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

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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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**How it Works**

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

The cool material to the sides constrains expansion

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**How it Works**

The material only expands through the thickness
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...
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, $\mu$, 
  Ratio of maximum strain to yield strain 

\[ \varepsilon = \frac{Y_{\text{max}}}{R} \]

\[ \mu = \frac{\varepsilon}{\varepsilon_y} = \frac{R_y}{R} \]

Where $R_y$ is curvature at yield
• 2nd parameter:
  External restraint, further restrain expansion or, called jacking ratio, j

\[
j = \frac{M}{M_p} \quad M_j, \text{bending moment due to jacking force}
\]
\[
M_p, \text{plastic bending moment capacity}
\]

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

- 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

J-integral test specimen.

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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

![Diagram showing J, JR, Jc, crack initiation, crack blunting, and stable crack growth]

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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 vs. Temperature, Weak Axis, $\mu = 65$
CVN vs. Temperature, Weak Axis, $\mu = 150$
CVN vs. Temperature, Weak Axis, $\mu = 200$
Tensile Tests

Stress vs. Strain for original and unrepaired specimens (A36)
Stress vs. Strain for weak axis, $\mu = 197$, $j = 90\%$
Yield Strength

The higher the strain ratio, the more sensitive to jacking ratio.
J-R curves for weak-axis $\mu = 65$
J-R curves for weak-axis $\mu = 150$
J-R curves for weak-axis $\mu = 200$
Fatigue Findings...

- The same pre-cracking length to be reached
- Fatigue pre-cracking load varies \( P_f = \frac{0.5Bb_0^2\sigma_y}{S} \)
- Recorded loading cycles decreases with \( \mu \) (not an evidence of fatigue resistance reduction though)
- Paris law expression \( \frac{da}{dN} = C\Delta K^m \)
Typical fatigue crack growth in metals

Larger m, faster crack growth

LOG da/dN vs. LOG \Delta K

Threshold

Fracture

Typical fatigue crack growth in metals
Crack growth curves from weak-axis J-Integral pre-cracking

\[ \frac{da}{dN} = 3.6 \times 10^{-10} (\Delta K_i)^{3.0} \]

Higher \( \mu \), lower fatigue resistance; no obvious effect from \( j \)

Ferrite-pearlite steel
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.