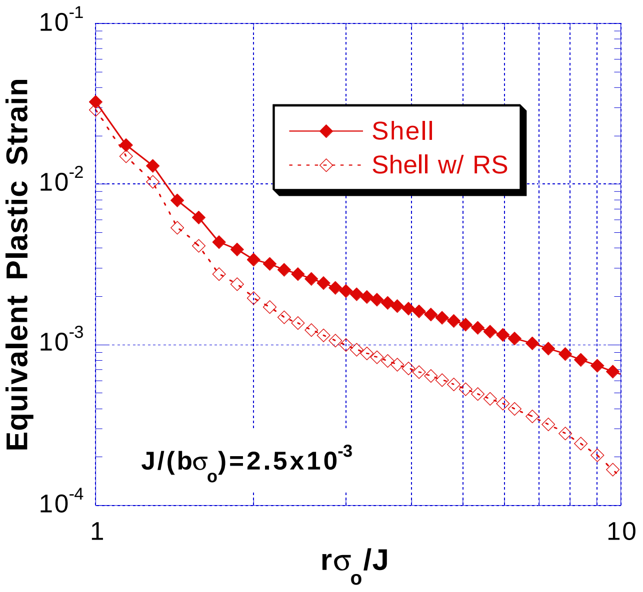
Welded Shell - Global Results



- ❑ RS alters *J*-integral
  - ◆ Driving force
- ❑ RS alters both load and *J* at fracture
- ❑ RS causes
  - ◆ 54% drop in P_c (load at fracture)
  - ◆ 63% drop in J_c (*J* at fracture)
- ❑ J_c is about 20% less than SE(B) with a/W = 0.3

Welded Shell - Local Results

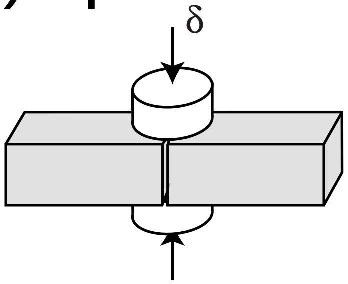


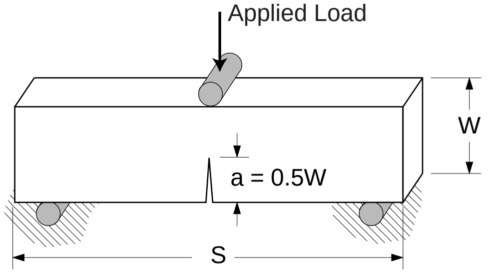


- *J-Q* analysis quantifies constraint change
- Residual stress *increases* constraint
- Low-constraint geometry *and* a well-constrained crack-tip field (~SSY)
- SE(B) does not bound behavior

Example: Locally-compressed SE(B)'s

- Locally-compressed, SE(B) specimens
  - 7050 T7415 aluminum
    - S_y = 530 MPa
  - Standard SE(B) specimens
    - W=25 mm
      S/W = 4
      a/W = 0.5
      Bx2B (W=2B) and BxB

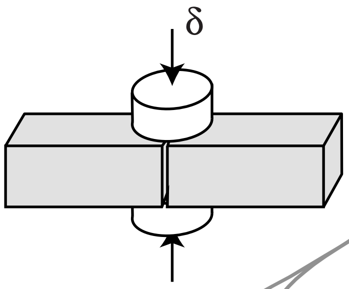




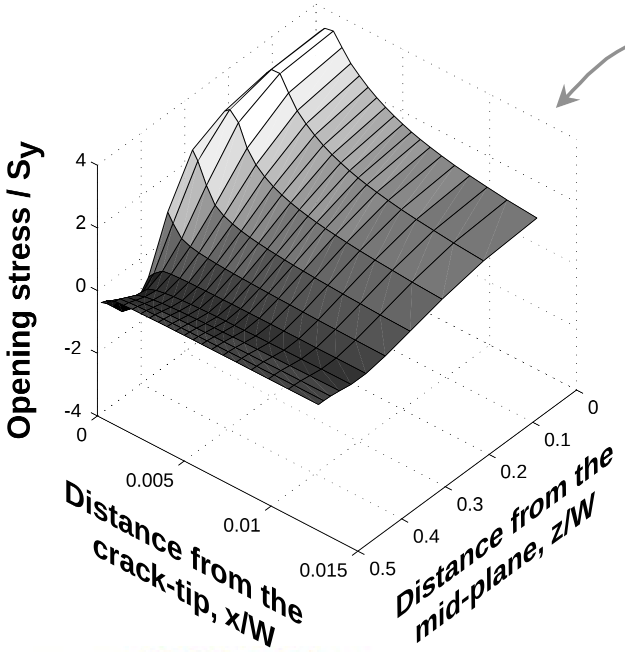
- Low-energy ductile fracture
  - SMCS micromechancial model:
    - $\varepsilon_p^{crit}(\sigma_m/\sigma_e)$ from notched tensiles, l_d^* = 150µ
- Test and compute

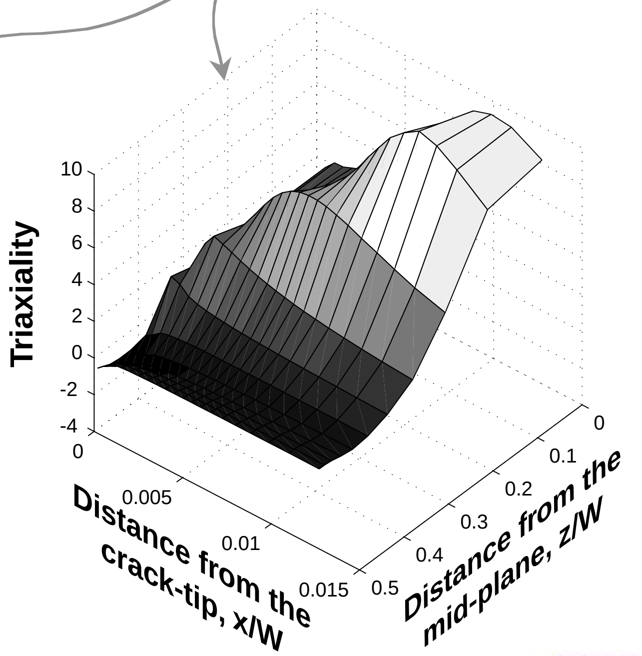
Residual Stress in SE(B)'s

- Residual stress from direct simulation
  - Positive driving force
  - Triaxial RS field



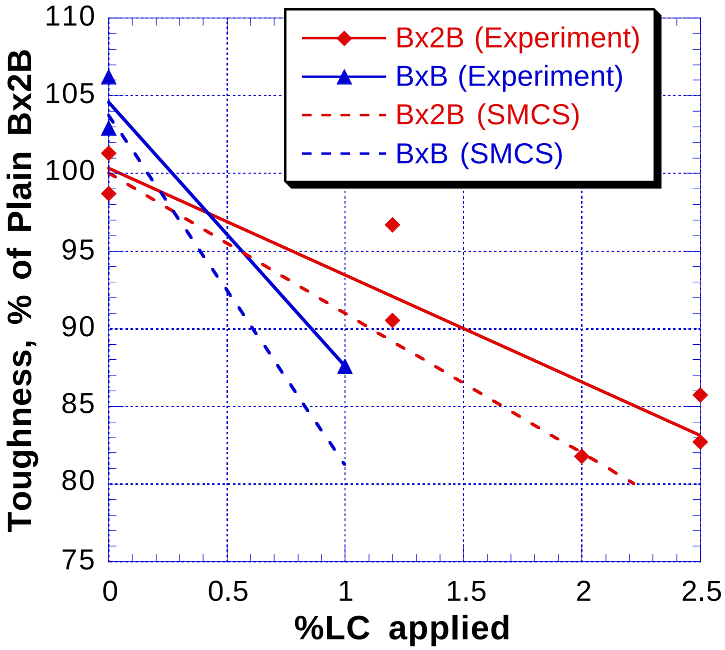
Analysis Steps:
1. Compress
2. Release
3. Extend Crack
4. Apply Load





Compressed SE(B)'s - Global Results

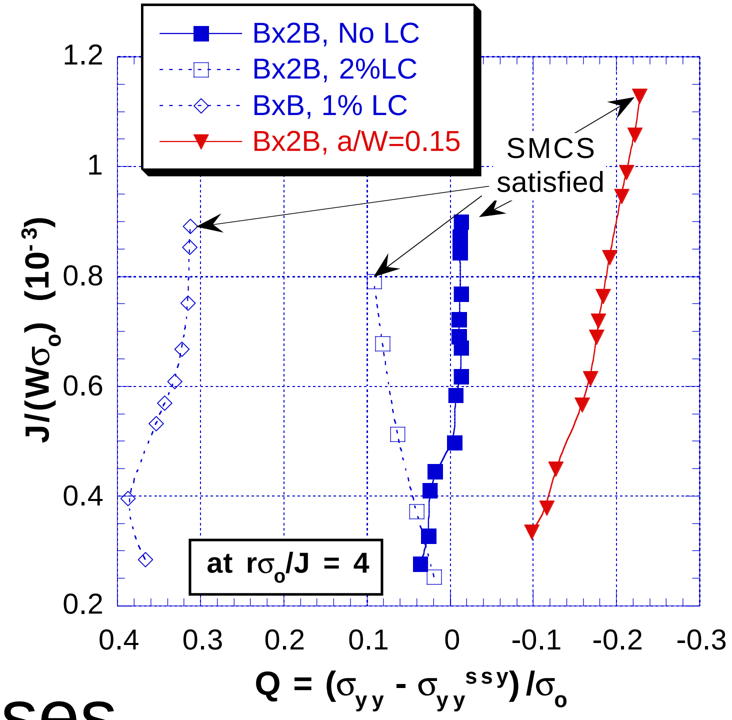
- Toughness determined using ASTM E399, K_Q
  - Based on load, geometry
- LC reduces toughness
  - Effect larger in BxB
  - Combination of driving force and constraint



- Computational results plotted using P_c
  - All crack-lengths the same
- SMCS over-estimates the effect of LC

Compressed SE(B)'s - Local Results

- Compression increases crack-tip constraint
- Effect of constraint change varies
  - Bx2B: reduced J_c
  - BxB: no change in J_c
- Load drop has different causes
  - Bx2B: driving force and constraint
  - BxB, 1%LC: driving force only



Conclusions

- ❑ Framework described fully accounts for RS
  - ◆ Models non-linear interaction of crack-tip fields
  - ◆ Predicts fracture using the crack-tip fields directly
  - ◆ Residual stress effects distinguished
    - Driving force *and* constraint
  - ◆ Predicts laboratory test results
- ❑ Residual stress changes constraint
  - ◆ Second effect, in addition to driving force
  - ◆ Ignored by superposition
  - ◆ Can lead to non-conservative assessment
    - Toughness does not follow from geometry
      - – Shell: SSY field in low-constraint geometry