Western Bridge Engineers' Seminar

ADVANCES IN DESIGN, CONSTRUCTION, INSPECTION & PRESERVATION OF BRIDGES

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Fracture and Fatigue Properties of Seriously Damaged Steel Bridge Structural Members Repaired through Heat-Straightening

Kaiyuan Liu, PhD, PE

Parsons Brinkerhoff in Seattle, email: liuk@pbworld.com

David Mukai, PhD, Associate Professor

University of Wyoming, email: dmukai@uwyo.edu

Outline

- A brief introduction of heat-Straightening

  - history, how it works, concerns...
- Current research and engineering practices
- Fracture properties of heat-straightened steel plate w/ weak-axis damage

  - methodology, results and discussions
- Conclusions

Brief History

- First publication: 1938
- Into 1980s: half of USA states still didn’t allow heat-straightening (for bridge)
- 1970s to 2000s: research into basic material properties

How it works-the V-heat

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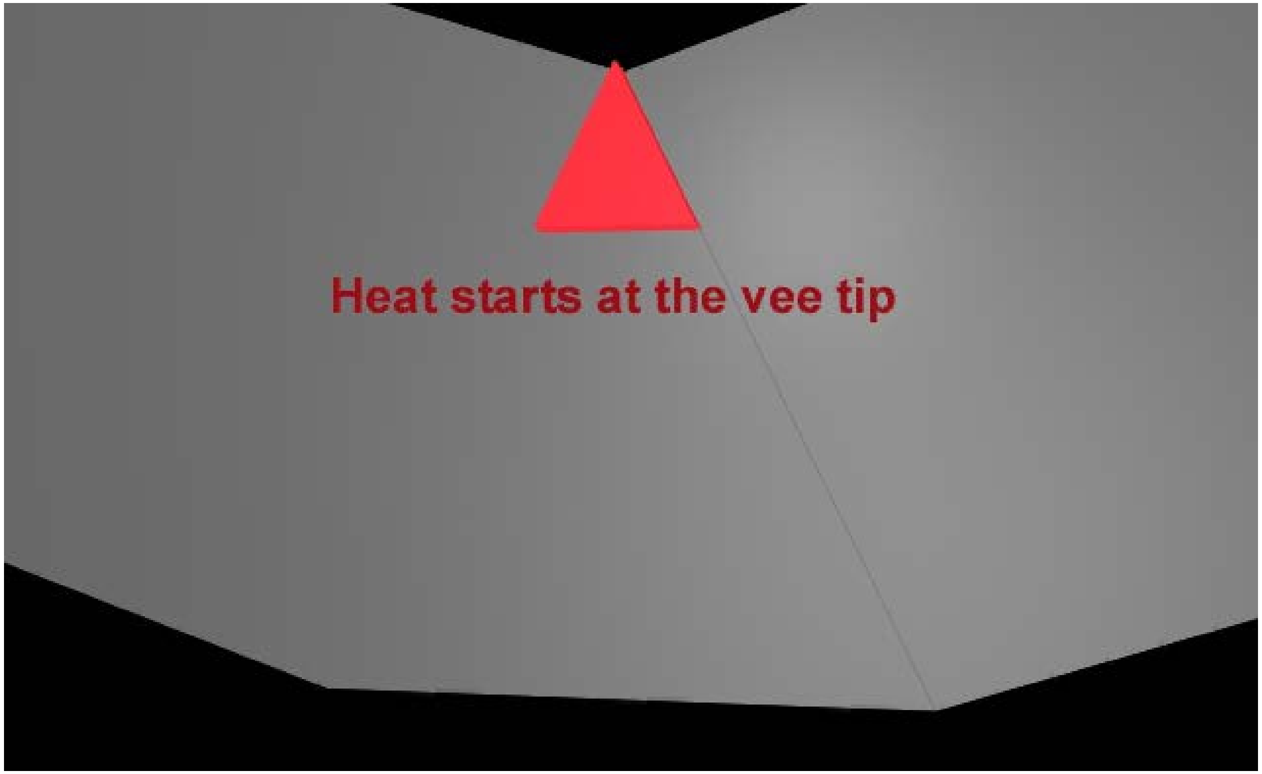

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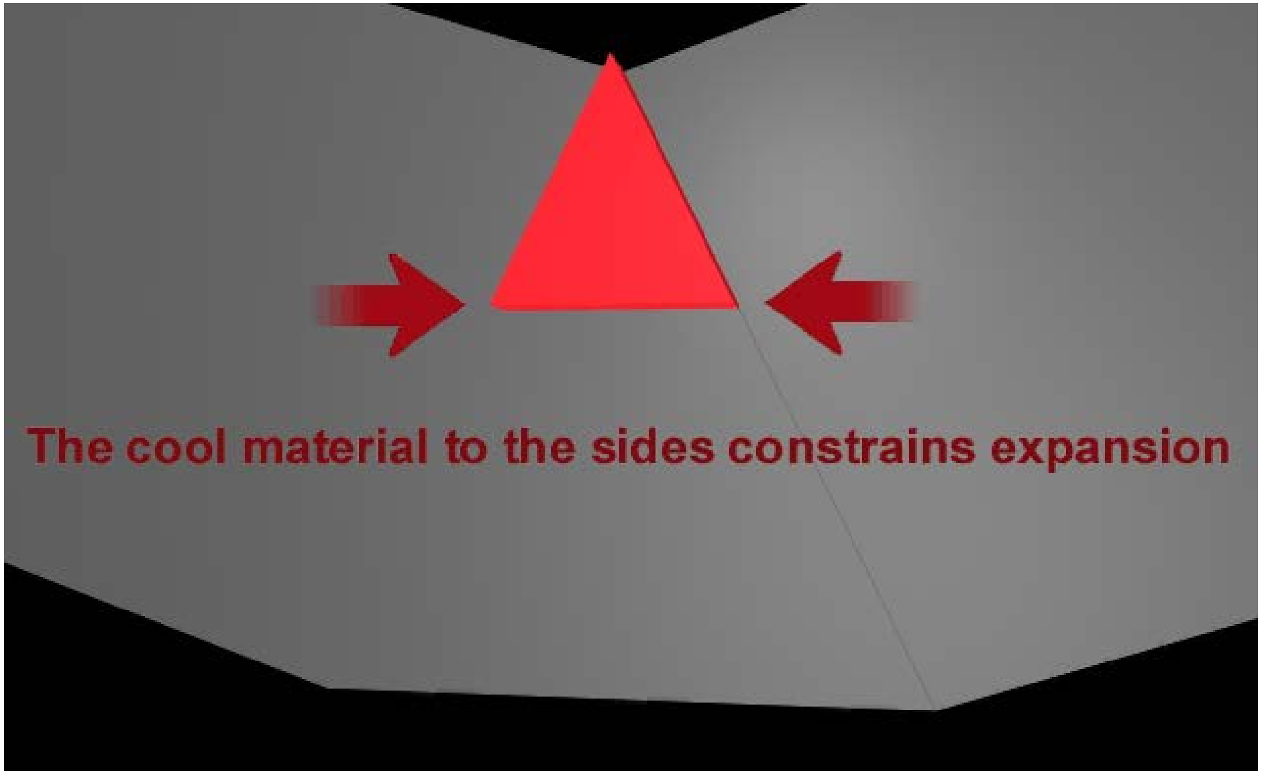
How it Works

V-heat starts at the tip, temperature below transition temperature, below 650 C



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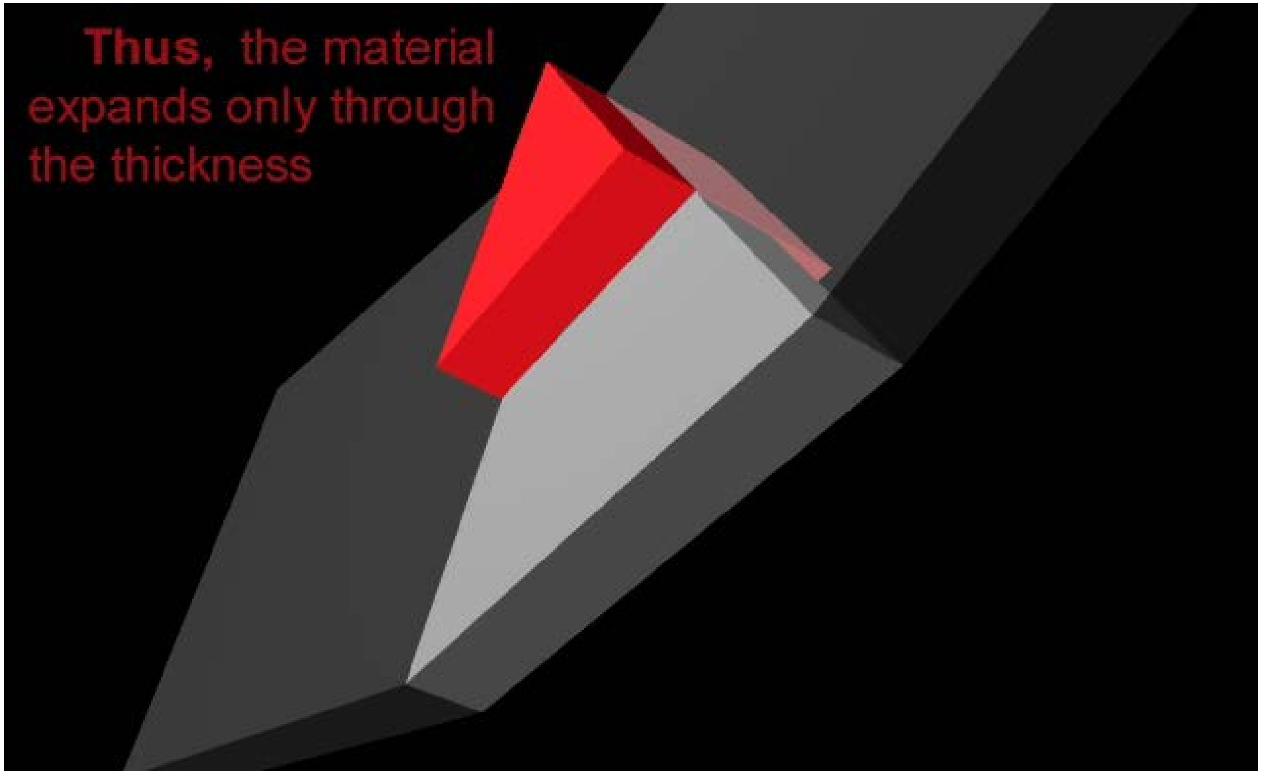
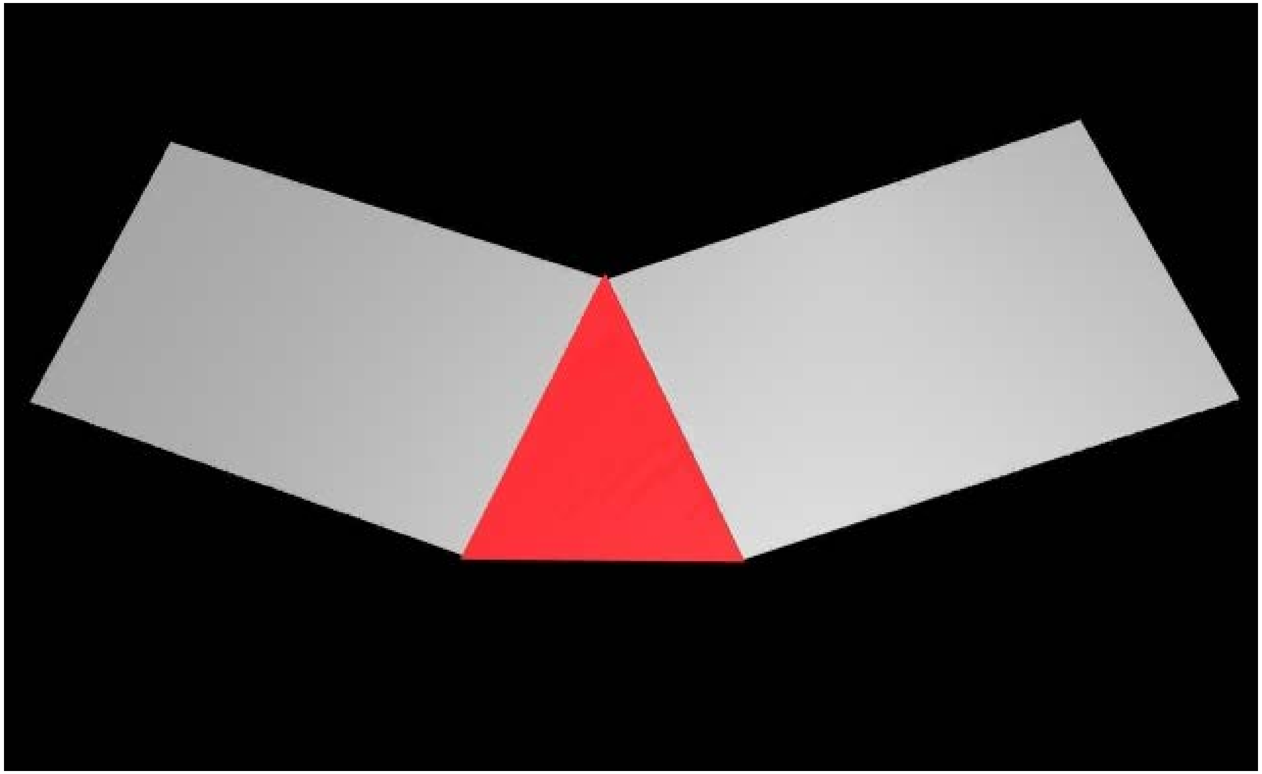
How it Works

The cool material to the sides constrains expansion



How it Works

The material only expands through the thickness



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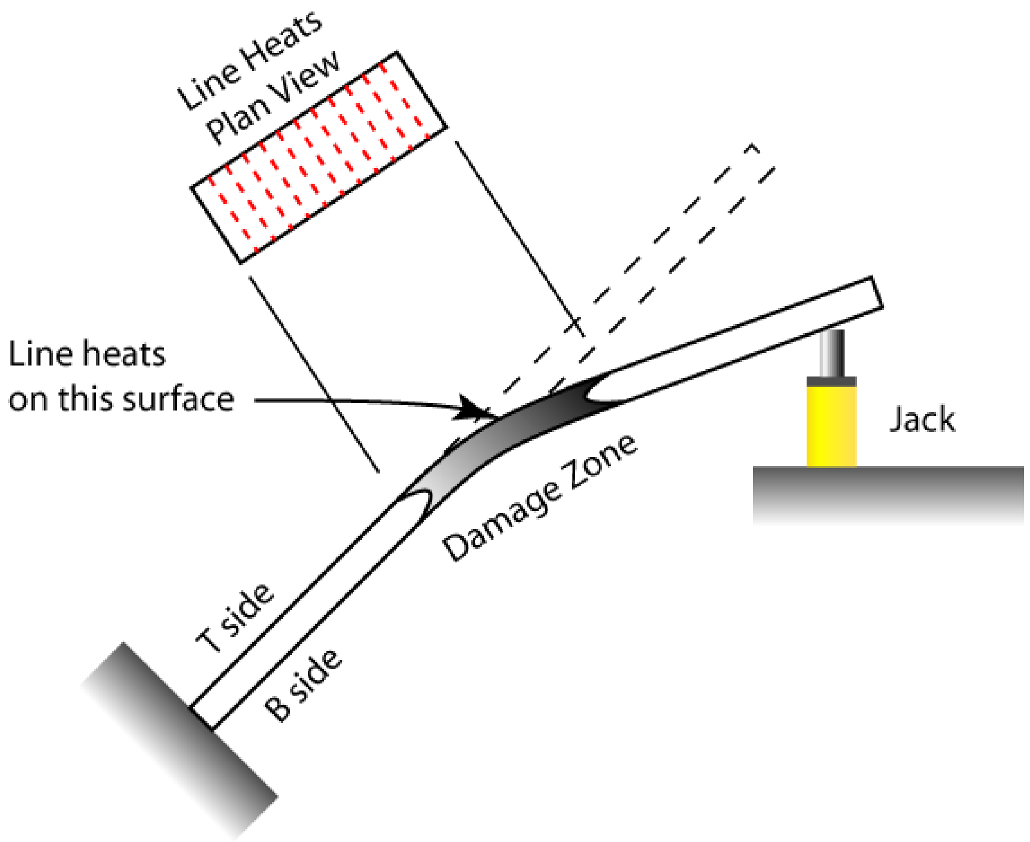
How it Works

As it cools, it contracts through the thickness as well as across the width.

How it works - line heats



Schematic of weak-axis damage repair with a jacking force

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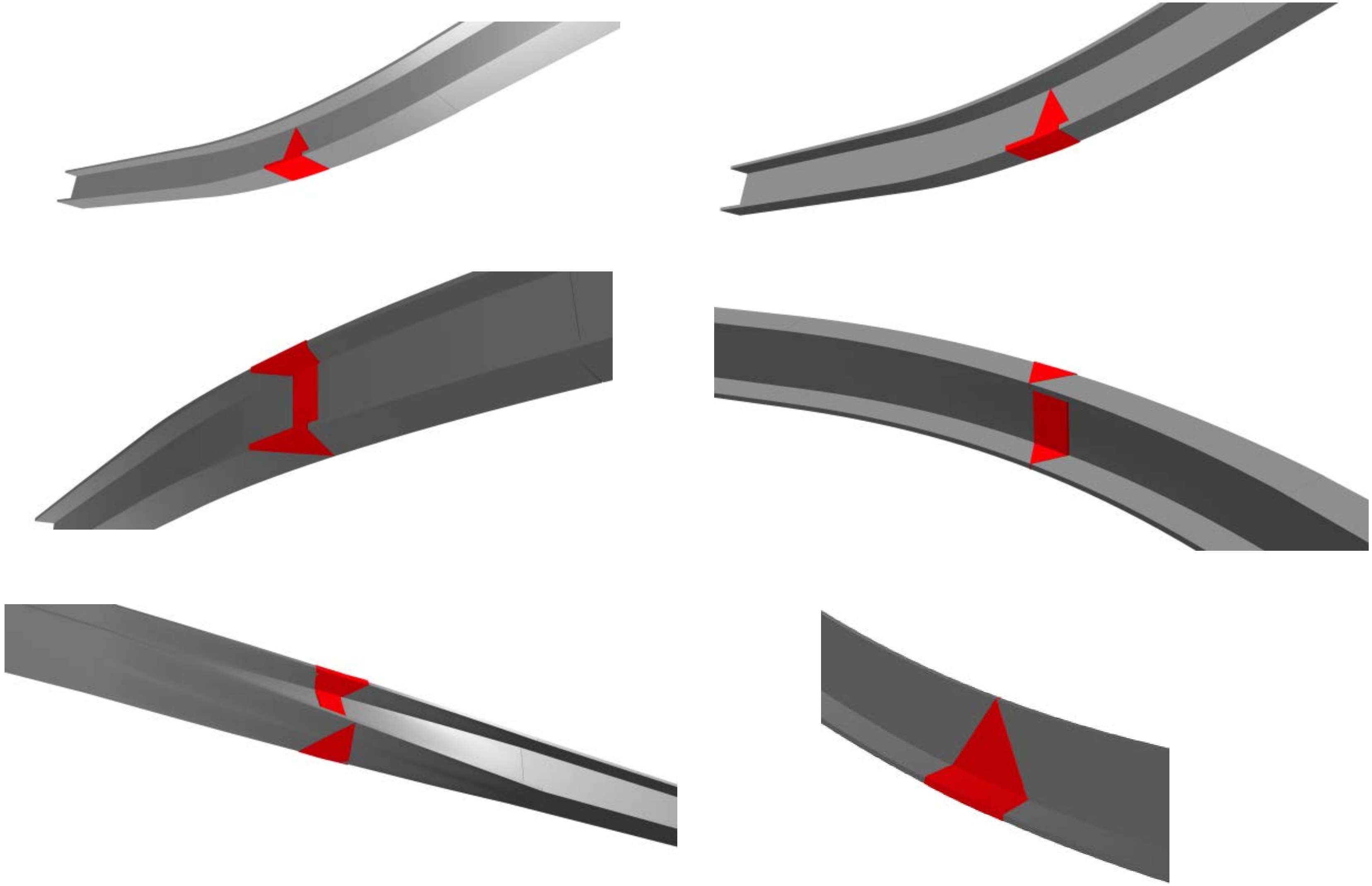
Combination of…



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Concerns . . .

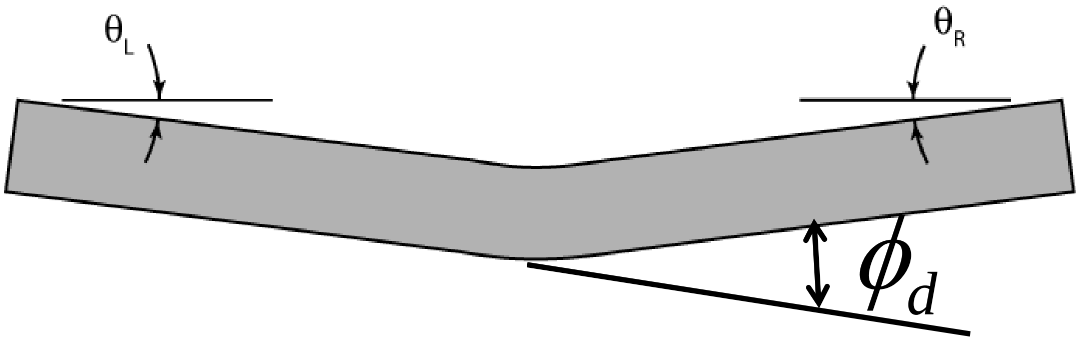
- Heat-straightening may be detrimental to material properties
- Limit of applying heat-straightening not very clear
- Engineers occasionally noticed cracks in heat-straightened steel members…

  - lack of extensive research in fracture

Current Practices-Parameters

- 1st parameter:

  Degree of damage or strain ratio
- Total angle change across damaged zone



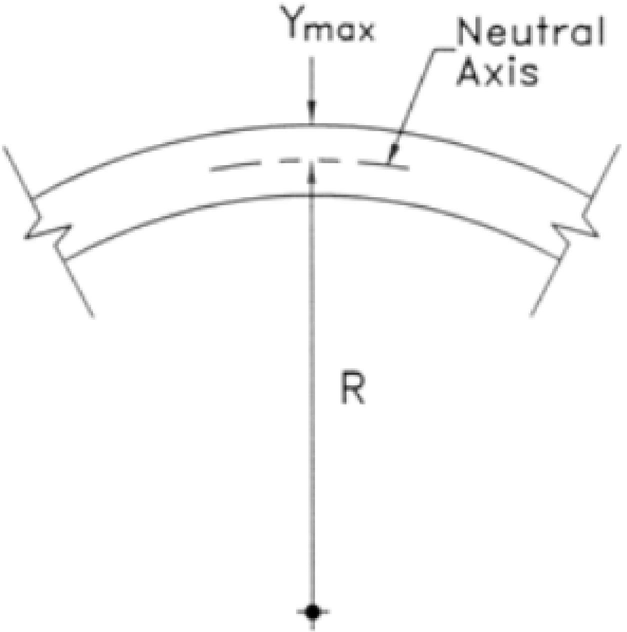
$$\phi_d = \theta_L + \theta_R$$

- Strain ratio, μ ,

  Ratio of maximum strain to yield strain

$$\varepsilon = \frac{Y_{max}}{R}$$

$$\mu = \frac{\varepsilon}{\varepsilon_y} = \frac{R_y}{R}$$



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Where Ry is curvature at yield

- 2nd parameter:
  External restraint, further restrain expansion or, called jacking ratio, j

$$j = \frac{M_j}{M_P}$$

$M_{j,}$ bending moment due to jacking force

M_p, plastic bending moment capacity

- Expedite the repair
  (j<50%, Fy reduced by 50% at 600 C)

Current Practices - Limit

- http://www.fhwa.dot.gov////bridge/hs17007.pdf, technical guide of heat-straightening
- Strain ratio less than 100
- Jacking ratio less than 50%
- Unknowns: Fracture behavior?

  What about $\mu > 100$?

  $j > 50\%$, up to 90%?

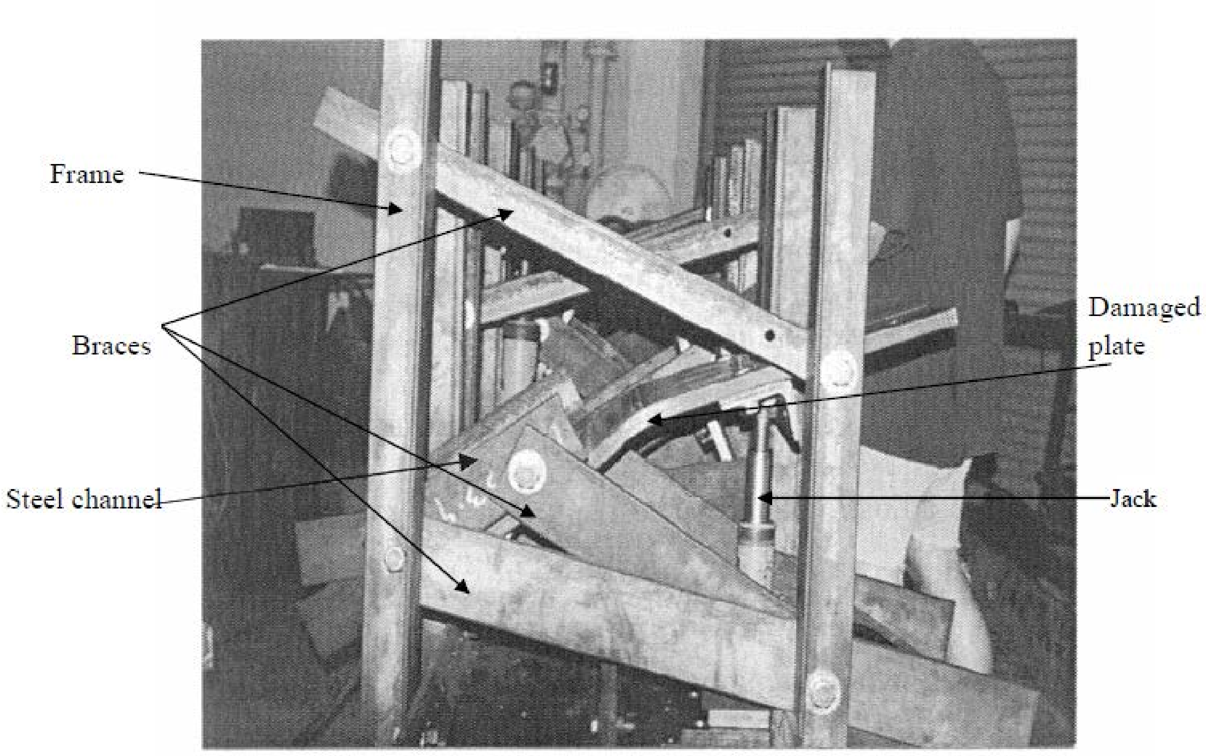
Project Objectives

- Simulate steel girder damage and repair
- Investigate steel material properties that relevant to fracture
- Further quantify allowable limits of repair and provide more guides for heat-straightening.

Methodology

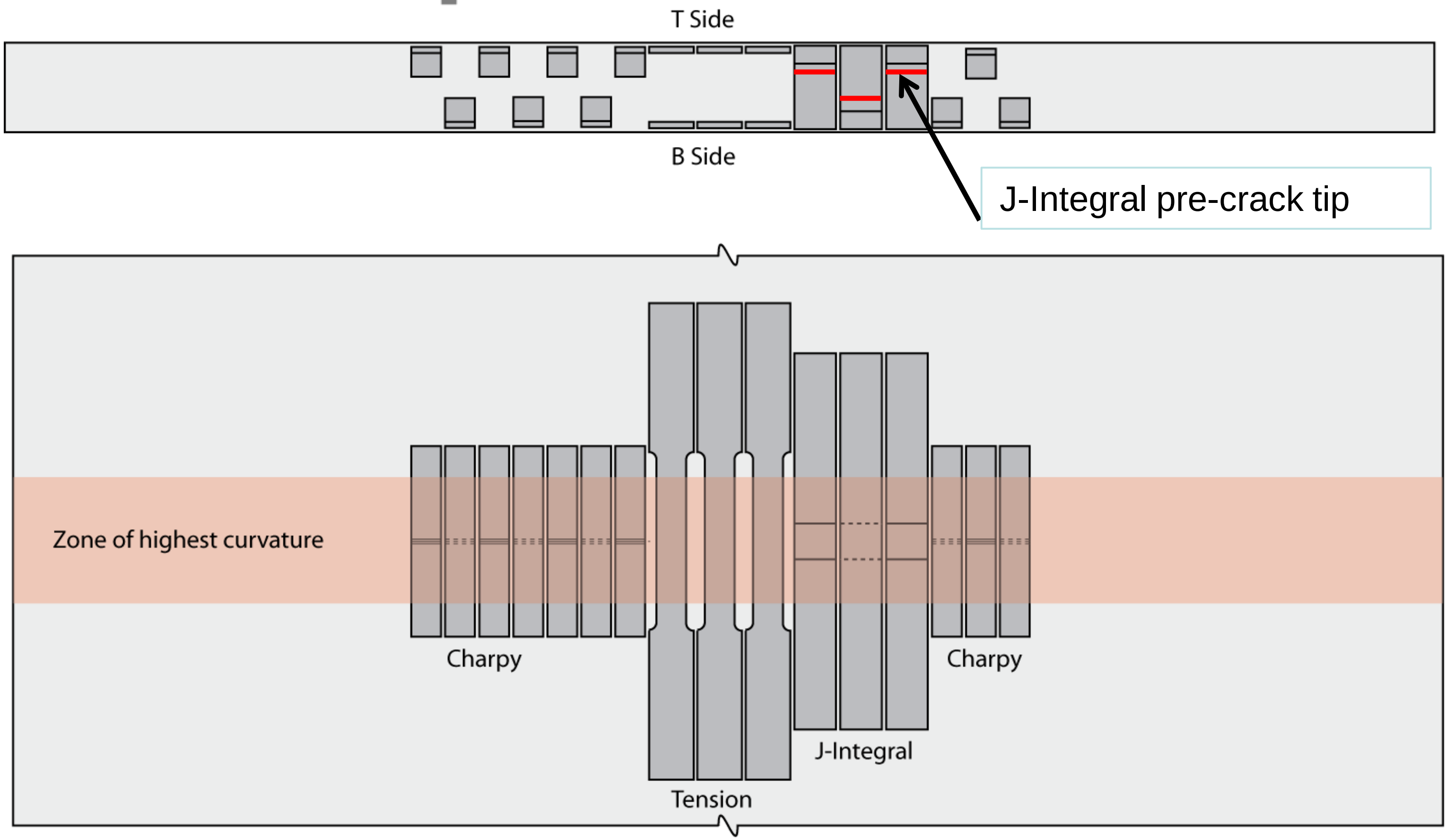
- Damage and Repair
- Coupons (μ up to 200, j up to 90%)
- Tensile & CVN
- J-R (including fatigue pre-cracking)

Damage and Repair



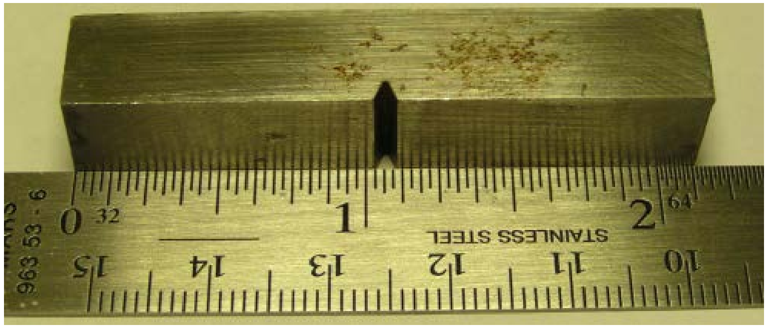
Heat-straightening repair setup (damage along weak axis)

Coupon Extraction



Coupon extraction scheme for weak-axis specimens.

CVN Toughness

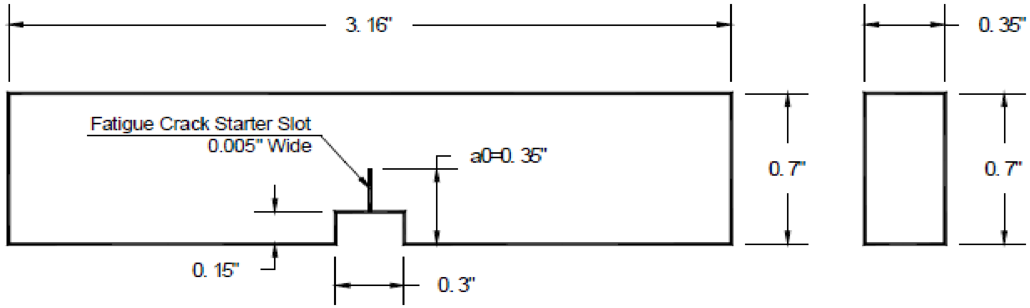


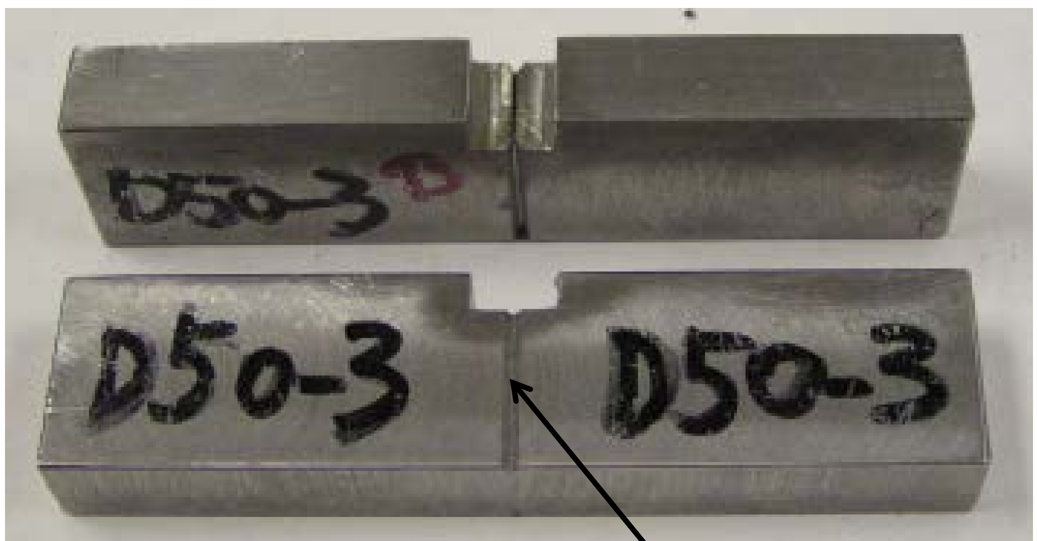
CVN tester and sample.

Tensile Tests

Tension test specimen.

J-R Testing



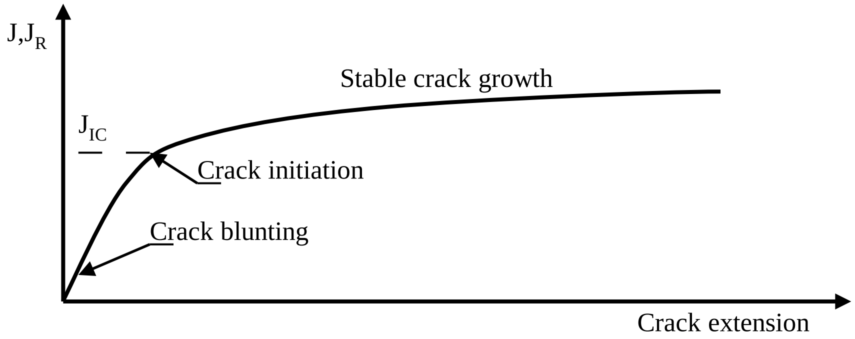


Side groove

J-integral test specimen.

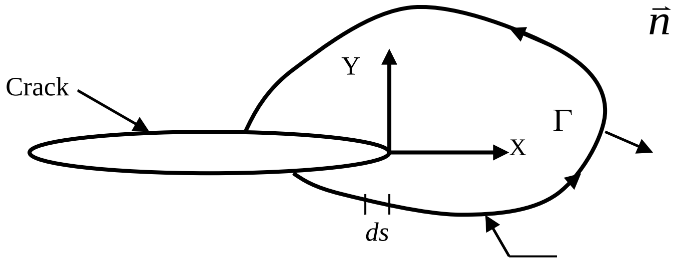
What is J?

- A parameter characterizing fracture toughness for EPFM
- Energy release rate, crack tip stress and strain condition
- Equivalent to “K” for LEFM
- J-Resistance curve



J-Integral

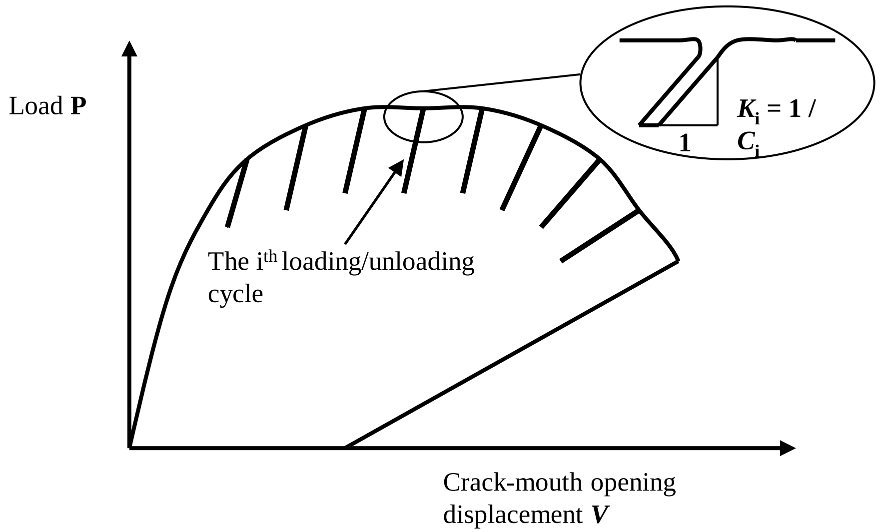
A path-independent line integral around the crack tip



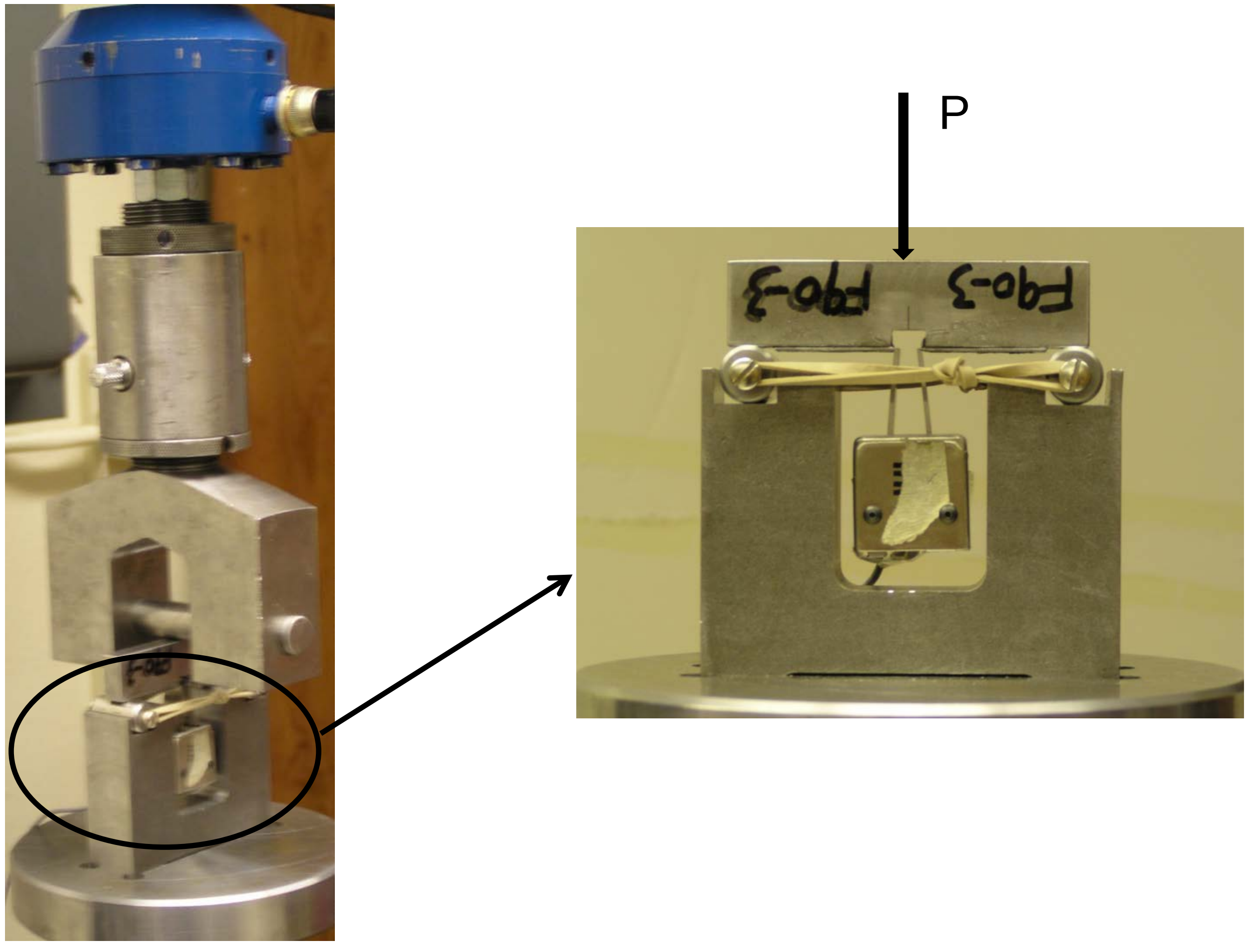
$$J = \int_{\Gamma} \left(W dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$

How to measure J?

- Multiple specimens with different starting crack lengths.
- Single specimen and measure crack length as you go (ASTM E1820)



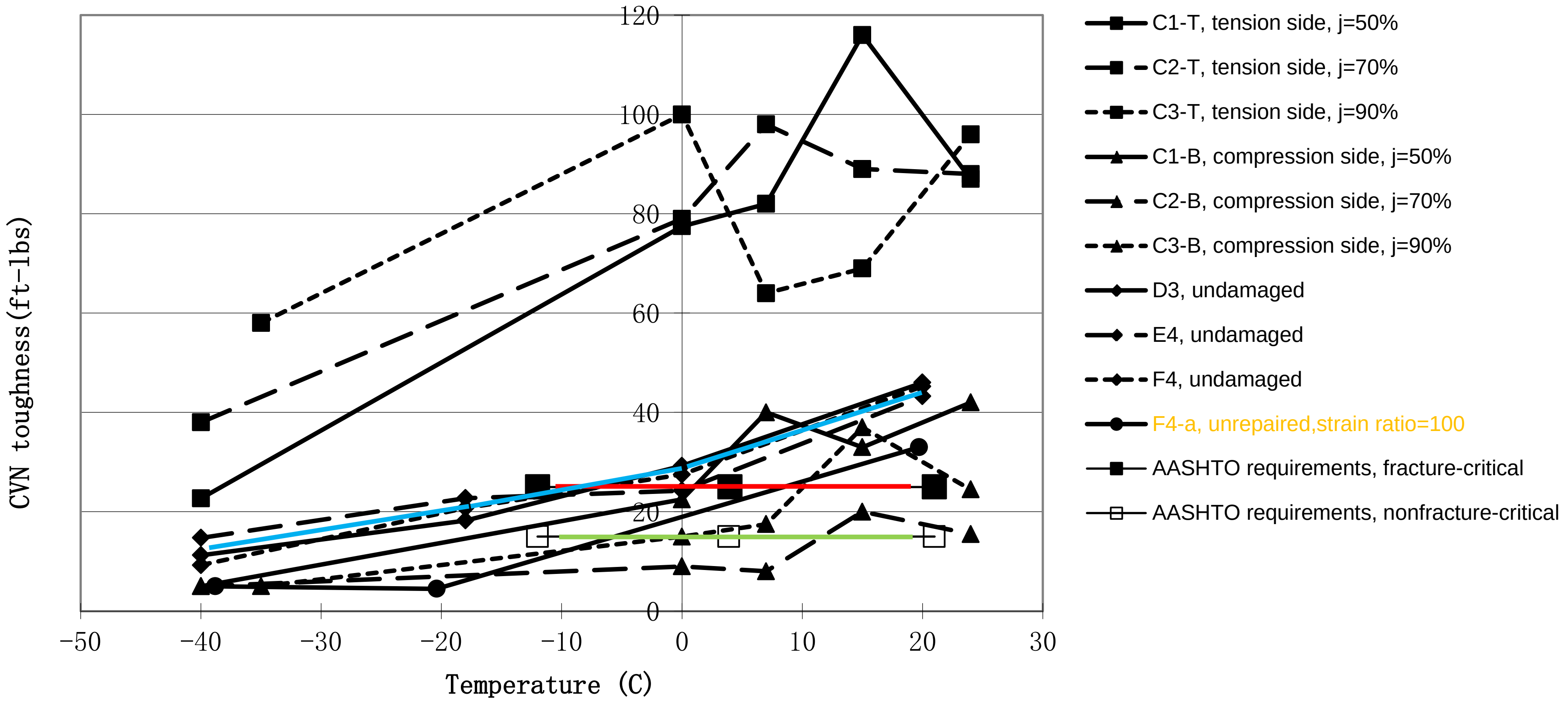
Test Set-up



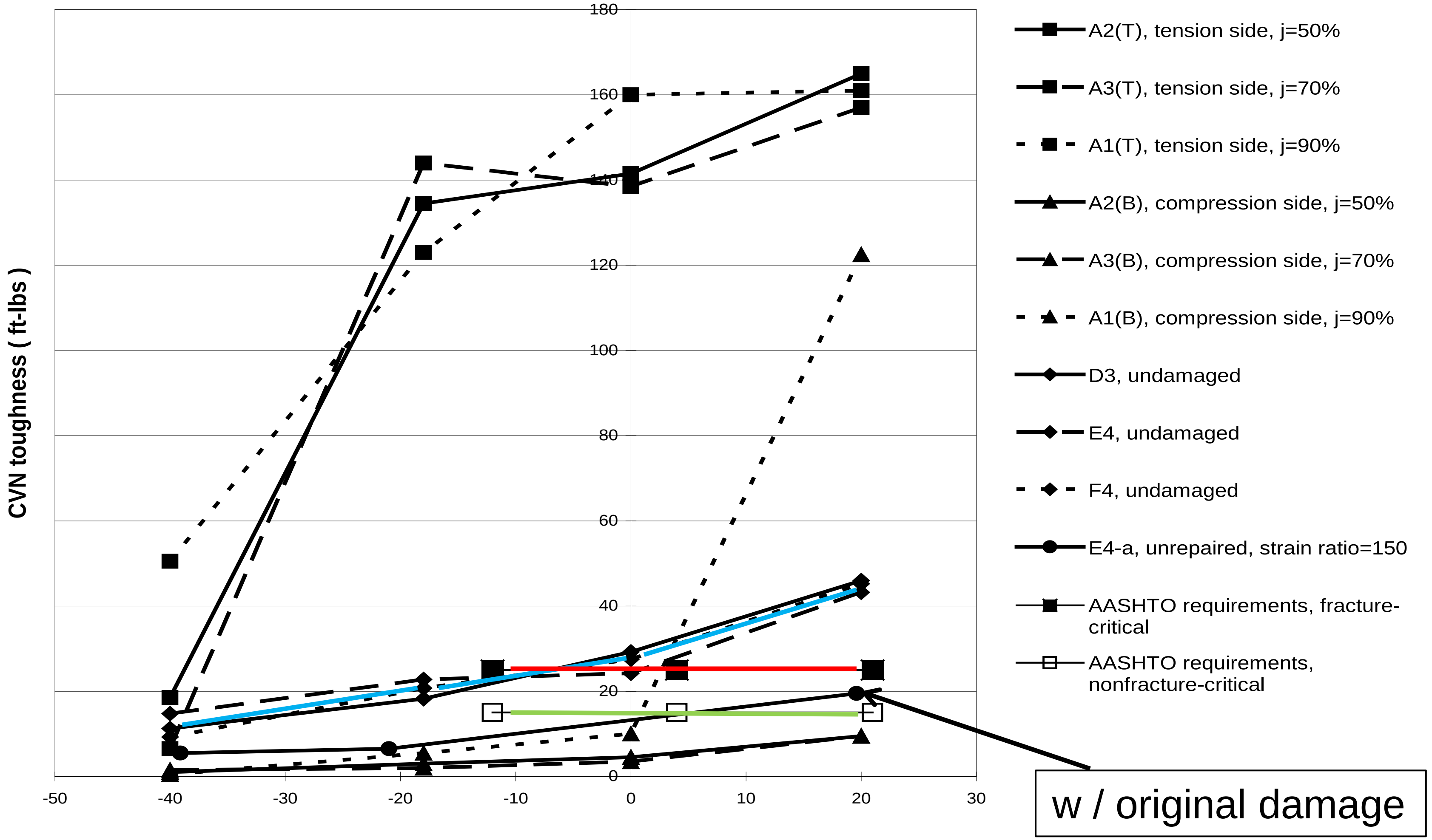
Fatigue Pre-cracking

- Assumption of Fracture Mechanics "infinitely sharp" crack tip….
- Ensure valid J-R results.
- Select fatigue load and record cycles until initial pre-crack length is reached

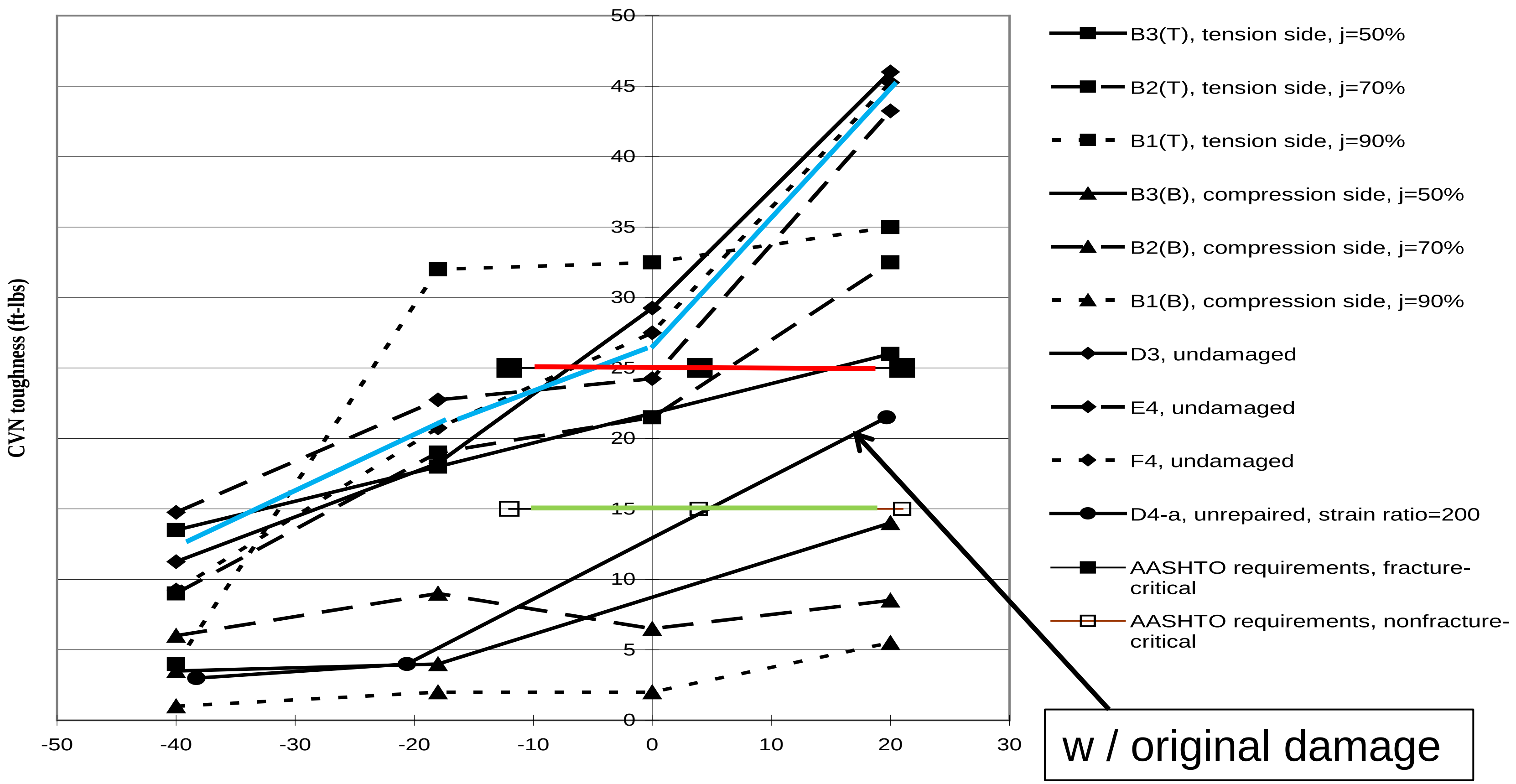
CVN Toughness



CVN vs. Temperature, Weak Axis, μ = 65

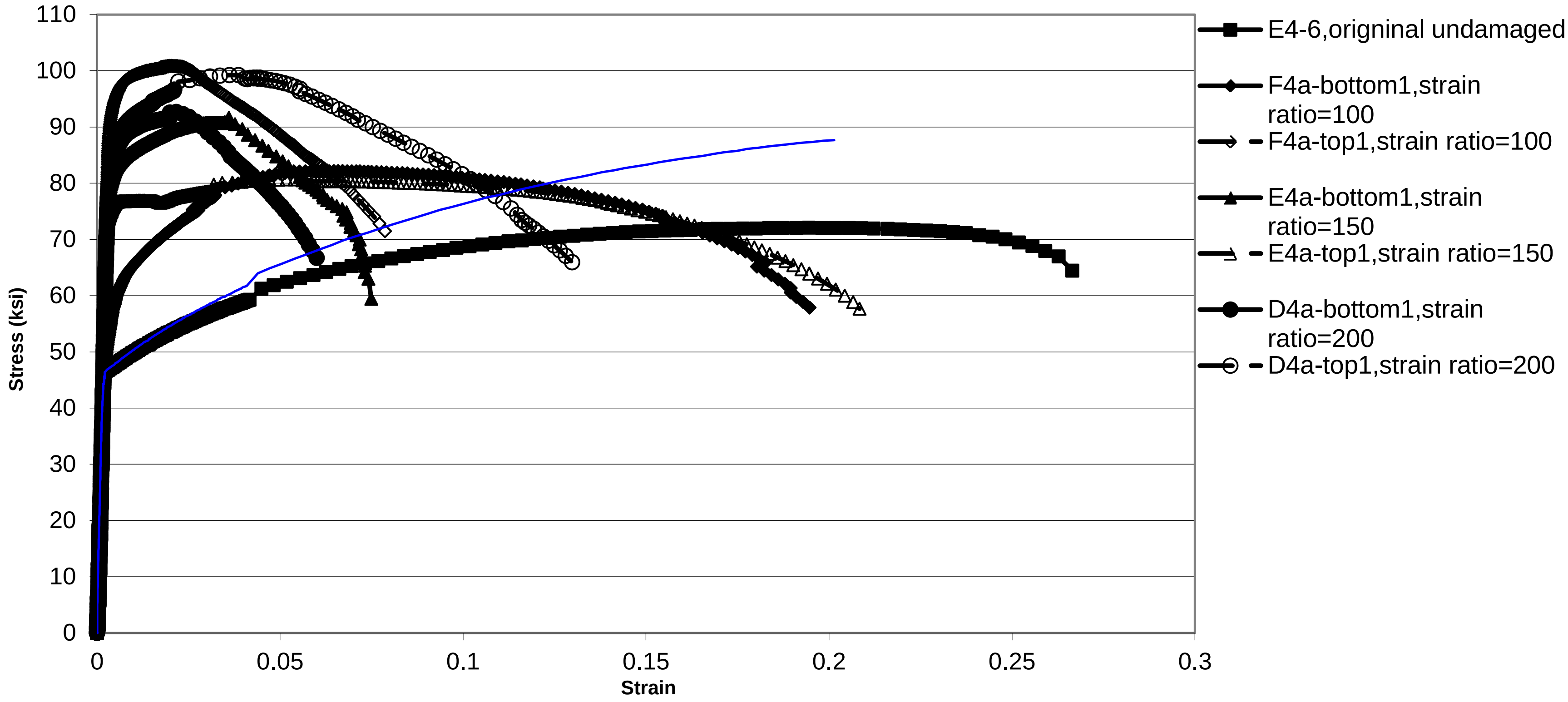


CVN vs. Temperature, Weak Axis, μ = 150

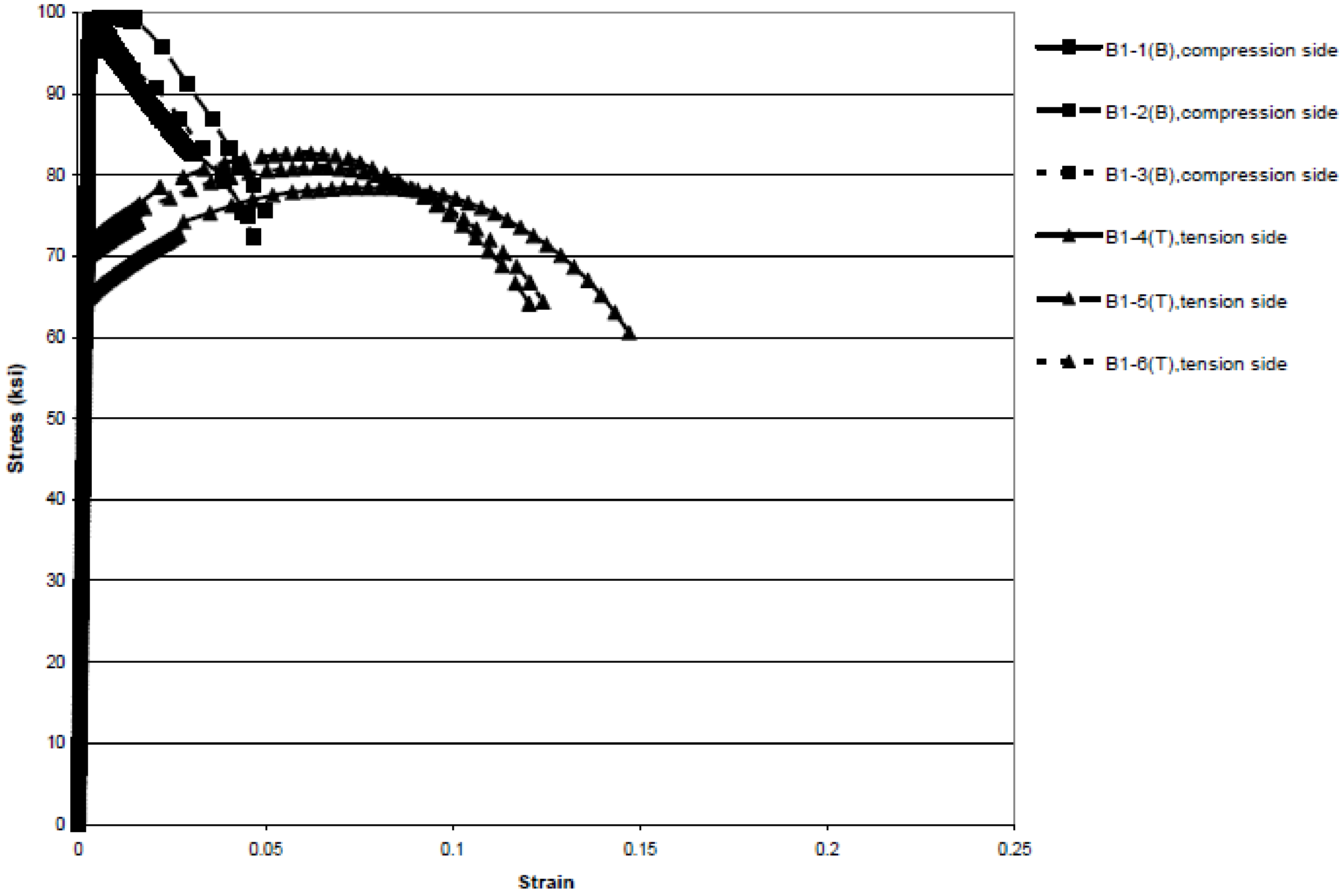


CVN vs. Temperature, Weak Axis, μ = 200

Tensile Tests

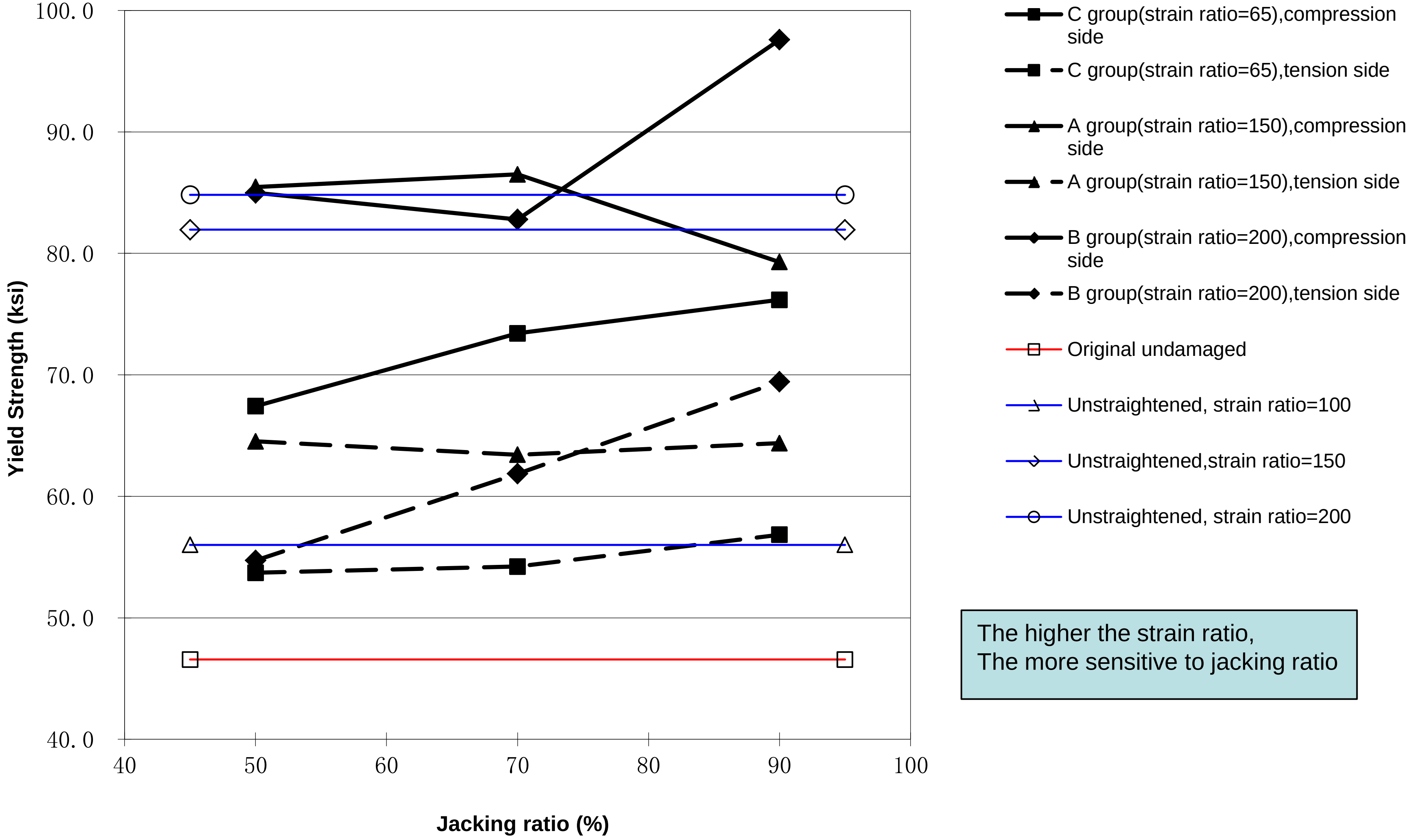


Stress vs. Strain for original and unrepaired specimens (A36)



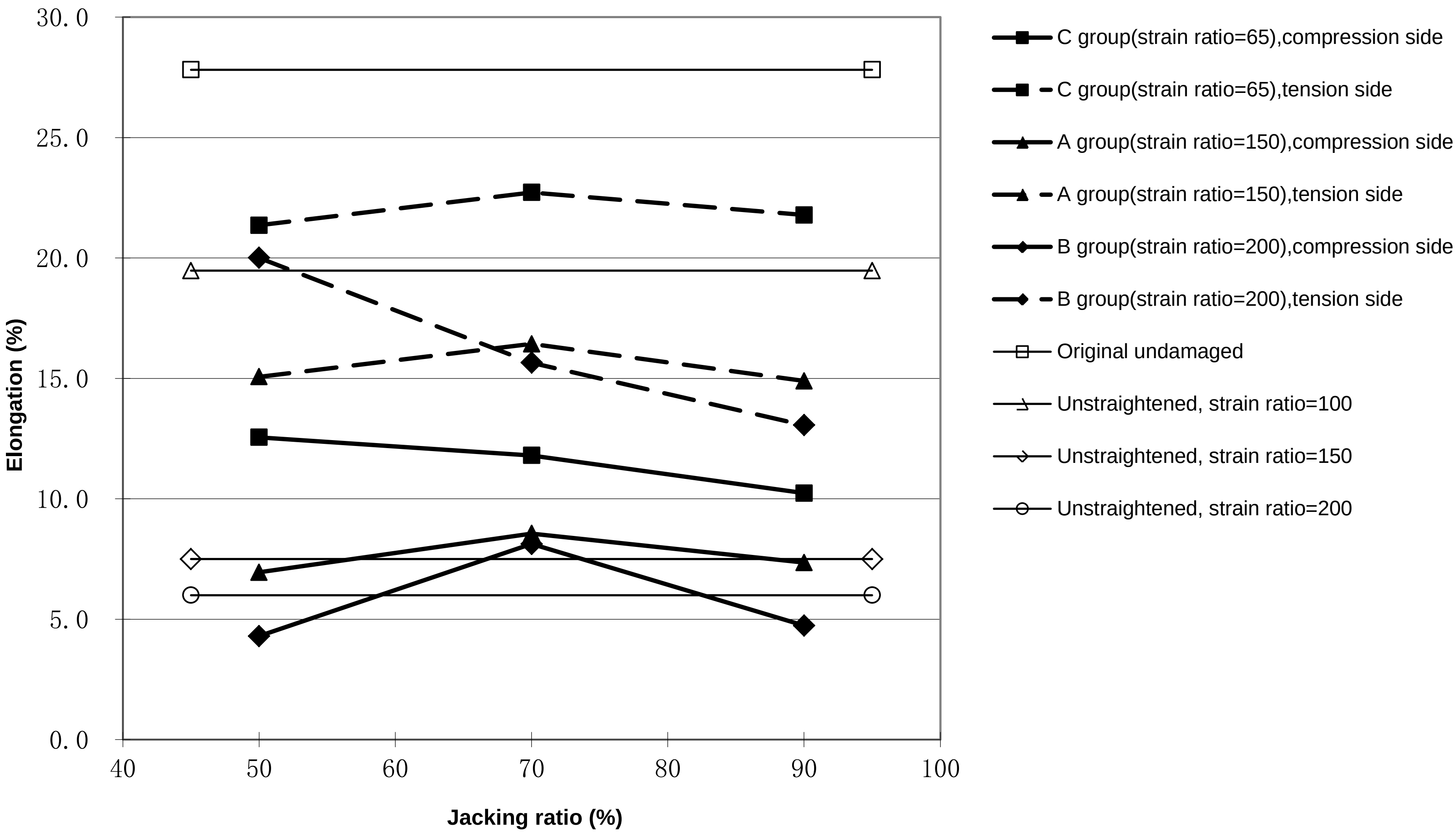
Stress vs. Strain for weak axis, μ = 197, j = 90%

Yield Strength

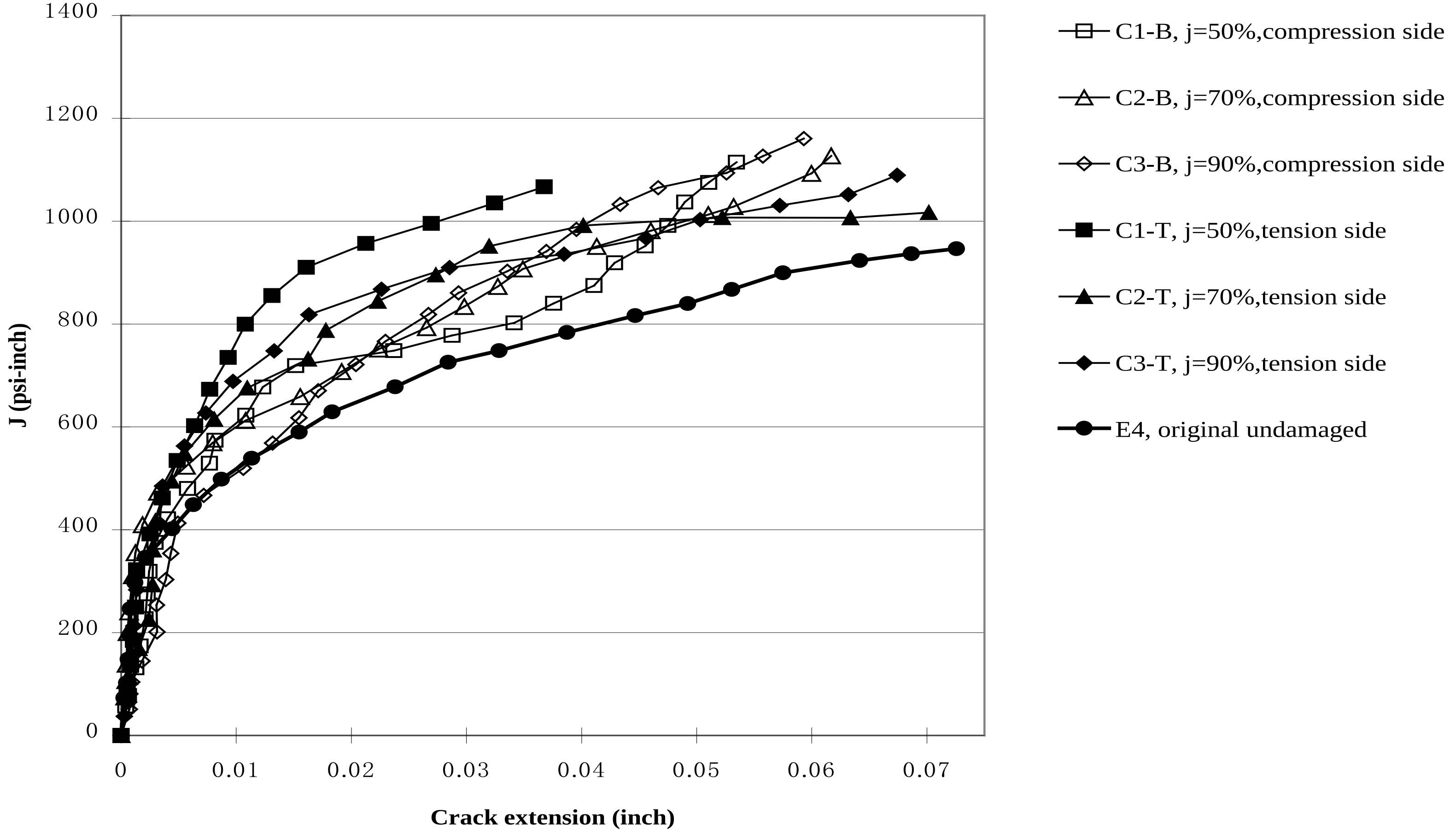


The higher the strain ratio,
The more sensitive to jacking ratio

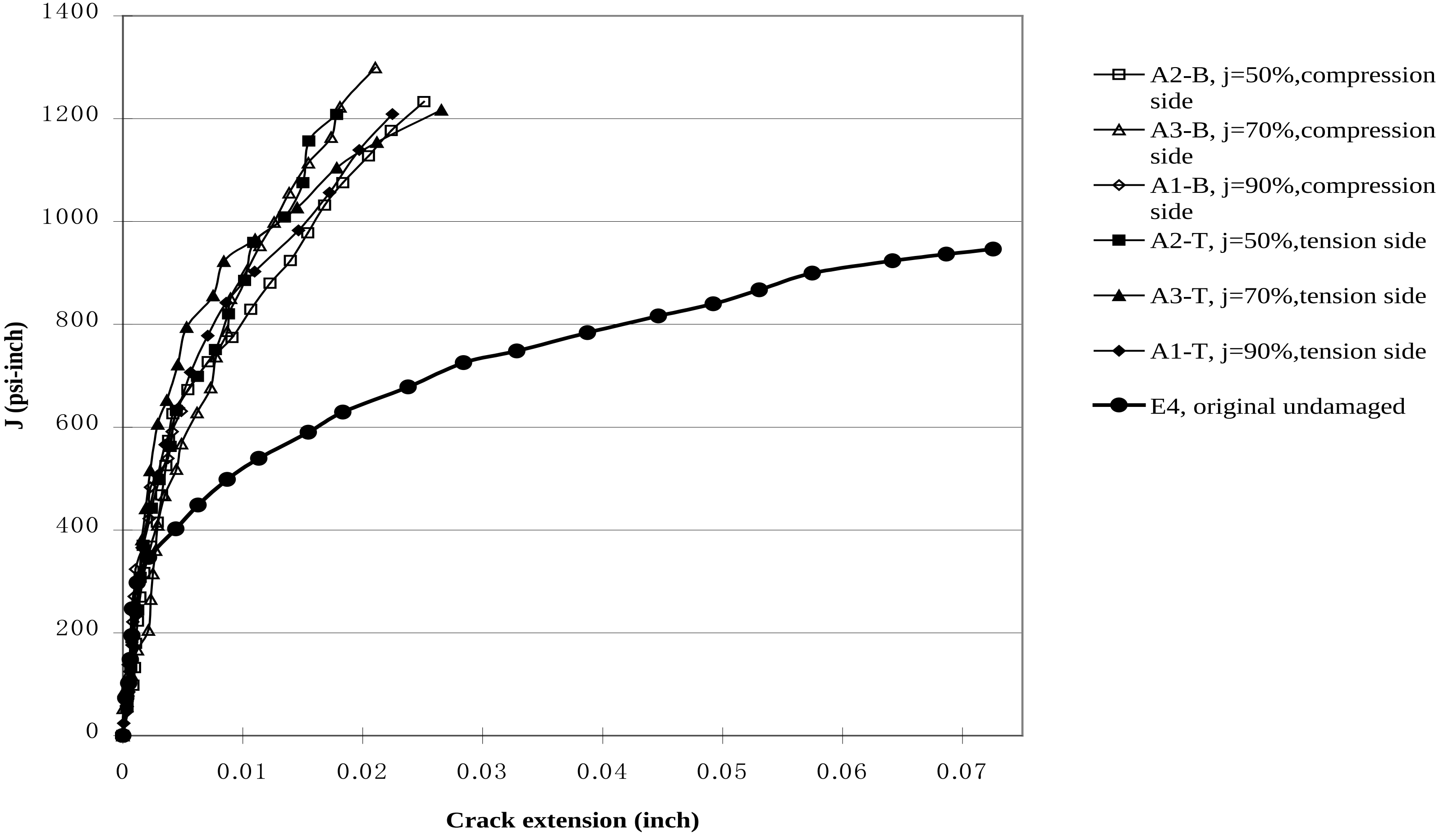
Elongation


30.0
25.0
20.0
15.0
10.0
5.0
0.0
40
50
60
70
80
90
100
Elongation (%)
Jacking ratio (%)
C group(strain ratio=65),compression side
C group(strain ratio=65),tension side
A group(strain ratio=150),compression side
A group(strain ratio=150),tension side
B group(strain ratio=200),compression side
B group(strain ratio=200),tension side
Original undamaged
Unstraightened, strain ratio=100
Unstraightened, strain ratio=150
Unstraightened, strain ratio=200

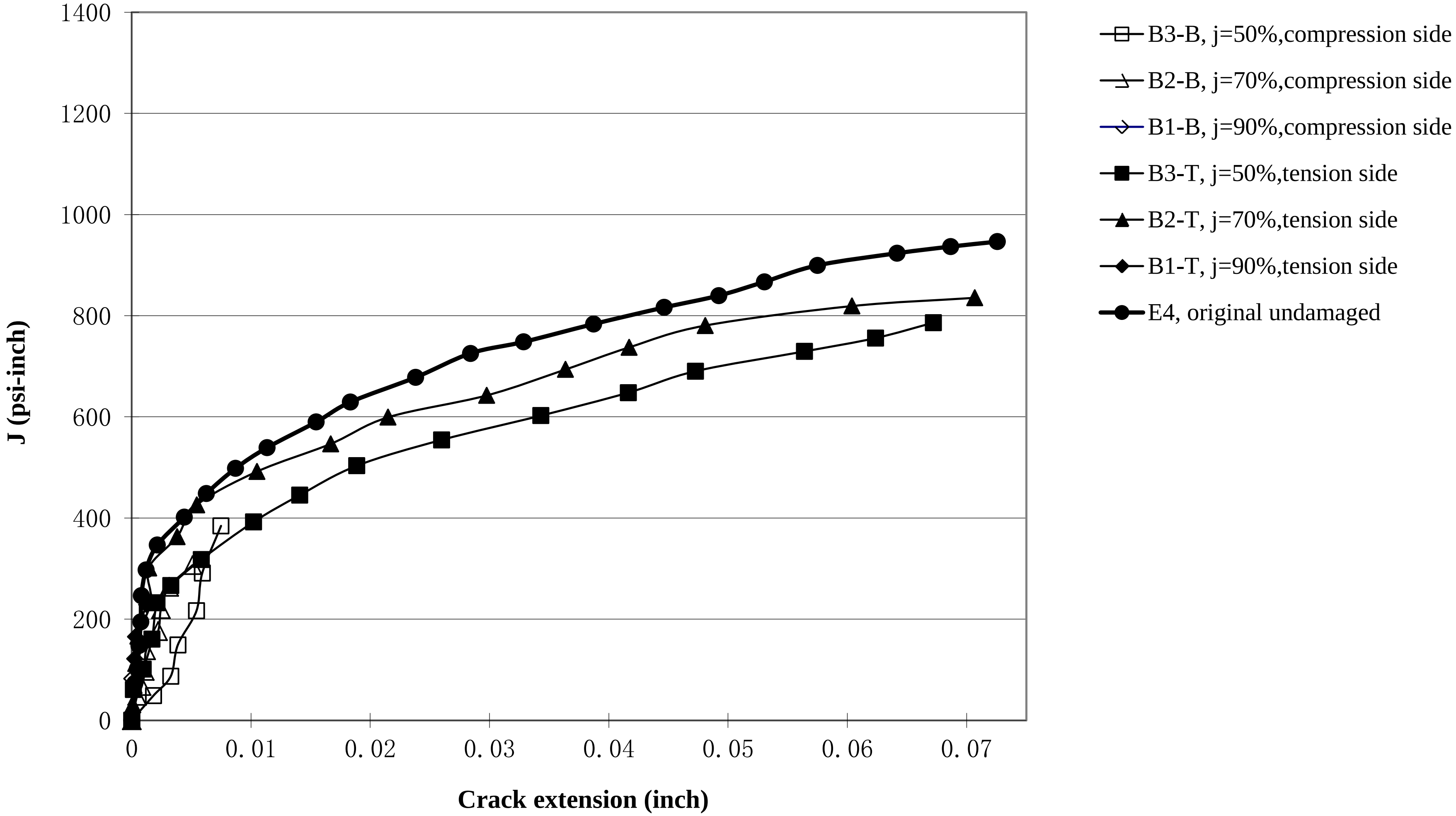
J-R Testing



J-R curves for weak-axis μ = 65



J-R curves for weak-axis $\mu = 150$

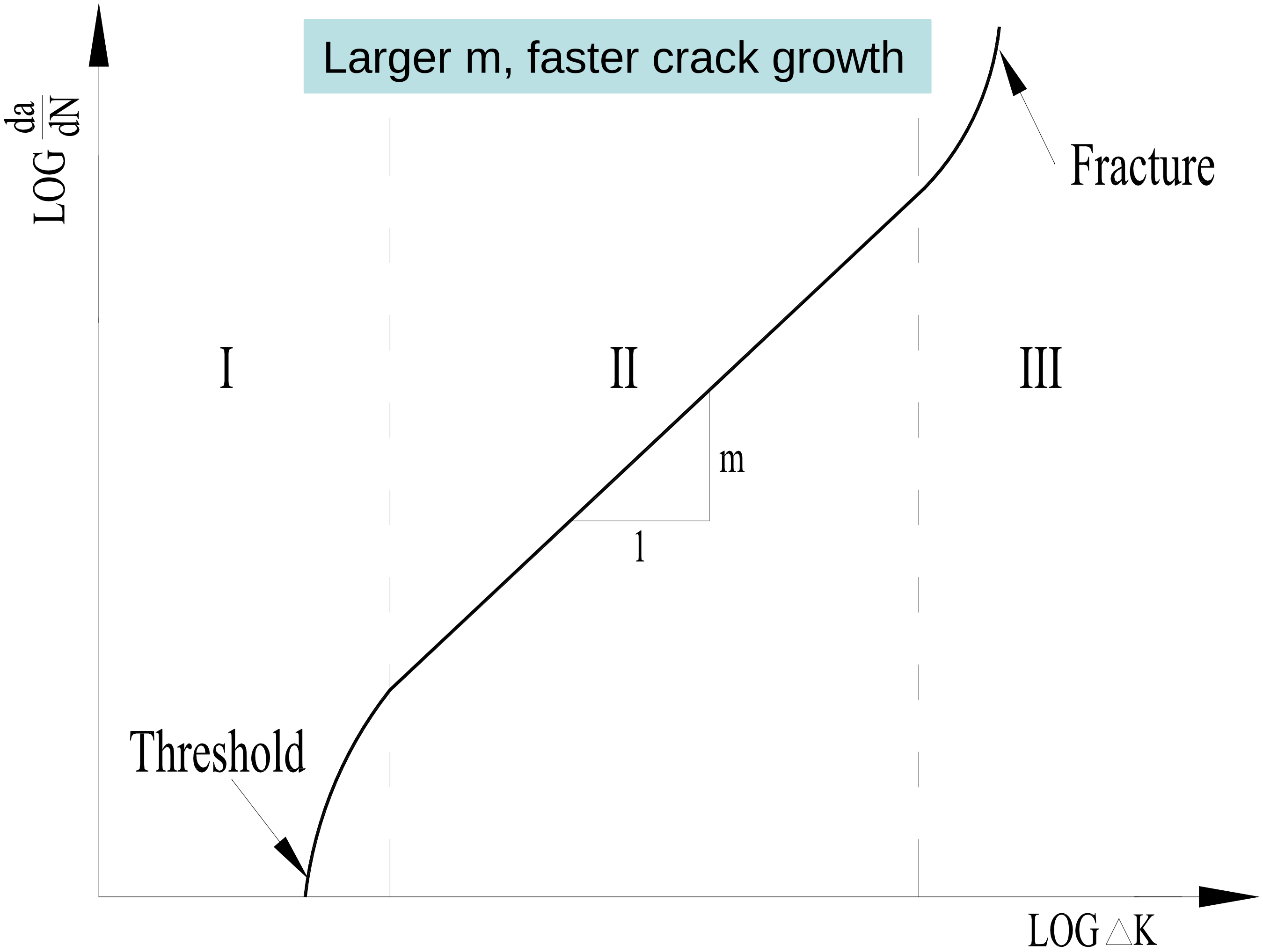


J-R curves for weak-axis μ = 200

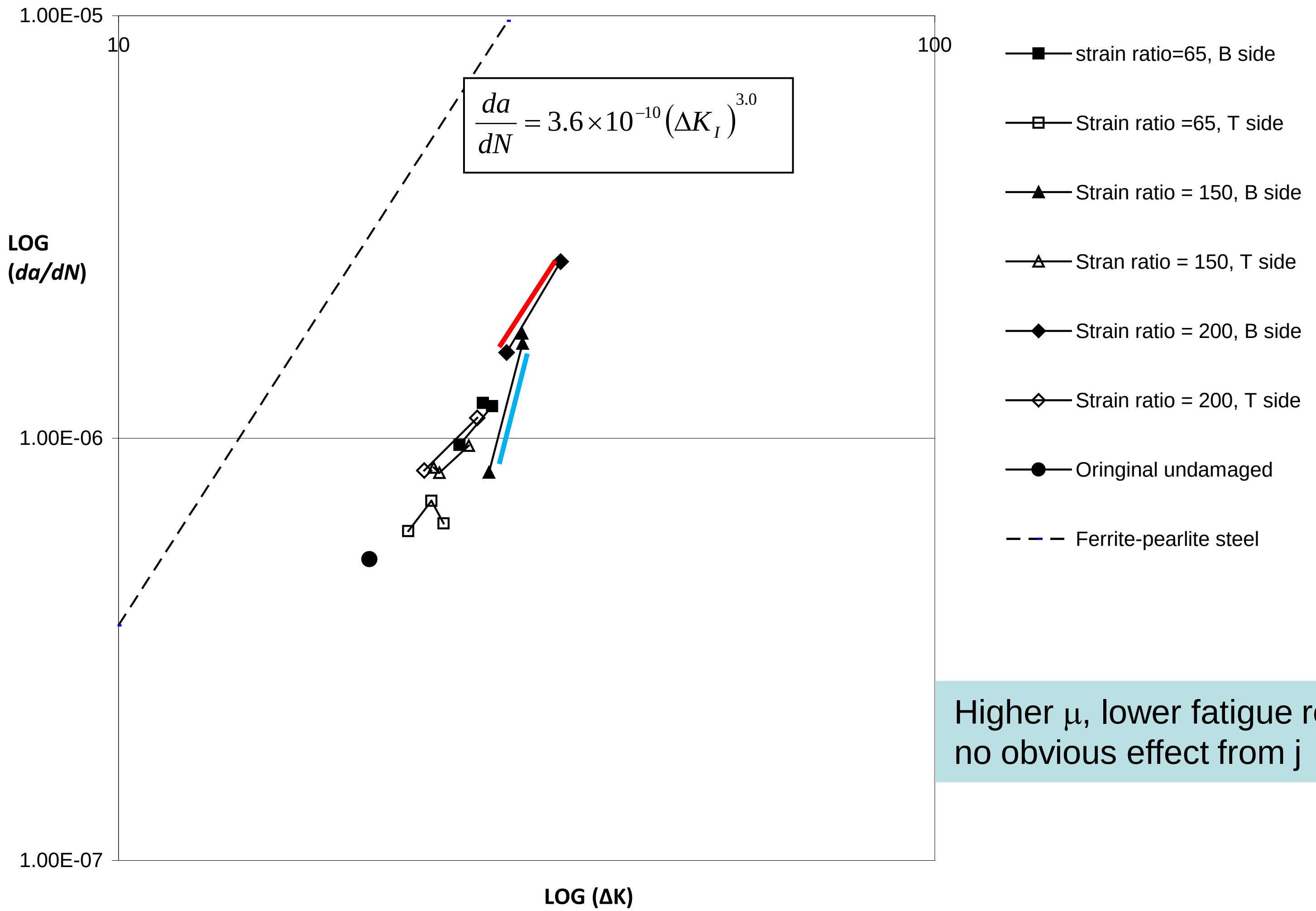
Fatigue Findings…

- The same pre-cracking length to be reached
- Fatigue pre-cracking load varies $P_f = \frac{0.5 B b_0^2 \sigma_y}{S}$
- Recorded loading cycles decreases with μ (not an evidence of fatigue resistance reduction though)
- Paris law expression $$\frac{da}{dN} = C \Delta K^m$$

Larger m, faster crack growth



Typical fatigue crack growth in metals



Higher μ, lower fatigue resistance; no obvious effect from j

Crack growth curves from weak-axis J-Integral pre-cracking

Conclusions
- Weak Axis Repair -

- Fracture and fatigue resistance decreases with increasing strain ratio
- Strain ratios larger than 150 should not be heat-straightened

- For strain ratios larger than 65, use caution for fracture critical members or non-fracture critical members with extremely low service temperature
- A higher jacking ratio (90% in place of 50%) can be used for strain ratios less than 65, but not recommended for higher strain ratios.