The Future of Fracture Critical
latest Research on FC Members

William Collins, University of Kansas

KSU Bridge Design Workshop
October 13, 2017
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Background for FC Discussion
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1967 - Silver Bridge Collapse
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1967- Silver Bridge Collapse
1968- Material Toughness
1970
1972- AISI Project 169
1978- Fracture Control Plan
1980
1983- Mianus River Bridge Collapse
Background for FC Discussion

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1970 - AISI Project 169
1978 - Fracture Control Plan
1980 - Mianus River Bridge Collapse
1983 - FCP Revisions
1980’s - FCP Revisions
Background for FC Discussion

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1972 - AISI Project 169
1978 - Fracture Control Plan
1980
1983 - Mianus River Bridge Collapse
1990
2000 - Hoan Bridge Fracture
2000
2007 - I-35 W Collapse
2010
2012 - FHWA Memo
2020

“System Redundant Member” (SRM)
NCHRP 12-87a
Fracture-Critical System Analysis for Steel Bridges

Three Types of Redundancy:

1. Load Path Redundancy
2. System Redundancy
3. Internal Member Redundancy

Traditional Redundancy (Non-FC)
System Analysis
System Redundant Member (SRM)
FEA Methodology:
- Benchmark with experimental data
- Evaluation of dynamic effects
- Loading for faulted condition
- Performance criteria for evaluation
- Bridge fabrication and detailing for fracture
- Development of guide specification
### System Redundancy: Research Plan

- **FEA Methodology Benchmarking**

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Type of Structure (Main Span Length)</th>
<th>Type of Failure</th>
<th>Summary of Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neville Island</td>
<td>3-span continuous 2-plate girder (350 ft)</td>
<td>Full-depth girder fracture</td>
<td>Successfully</td>
</tr>
<tr>
<td>Hoan Bridge</td>
<td>3-span continuous 3-plate girder (217 ft)</td>
<td>Multiple full-depth girder fractures</td>
<td>Successfully</td>
</tr>
<tr>
<td>UT Texas Twin Tub Girder</td>
<td>Simple span twin tub girder (120 ft)</td>
<td>Simulated full-depth fracture</td>
<td>Successfully</td>
</tr>
<tr>
<td>Milton Madison Truss</td>
<td>Simple span truss (147 ft)</td>
<td>Lower chord partial and full fracture</td>
<td>Successfully</td>
</tr>
<tr>
<td>White River</td>
<td>2-span continuous 2-plate girder (155 ft)</td>
<td>Girder fracture</td>
<td>Successfully</td>
</tr>
<tr>
<td>Dan Ryan Expressway</td>
<td>Cross-girder (40 ft)</td>
<td>Partial-depth fracture</td>
<td>AVAILABLE</td>
</tr>
</tbody>
</table>

**Notes:**
1. Performance criteria do not apply since it is a light rail commuter bridge.
System Redundancy: Research Plan
System Redundancy: Results

- Reliability-based load combinations developed:
  - Redundancy I: Instant that fracture occurs
  - Redundancy II: Post-failure extended service

- Set of minimum requirements in the faulted state established

- Set of recommendations for new designs
System Redundancy: Results

- Application of methodology will lead to classification of bridges based on analysis, not opinion
- Further use of methodology results in simplifications
- Establishment of inspection practices based on analyzed bridge performance
- Proposed analysis has been used by Wisconsin DOT for tub girder
- A guide specification is being discussed at AASHTO
- Application examples developed

System Redundancy: Implementation
TPF-5(253): Member-level Redundancy in Built-up Steel Members

R. Connor, M. Hebdon
Member-level Redundancy
Member-level Redundancy

Three Types of Redundancy:
1. Load Path Redundancy
2. System Redundancy
3. Internal Member Redundancy

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Built-up Members
Member-level Redundancy: Objectives

- Determine whether Built-up Members are Fracture Resilient
- Capacity of partially failed members
- Remaining Fatigue Life
  - Possible contributing parameters:
    - Hole preparation (drilled vs. punched)
    - Fastener type (riveted vs. high-strength bolted)
    - Section properties (number of cover plates, height of web plate)
Member-level Redundancy: Testing

- **Test procedure**
  - Notch a component
    - Controlled location (angle/cover plate)
      - Not looking at initial fatigue life – already documented
      - Crack growth through fatigue to critical length (LEFM)
  - Cool beam to lower shelf behavior (max. temp = -60°F)
    - AASHTO Zone 3 Temperature
  - Load to induce a fracture
    - 0.55 $F_y$ (Minimum)
    - If no fracture, grow crack and repeat
    - Increase stress concentration when required
  - Examine stress redistribution
  - Determine fatigue life of partially failed specimen
Member-level Redundancy: Testing

- Fracture Test Conditions
  - All material on lower shelf
    - Single digit ft-lbs
    - Test temperature -60° F (warmest)
      - As low as -120° F
  - Applied stress = 0.55F_y (Minimum)
  - Substantial portion of component cracked
    - Greater than critical crack length per LEFM
    - Multiple attempts as crack length increased
  - Very challenging to obtain brittle fracture in a cracked component
Member-level Redundancy: Testing

- Fracture Test Conditions
  - Load shedding
  - Had to get creative
    - Initial cracks were at holes
    - Moved cracks to edges
    - Driven wedges
    - Fastener removal near crack
      - Decrease constraint at crack tip
      - Increase strain energy
Member-level Redundancy: Testing

- Fracture resilience

**Specimen 46-3**
Member-level Redundancy: Analytical Evaluation

- 3D Finite Element Modeling
  - Parametric study
  - Local stress distribution
**Member-level Redundancy: Analytical Evaluation**

- **Parametric Study: Number of cover plates**

\[ \beta_{AF} = 1 + 0.2 \left( 1 + \frac{N}{4} \right) \]

- **\( \sigma_{AF} = \beta_{AF} \frac{M_u}{S_{x-AF}} \)**

- Where:
  - \( \sigma_{AF} \) = Stress in critical component in the ‘faulted state’
  - \( M_u \) = Applied moment
  - \( S_{x-AF} \) = Section modulus in the ‘faulted state’
  - \( \beta_{AF} = 1 + 0.2 \left( 1 + \frac{N}{4} \right) \)  Stress adjustment factor
  - \( N \) = Number of cover plates
Member-level Redundancy: Testing Phase 2

- Fatigue life of partially failed cross-sections
  - How long until 2\textsuperscript{nd} component fails?
Member-level Redundancy: Testing Phase 2

- Fatigue life of partially failed cross-sections
Member-level Redundancy: Results

- Fracture Resilience of Built-up Girders
  - Fracture of an individual component is unlikely
  - Fracture does not propagate into adjacent components

- Localized stress redistribution
  - Concentrated in component adjacent to failed

- Substantial remaining fatigue life in faulted state
  - Category C for drilled or subpunched & reamed holes
  - Category E’ for punched holes
Guide Specification integrate methodology for setting maximum intervals for hands-on inspection

Based on remaining fatigue life in faulted state
  - Using minimum evaluation life with a safety factor on inspection interval
  - Max hands-on inspection interval of ten (10) years
  - Looking for broken components, not tiny cracks which have low POD

What about the FHWA memo? CFR?
TPF-5(328): Design and Fabrication Standards to Eliminate Fracture Critical Concerns in Two Girder Bridge Systems

Flange 1.5” x 18”

Integegrated Fracture Control Plan

SPECIMEN 70_1-5_2B

R. Connor, W. Collins, R. Sherman
Integrated FCP

- High-performance steel (HPS)
  - High-strength
  - Improved weldability
  - Corrosion resistance
  - Increased fracture resistance

- Achieved through
  - Chemical composition
  - Processing
Integrated FCP: Overview

- Experimental testing
  - Small-scale
  - Large-scale
- FE modeling
  - Fracture toughness
- Framework
  - Material toughness
  - Inspection interval
Integrated FCP: Material Requirement

- CVN energy: 125 ft-lbf
## Integrated FCP: Large-scale Test Matrix

<table>
<thead>
<tr>
<th>Plate Designation</th>
<th>Specimen</th>
<th>Type</th>
<th>(F_y) (ksi)</th>
<th>(t_f) (in.)</th>
<th>(b_f) (in.)</th>
<th>(h_w) (in.)</th>
<th>(L) (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>50_2-5_1B</td>
<td>Bending</td>
<td>50</td>
<td>2.5</td>
<td>14</td>
<td>33</td>
<td>46</td>
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<tr>
<td>E</td>
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<td>2.5</td>
<td>14</td>
<td>33</td>
<td>46</td>
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<tr>
<td>E</td>
<td>50_2-5_1A</td>
<td>Axial</td>
<td>50</td>
<td>2.5</td>
<td>14</td>
<td>N/A</td>
<td>16</td>
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<tr>
<td>H</td>
<td>70_1-5_1B</td>
<td>Bending</td>
<td>70</td>
<td>1.5</td>
<td>18</td>
<td>33</td>
<td>50</td>
</tr>
<tr>
<td>H</td>
<td>70_1-5_2B</td>
<td>Bending</td>
<td>70</td>
<td>1.5</td>
<td>18</td>
<td>33</td>
<td>50</td>
</tr>
<tr>
<td>H</td>
<td>70_1-5_1A</td>
<td>Axial</td>
<td>70</td>
<td>1.5</td>
<td>18</td>
<td>N/A</td>
<td>16</td>
</tr>
<tr>
<td>H</td>
<td>70_1-5_2A</td>
<td>Axial</td>
<td>70</td>
<td>1.5</td>
<td>18</td>
<td>N/A</td>
<td>16</td>
</tr>
<tr>
<td>I</td>
<td>50_2-0_1B</td>
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<td>33</td>
<td>40</td>
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<tr>
<td>J</td>
<td>50_1-5_1A</td>
<td>Axial</td>
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<td>1.5</td>
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<td>50</td>
<td>1.5</td>
<td>22</td>
<td>N/A</td>
<td>16</td>
</tr>
</tbody>
</table>
Integrated FCP: Experimental Testing

Test process

- Incremental growth
  - Notch specimen
  - Crack growth through fatigue
  - Cool to desired behavior
  - Load to induce fracture
  - Repeat until fracture achieved

- Grow to fracture length
Integrated FCP: Experimental Testing

Bending Test Setup
Integrated FCP: Experimental Testing

Temperature Chamber
Integrated FCP: Experimental Testing

Bending Fracture Test
Integrated FCP: Experimental Testing
Axial Test Setup
Integrated FCP: Experimental Testing

Axial Fracture Test
## Test Results

### Integrated FCP: Experimental Testing

<table>
<thead>
<tr>
<th>Plate Designation</th>
<th>Specimen</th>
<th>Type</th>
<th>Final Crack (in.)</th>
<th>Fracture Load (kip)</th>
<th>Fracture Stress (ksi)</th>
<th>Deflection (in.)</th>
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</thead>
<tbody>
<tr>
<td>E</td>
<td>50_2-5_1B</td>
<td>Bending</td>
<td>5.00</td>
<td>104.6</td>
<td>18.7</td>
<td>0.96</td>
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<td>4.94</td>
<td>581.7</td>
<td>16.6</td>
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<td>Bending</td>
<td>5.06</td>
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<td>40.4</td>
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<td></td>
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<td>70_1-5_2A</td>
<td>Axial</td>
<td>6.94</td>
<td>728.3</td>
<td>22.1</td>
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<td>50_2-0_1B</td>
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<td>1.69</td>
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<td>1.06</td>
<td>128.6</td>
<td>22.6</td>
<td>0.94</td>
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<tr>
<td>J</td>
<td>50_1-5_1A</td>
<td>Axial</td>
<td>6.00</td>
<td>424.4</td>
<td>15.7</td>
<td>N/A</td>
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<td>Axial</td>
<td>4.63</td>
<td>871.0</td>
<td>32.3</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Integrated FCP: Analytical Evaluation

General Parameters

- Load at failure
- Crack length at failure
- Material model
  - Grade 50 and 70
  - Elastic properties
  - Plastic properties
- Solid (continuum) elements
## Integrated FCP: Analytical Evaluation

### Results

<table>
<thead>
<tr>
<th>Plate Designation</th>
<th>Specimen</th>
<th>FEA Model J (ksi*in.)</th>
<th>FEA Model K&lt;sub&gt;J&lt;/sub&gt; (ksiVin.)</th>
<th>FEA K&lt;sub&gt;J(1T)&lt;/sub&gt; (ksiVin.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>50_2-5_1B</td>
<td>0.52</td>
<td>128.3</td>
<td>156.6</td>
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<td>1.28</td>
<td>200.1</td>
<td>246.9</td>
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<td>0.64</td>
<td>142.7</td>
<td>174.8</td>
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<tr>
<td>H</td>
<td>70_1-5_1B</td>
<td>2.76*</td>
<td>295.8*</td>
<td>325.4*</td>
</tr>
<tr>
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<td>70_1-5_2B</td>
<td>6.63*</td>
<td>458.2*</td>
<td>505.1*</td>
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<td>244.0</td>
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<td>54.8</td>
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<td>200.2</td>
<td>219.6</td>
</tr>
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<td></td>
<td>50_1-5_2A</td>
<td>2.29</td>
<td>269.4</td>
<td>296.2</td>
</tr>
</tbody>
</table>
Critical Flaw Size

- **CVN→K**
  - Correlation from BS7910
    - Lower bound
  - Size correction
- **K→a_c**
  - Signal Fitness-for-Service (FFS)
    - Option 1 Failure Assessment Diagram (FAD)
  - 0.75F_y

Integrated FCP: Rational Inspection Interval
### CURRENT SPECIFICATION

<table>
<thead>
<tr>
<th>Grade</th>
<th>Thickness (in.)</th>
<th>Minimum Test Value Energy (ft.-lb.)</th>
<th>Minimum Average Energy (ft.-lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zone 1</td>
</tr>
<tr>
<td>HPS 50 WF</td>
<td>to 4</td>
<td>24</td>
<td>30 @ 10 °F</td>
</tr>
<tr>
<td>HPS 70 WF</td>
<td>to 4</td>
<td>28</td>
<td>35 @ -10 °F</td>
</tr>
<tr>
<td>HPS 100 WF</td>
<td>to 2.5</td>
<td>28</td>
<td>35 @ -30 °F</td>
</tr>
<tr>
<td></td>
<td>2.5 - 4</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### POTENTIAL SPECIFICATION

<table>
<thead>
<tr>
<th>Grade</th>
<th>Thickness (in.)</th>
<th>Minimum Test Value Energy (ft.-lb.)</th>
<th>Minimum Average Energy (ft.-lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zone 1</td>
</tr>
<tr>
<td>Damage Tolerant</td>
<td>TBD</td>
<td>TBD</td>
<td>125 @ 0 °F</td>
</tr>
</tbody>
</table>
## Integrated FCP: Rational Inspection Interval

### Critical Flaw Size

<table>
<thead>
<tr>
<th>Grade (ksi)</th>
<th>Applied Stress (ksi)</th>
<th>( K_{\text{new}} ) (ksi√in.)</th>
<th>Edge a (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>37.5</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>52.5</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>75</td>
<td>122</td>
<td></td>
</tr>
</tbody>
</table>
## Integrated FCP: Rational Inspection Interval

### Critical Flaw Size

<table>
<thead>
<tr>
<th>Grade (ksi)</th>
<th>Applied Stress (ksi)</th>
<th>$K_{\text{new}}$ (ksi√in.)</th>
<th>Edge a (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>37.5</td>
<td>122</td>
<td>1.3</td>
</tr>
<tr>
<td>70</td>
<td>52.5</td>
<td>122</td>
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</tr>
<tr>
<td>100</td>
<td>75</td>
<td>122</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Integrated FCP: Rational Inspection Interval

Fatigue Life

- Initial flaw (0.125”)
- In-service stresses
  - Live load stress range (3 ksi)
  - R-ratio > 0.5
  - Overload to 0.75$F_y$
- Same crack growth rate

<table>
<thead>
<tr>
<th>Grade (ksi)</th>
<th>Initial a (in.)</th>
<th>Cycles (millions)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.125</td>
<td>30.6</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>28.9</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>26.0</td>
</tr>
</tbody>
</table>
Set interval based on fatigue crack growth

Assumed ADTT = 1,000
  - Represents >75% of bridges (in Indiana)

“Raw” years of life presented
  - Actual inspection interval to be less
## Integrated FCP: Rational Inspection Interval

**Calculate Interval**

<table>
<thead>
<tr>
<th>Grade (ksi)</th>
<th>Initial Crack (in.)</th>
<th>Years</th>
<th>Final Crack (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
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<td>83.9</td>
<td></td>
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<tr>
<td>70</td>
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<tr>
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<td>0.125</td>
<td>71.2</td>
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</tr>
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</table>
## Integrated FCP: Rational Inspection Interval Summary

<table>
<thead>
<tr>
<th>Grade (ksi)</th>
<th>Initial (in.)</th>
<th>Years</th>
<th>Final Crack (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.125</td>
<td>83.9</td>
<td>1.3</td>
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<tr>
<td>70</td>
<td>0.125</td>
<td>79.2</td>
<td>0.8</td>
</tr>
<tr>
<td>100</td>
<td>0.125</td>
<td>71.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Integrated FCP: Conclusions

- Fatigue life can be calculated
  - Rational interval can be established
  - Multiple opportunities to detect a defect
- Critical flaw size can be calculated
  - Match inspection technique to flaw with POD
- Integrated fracture control plan
  - Lead to safer structures
  - Provide a better allocation of owner resources
Acknowledgements

Robert Connor, Purdue University
Francisco Bonachera Martin, Purdue University
Matthew Hebdom, Virginia Tech
Ryan Sherman, University of Nevada Las Vegas
Thank You!

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University of Kansas
Office: 785.864.0672
E-mail: william.collins@ku.edu
Additional Material

Fracture Mechanics Introduction
Fracture Mechanics Introduction

Load/Stress

Material Properties

Flaws

\[ F_{\text{applied}} < F_y \]

OK

σ

ε

\[ F_{\text{Y}} \]

? ?
Fracture Mechanics Introduction

Why do flaws matter?

Stress Concentration Factor, $k_t$

$$\sigma_{\text{max}} = k_t \times \sigma_{\text{nom}}$$
Fracture Mechanics Introduction

Stress concentration factors cannot be used for infinitely sharp cracks

\[ k_t = 3 \]

\[ k_t = 1 + 2a/b \]
Fracture Mechanics Introduction

Stress Intensity Factor, $K$
- Characterizes crack tip conditions
- $K = F \times \sigma \sqrt{\pi a}$

Function of geometry

Crack size (CAUTION!)

Applied Stress

Load/Stress/Stress Intensity  Material Properties

Applied Stress  $F_{applied} < F_y$  Yield Strength

Applied Stress Intensity  $K_l < K_c$  Fracture Toughness
Fracture Mechanics Introduction

**Stress Intensity Factor, $K$**
- Material property - ASTM test methods
- Evaluate for specific:
  - Temperature
  - Constraint
  - Loading rate
Additional Material

Weakest Link Behavior

and

Master Curve
Fracture Mechanics - Behavior

Fracture Toughness

Temperature

Upper Shelf

Transition Region

Lower Shelf
Fracture Mechanics - Behavior

Thought exercise...

- Same Material
- Same Size
- Same Load

Which one will break first?

12 Links

120 Links

The one with more links! Weakest Link Theory!
Future of Fracture Critical - Advances

Fracture Behavior Characterization

How do we deal with scatter in the transition region?

• Scatter in data
• Specimen size effects
• Constraint at crack tip
Future of Fracture Critical- Advances

Fracture Behavior Characterization

Master Curve

- Median initiation toughness
- Temperature dependence
- Exponential function for all ferritic steels

Future of Fracture Critical- Advances

Fracture Behavior Characterization

Master Curve
• Landes and Shaffer applied statistical rationale (1980)
• Recognition of initiation points and statistical flaw distribution
• Wallin’s work adapted this to be more “engineering friendly” (1984-present)
Future of Fracture Critical- Advances

Fracture Behavior Characterization

Master Curve

- Median Toughness vs Temperature
  - Single Value Characterization, $T_o$
- Size Correction- Weakest Link
  - Size to 1T specimens

\[ K_{JC(25.4)} = K_{min} + [K_{JC(o)} - K_{min}] \left( \frac{B_o}{B_{25.4}} \right)^{1/4} \]

- Statistical Analysis of Data Scatter
  - Weibull distribution probability of failure

\[ P_f = 1 - \exp \left\{ - \left[ \frac{K_{JC} - 20}{K_o - K_{min}} \right]^4 \right\} \]
Future of Fracture Critical- Advances

Fracture Behavior Characterization

Master Curve: Applied to “Legacy” Data

- Over 800 tests of conventional steel
- Early 1970’s - Present
- C(T), SE(B)
- Static, Intermediate, Dynamic
- Multiple thicknesses
- Varying testing protocols
- Linear-Elastic Fracture Mechanics
Future of Fracture Critical - Advances

Test Temperature (°F)

$K_{eff}$ (MPa$^{	ext{m}}$, M$^{	ext{m}}$)

0 100 200 300 400 500

$K_{eff}$ (ksi$,^{	ext{in}}$, M$^{	ext{m}}$)

0 100 200 300 400 500

Cleavage
Ductile
Future of Fracture Critical - Advances

![Diagram showing fracture critical values with labels for Cleavage, Ductile, Master Curve, and various tolerance levels. The x-axis represents temperature deviation from a reference temperature $T_0$ ($^\circ$C), and the y-axis represents $1T_Kc$ values in MPa m$^{1/2}$ and ksi in$^{1/2}$.)
Future of Fracture Critical - Advances

![Graph showing the relationship between 1TKc (MPa m^1/2) and (T - T_o) (°C). The graph includes data points for cleavage and various tolerance bands.](image-url)
<table>
<thead>
<tr>
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<th>Ductile Failure Excluded (681)</th>
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## Future of Fracture Critical - Advances

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Additional Material

FFS and FADs
Future of Fracture Critical - Existing Structures

Fitness for Service (FFS) Evaluation

- Evaluate structural components with existing flaws
- Ability of component to serve its intended function
- Commonly used in other industries
  - Oil and Gas, Offshore, Nuclear
- Codified Procedures
  - BS 7910 “Guide to methods for assessing the acceptability of flaws in metallic structures”
  - API 579 “Fitness-for-Service”
- Multiple Levels of Rigor
Future of Fracture Critical - Existing Structures

Failure Assessment Diagrams (FADs)

- Limit states of Strength and Fracture
  - Interaction between the two
- Developed in 1970’s for UK nuclear industry
- Normalized ratio of applied loads to resistance:
  - Brittle fracture, $K_r$
  - Plastic collapse, $L_r$
- Failure Envelope vs. Assessment Point

![Fracture Toughness Ratio vs. Load Ratio](image-url)
Riveted Bridge

- Inspection for fatigue cracks (0.125”)
- 0.55 $F_y$ and 0.75 $F_y$
- CVN values known

Bridge Posting? Permit Loads?
Future of Fracture Critical - Existing Structures

Riveted Bridge

Fracture Toughness Ratio, $K_F$

Load Ratio, $L_r$

5% Master Curve Tolerance Bound

0.75 $F_Y$ ($L_r = 0.867$, $K_F = 0.772$)

0.65 $F_Y$ ($L_r = 0.752$, $K_F = 0.669$)

0.55 $F_Y$ ($L_r = 0.636$, $K_F = 0.567$)

Increasing Load
Future of Fracture Critical - Existing Structures

Riveted Bridge

[Graph showing the relationship between Fracture Toughness Ratio, $K_f$, and Load Ratio, $L_r$. The graph includes various tolerance bounds and master curve tolerance bounds.]
Future of Fracture Critical- Existing Structures

Fitness for Service (FFS) Evaluation

Failure Assessment Diagrams
• Provide more information to owners
• Fracture behavior not “binary”
Additional Material

Current FCP Approach
Fracture Control Plan- Current Approach

**Fracture Control Plan**

1) Material Toughness
2) Fabrication Requirements
3) In-service Inspections
Fracture Control Plan - Current Approach

Fracture Critical Members (FCM)

• Defined in multiple places
  • AASHTO/AWS
  • Code of Federal Regulations
  • American Railway Engineering and Maintenance of Way Association (AREMA)

AASHTO/AWS 2010:

Fracture critical members or member components (FCMs) are tension members or tension components of members whose failure would be expected to result in collapse of the bridge.
Fracture Control Plan- Current Approach

Fracture Critical Members (FCM)

AASHTO/AWS 2010:

*Tension components of a bridge member consist of components of tension members and portions of a flexural member that are subject to tension stress. Any attachment having a length in the direction of the tension stress greater than 4 inches that is welded to a tension component of a “fracture critical” member shall be considered part of the tension component...*
Fracture Control Plan- Current Approach

Fracture Critical Members (FCM)

Two Requirements:
1. FCM must be subjected to net tensile stresses
2. FCM must be determined to be non-redundant

Classification of FCMs is responsibility of the design engineer
Fracture Control Plan- Current Approach

Fracture Critical Members (FCM)

from the AAHSTO/AWS Commentary:

*The fracture control plan should not be used indiscriminately by the designers as a crutch ‘to be safe’ and to circumvent good engineering practice. Fracture critical classification is not intended for ‘important’ welds on non-bridge members or ancillary products; rather it is only intended to be for those members whose failure would be expected to result in catastrophic collapse of the bridge.*
Fracture Control Plan- Impact

• Design
• Material
• Fabrication
  • Shop Inspection
• Inspection Burden
  • Cost
  • Safety
• FC Avoidance
  • Many states/designers
Future of Fracture Critical- Advances

Then versus now...

1960s
- Manual or simple computer structural analysis
- No explicit fatigue provisions
- No special fabrication QA/QC
- High toughness materials not economically feasible
- No knowledge of CIF
- Limited shop inspection

2010s
- 3D non-linear finite element analysis
- In-plane & distortional fatigue problems addressed
- Fracture critical fabrication per AASHTO/AWS
- High performance steels readily available
- Know to avoid intersecting welds and CIF details
- Significant advances in NDT
Future of Fracture Critical - Advances

Advanced Shop Inspection

• Phased Array Ultrasonic Testing (PAUT)
• Potential to Characterize Defects
  • Size
  • Shape
  • Orientation
• Safer, Faster than RT