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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William Collins, University of Kansas

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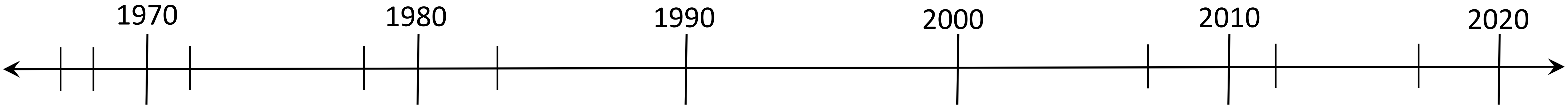
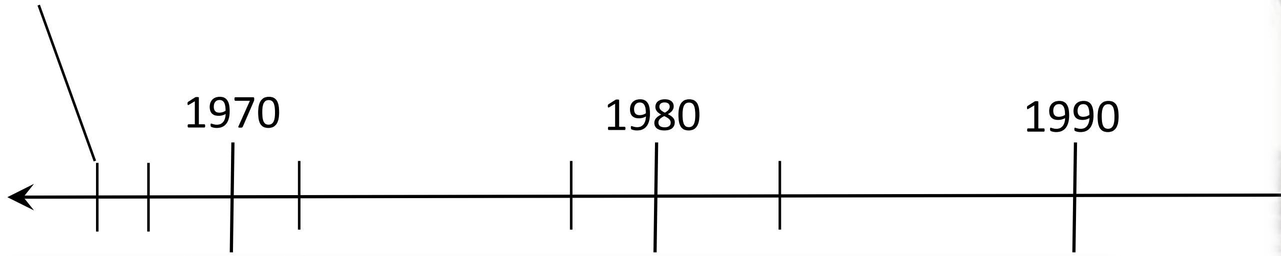
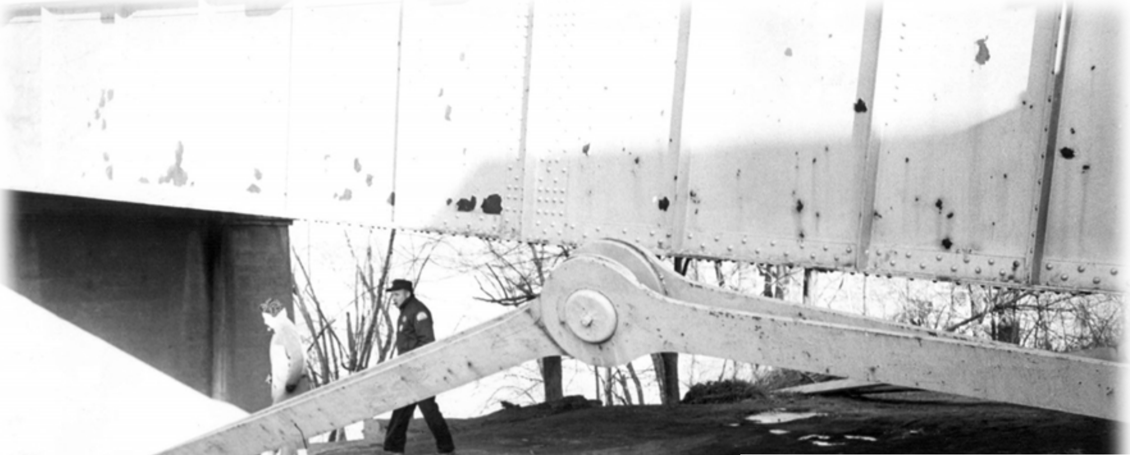
Background for FC Discussion

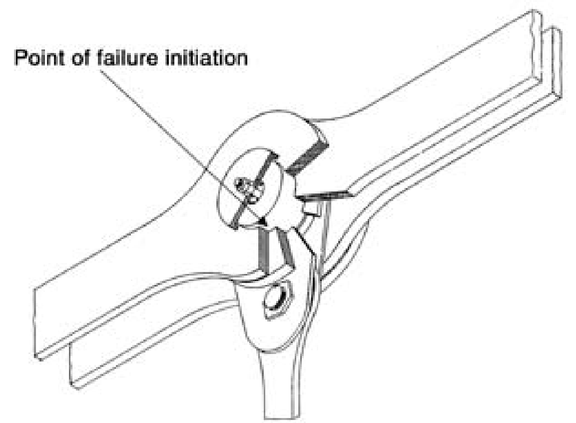


Background for FC Discussion

1967- Silver Bridge Collapse







Background for FC Discussion

1967- Silver Bridge Collapse

1968- Material Toughness

1970

1972- AISI Project 169

1978- Fracture Control Plan

1980

1983- Mianus River Bridge Collapse

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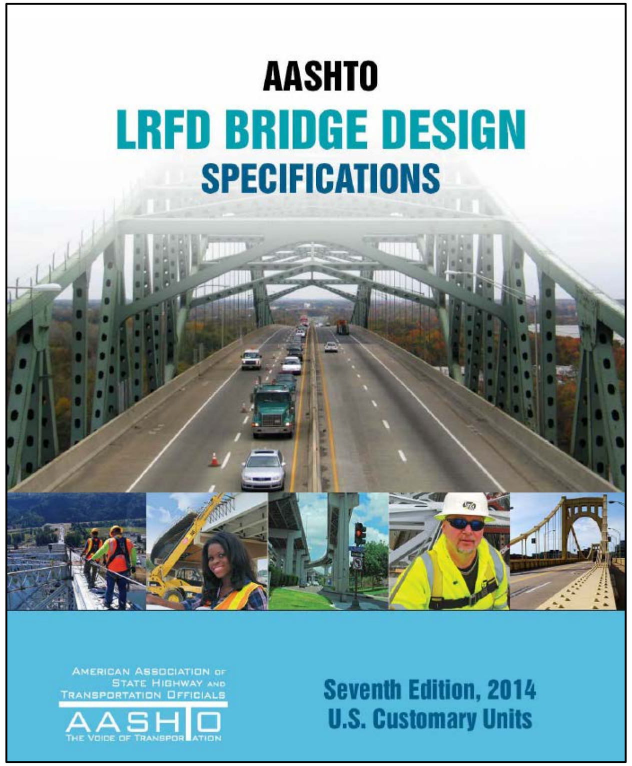
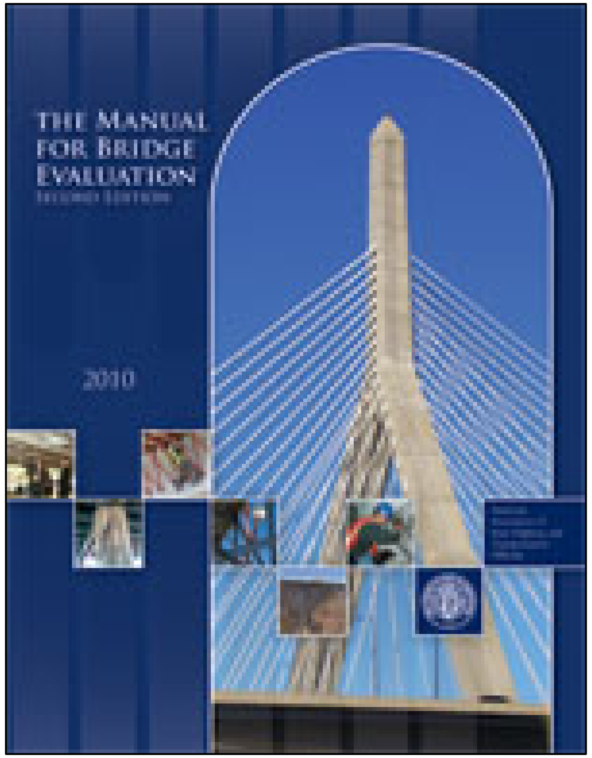
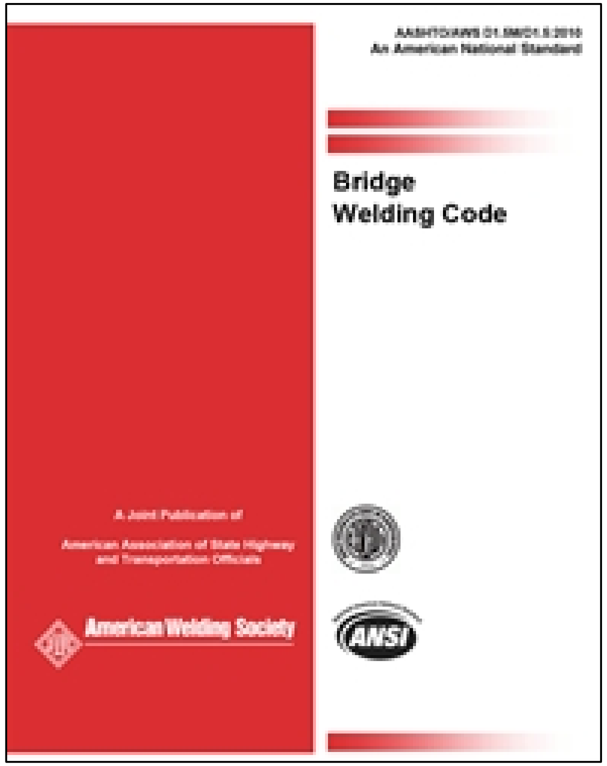
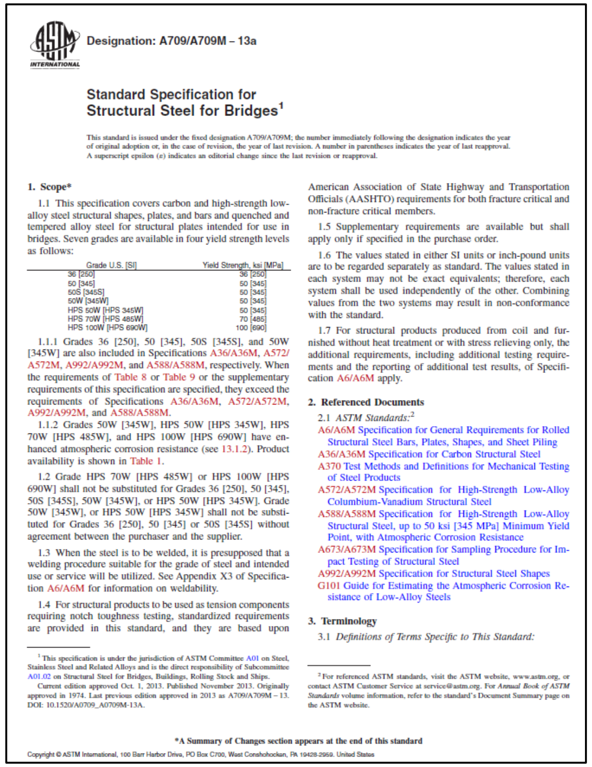
1980's- FCP Revisions

1970 1980 1990 2000 2010 2020









Designation: A709/A709M – 13a

Standard Specification for Structural Steel for Bridges[1]

This standard is issued under the fixed designation A709/A709M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This specification covers carbon and high-strength low-alloy steel structural shapes, plates, and bars and quenched and tempered alloy steel for structural plates intended for use in bridges. Seven grades are available in four yield strength levels as follows:

Grade U.S. [SI]	Yield Strength, ksi [MPa]
36 [250]	36 [250]
50 [345]	50 [345]
50S [345S]	50 [345]
50W [345W]	50 [345]
HPS 50W [HPS 345W]	50 [345]
HPS 70W [HPS 485W]	70 [485]
HPS 100W [HPS 690W]	100 [690]

1.1.1 Grades 36 [250], 50 [345], 50S [345S], and 50W [345W] are also included in Specifications A36/A36M, A572/A572M, A992/A992M, and A588/A588M, respectively. When the requirements of Table 8 or Table 9 or the supplementary requirements of this specification are specified, they exceed the requirements of Specifications A36/A36M, A572/A572M, A992/A992M, and A588/A588M.

1.1.2 Grades 50W [345W], HPS 50W [HPS 345W], HPS 70W [HPS 485W], and HPS 100W [HPS 690W] have enhanced atmospheric corrosion resistance (see 13.1.2). Product availability is shown in Table 1.

1.2 Grade HPS 70W [HPS 485W] or HPS 100W [HPS 690W] shall not be substituted for Grades 36 [250], 50 [345], 50S [345S], 50W [345W], or HPS 50W [HPS 345W]. Grade 50W [345W], or HPS 50W [HPS 345W] shall not be substituted for Grades 36 [250], 50 [345] or 50S [345S] without agreement between the purchaser and the supplier.

1.3 When the steel is to be welded, it is presupposed that a welding procedure suitable for the grade of steel and intended use or service will be utilized. See Appendix X3 of Specification A6/A6M for information on weldability.

1.4 For structural products to be used as tension components requiring notch toughness testing, standardized requirements are provided in this standard, and they are based upon American Association of State Highway and Transportation Officials (AASHTO) requirements for both fracture critical and non-fracture critical members.

1.5 Supplementary requirements are available but shall apply only if specified in the purchase order.

1.6 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.7 For structural products produced from coil and furnished without heat treatment or with stress relieving only, the additional requirements, including additional testing requirements and the reporting of additional test results, of Specification A6/A6M apply.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A6/A6M Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling
A36/A36M Specification for Carbon Structural Steel
A370 Test Methods and Definitions for Mechanical Testing of Steel Products
A572/A572M Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel
A588/A588M Specification for High-Strength Low-Alloy Structural Steel, up to 50 ksi [345 MPa] Minimum Yield Point, with Atmospheric Corrosion Resistance
A673/A673M Specification for Sampling Procedure for Impact Testing of Structural Steel
A992/A992M Specification for Structural Steel Shapes
G101 Guide for Estimating the Atmospheric Corrosion Resistance of Low-Alloy Steels

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

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[1] This specification is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloys and is the direct responsibility of Subcommittee A01.02 on Structural Steel for Bridges, Buildings, Rolling Stock and Ships.
Current edition approved Oct. 1, 2013. Published November 2013. Originally approved in 1974. Last previous edition approved in 2013 as A709/A709M – 13. DOI: 10.1520/A0709_A0709M-13A.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

*A Summary of Changes section appears at the end of this standard

Background for FC Discussion

1967- Silver Bridge Collapse

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1983- Mianus River Bridge Collapse

2000- Hoan Bridge Fracture

2007- I-35 W Collapse

2012- FHWA Memo

1970

1980

1990

2000

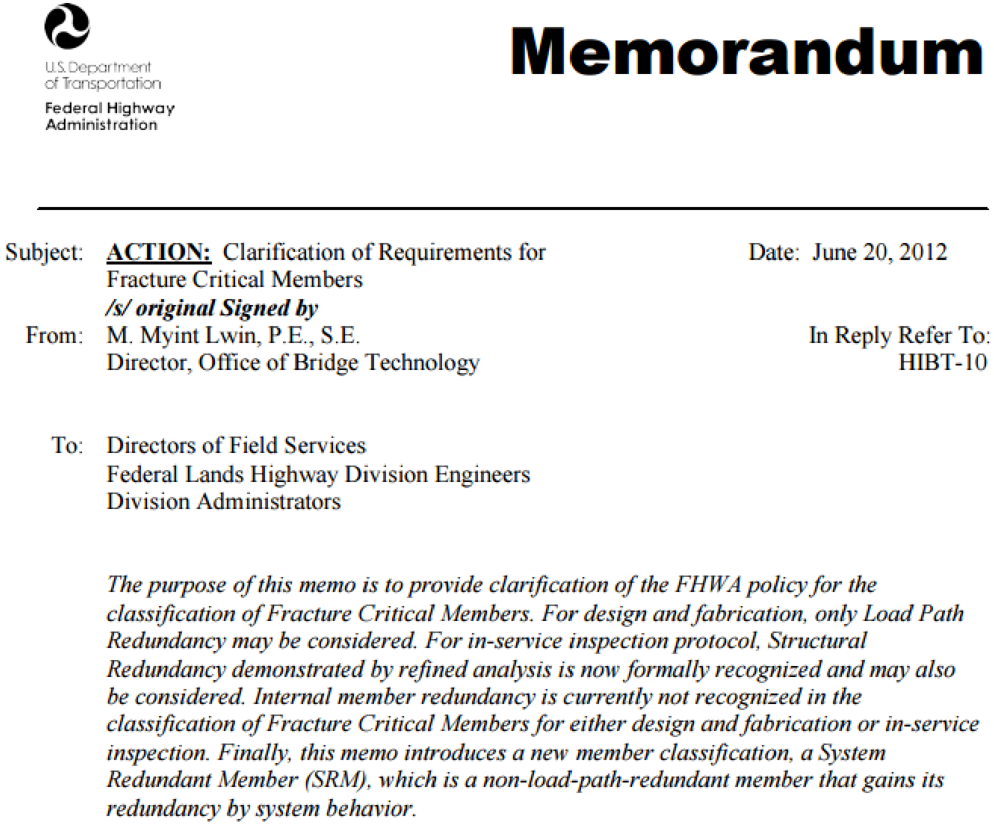
2010

2020

1972- AIS

arch Efforts

2000's- Texas Tub Girder



U.S. Department of Transportation
Federal Highway Administration

Memorandum

Subject: **ACTION:** Clarification of Requirements for Fracture Critical Members

Date: June 20, 2012

/s/ original Signed by

From: M. Myint Lwin, P.E., S.E.
Director, Office of Bridge Technology

In Reply Refer To:
HIBT-10

To: Directors of Field Services
Federal Lands Highway Division Engineers
Division Administrators

The purpose of this memo is to provide clarification of the FHWA policy for the classification of Fracture Critical Members. For design and fabrication, only Load Path Redundancy may be considered. For in-service inspection protocol, Structural Redundancy demonstrated by refined analysis is now formally recognized and may also be considered. Internal member redundancy is currently not recognized in the classification of Fracture Critical Members for either design and fabrication or in-service inspection. Finally, this memo introduces a new member classification, a System Redundant Member (SRM), which is a non-load-path-redundant member that gains its redundancy by system behavior.

"System Redundant Member" (SRM)

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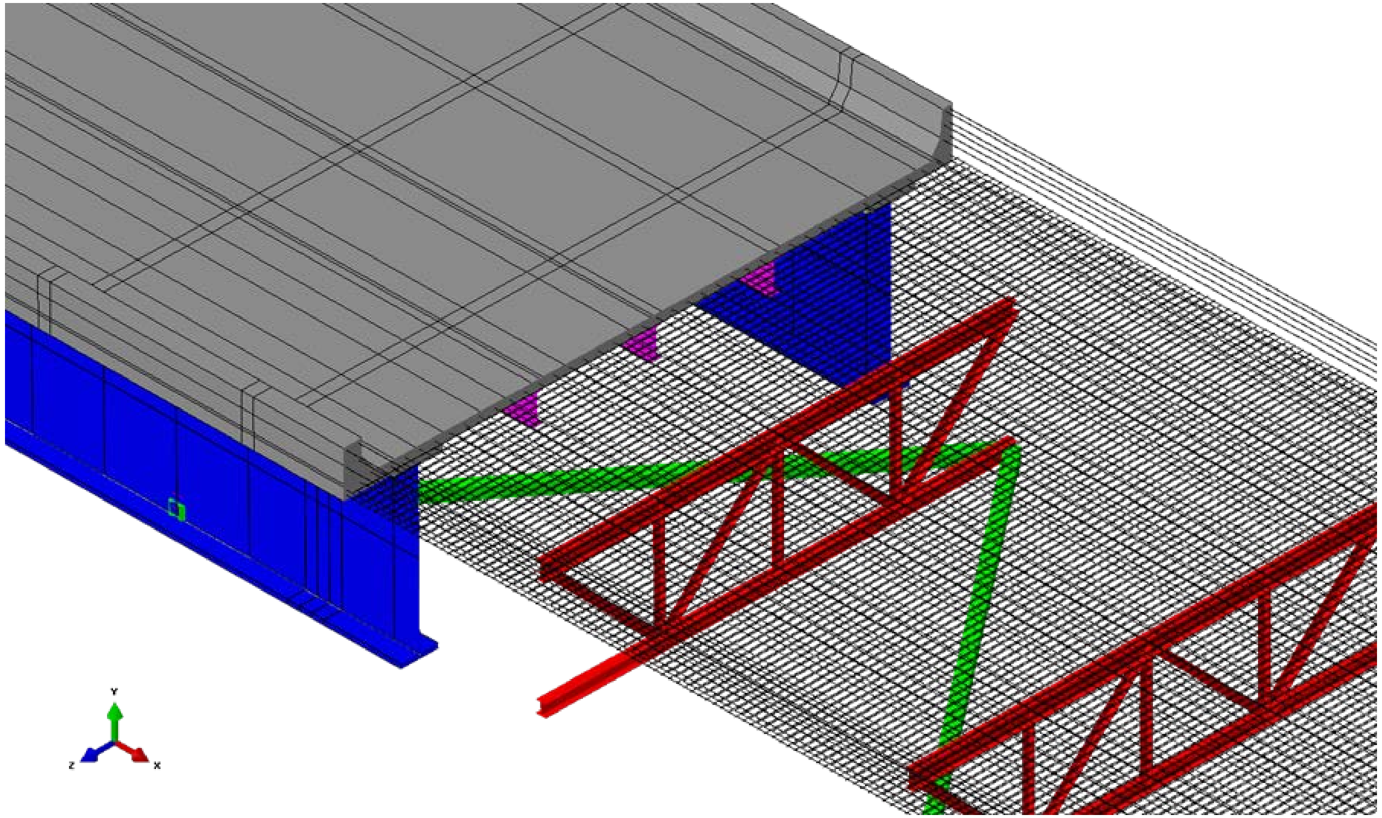
1970 1980 1990 2000 2010 2020

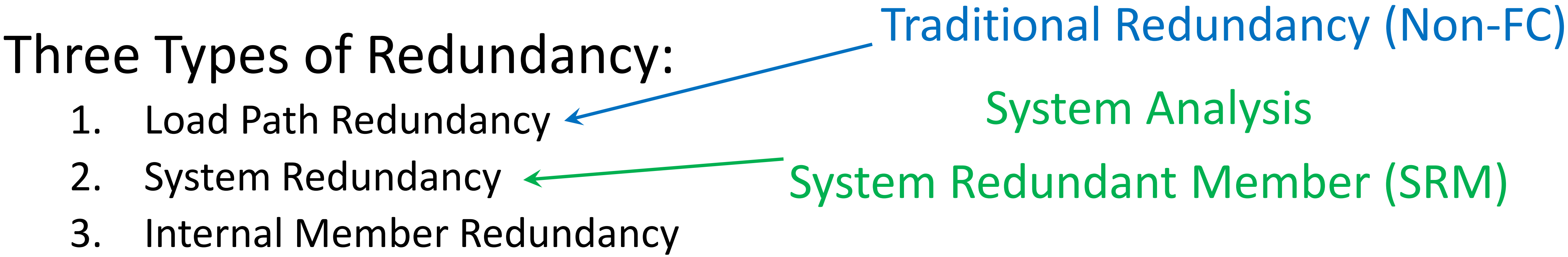
2017- Current State of FC Research

NCHRP 12-87a
Fracture-Critical System Analysis for Steel Bridges



R. Connor, A. Varma, F. Bonachera M., C. Korkmaz, Z. Lai

System Redundancy



Three Types of Redundancy:

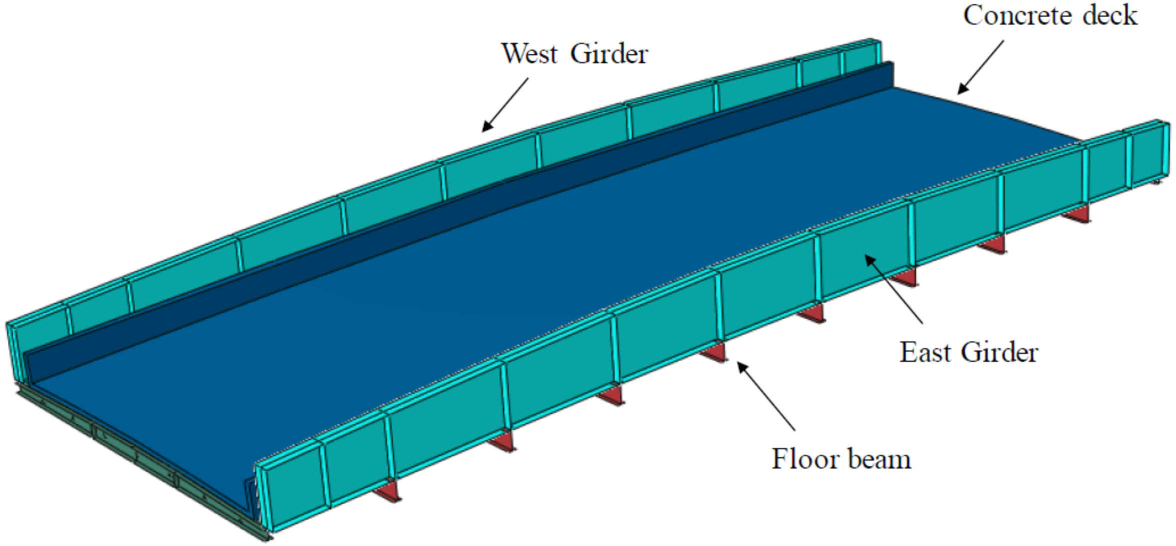
1. Load Path Redundancy
2. System Redundancy
3. Internal Member Redundancy

Traditional Redundancy (Non-FC)

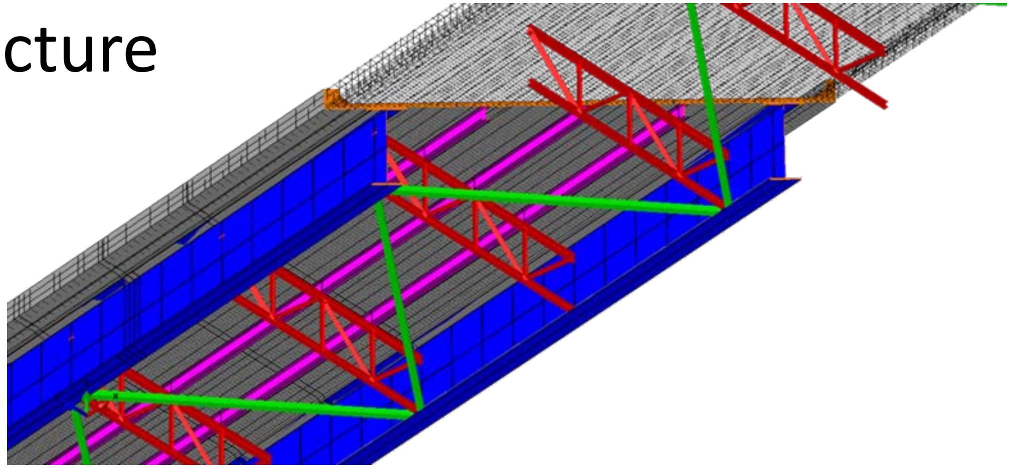
System Analysis

System Redundant Member (SRM)

System Redundancy: Research Plan

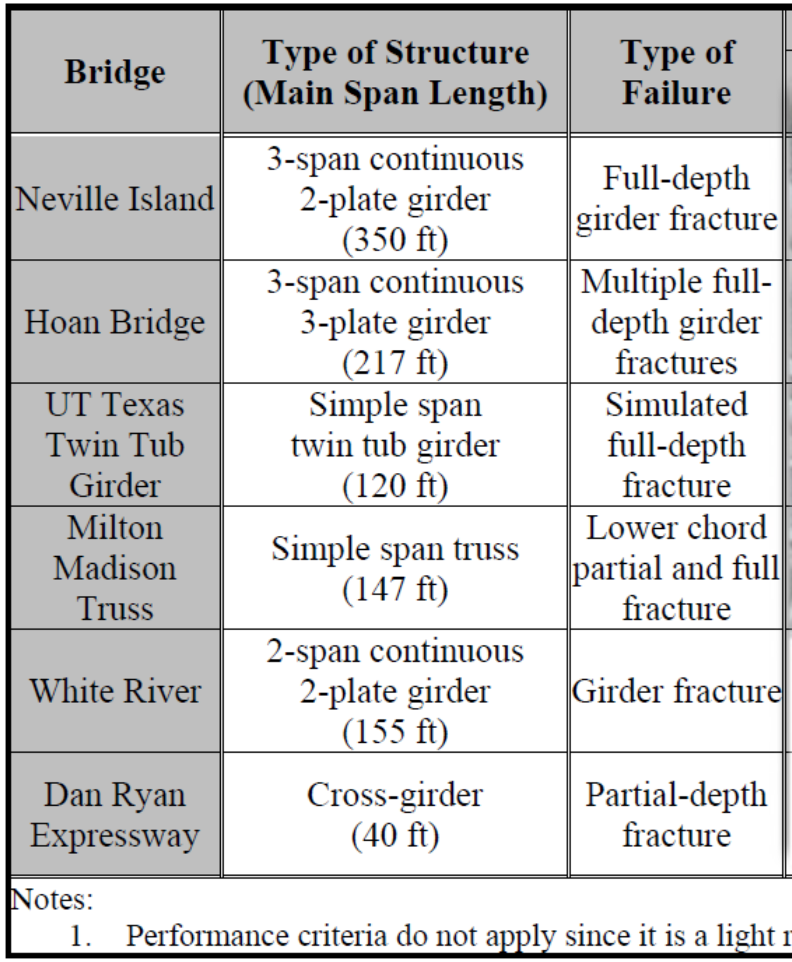


- FEA Methodology:
  - Benchmark with experimental data
  - Evaluation of dynamic effects
- Loading for faulted condition
- Performance criteria for evaluation
- Bridge fabrication and detailing for fracture
- Development of guide specification



System Redundancy: Research Plan

- FEA Methodology Benchmarking



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

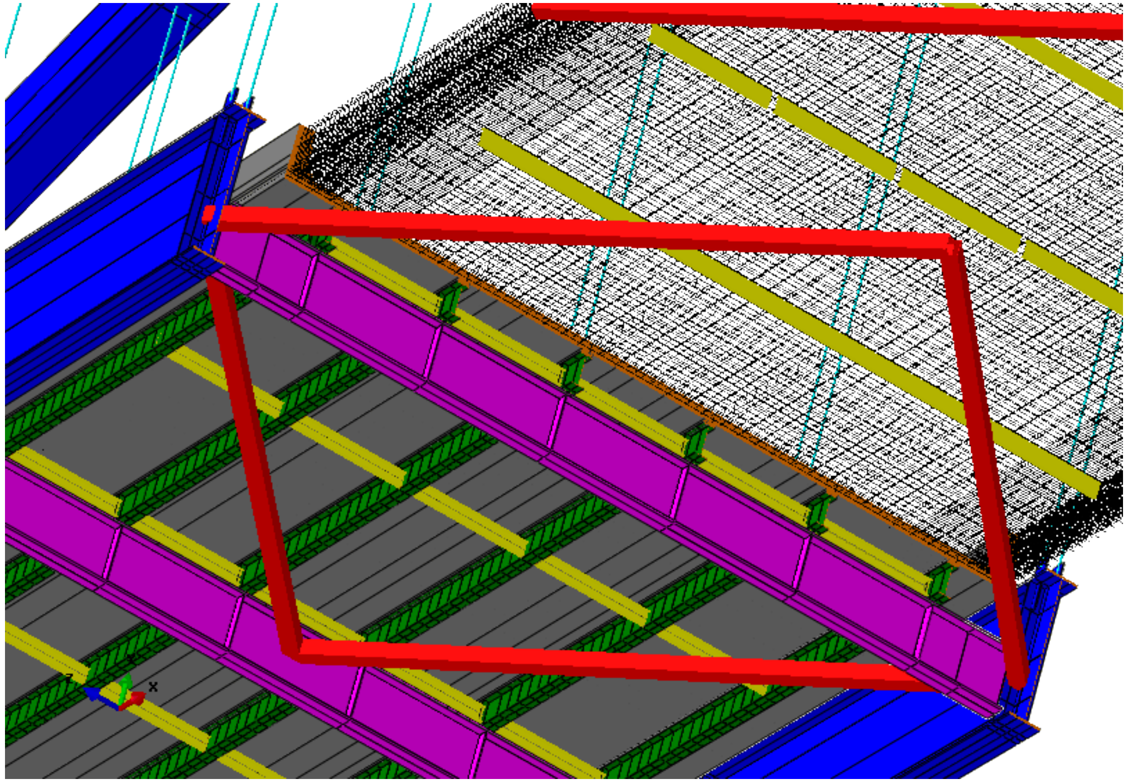
Notes:

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

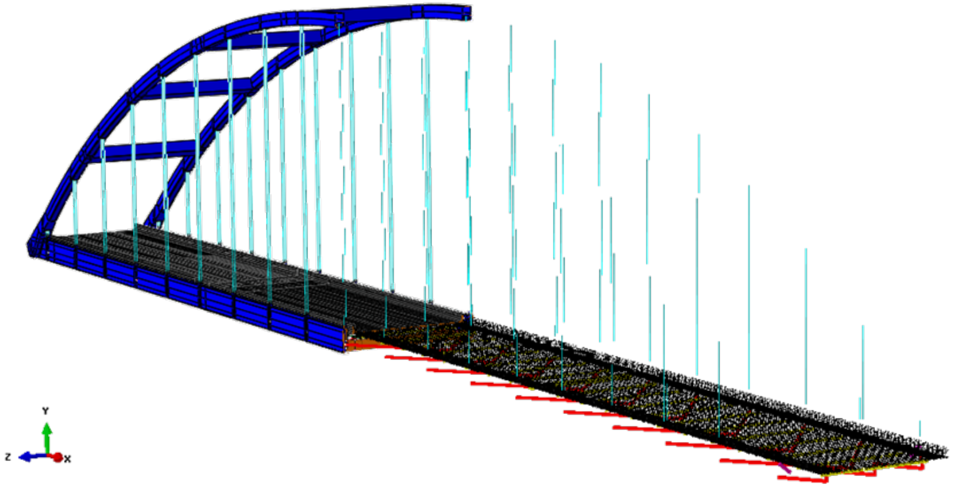


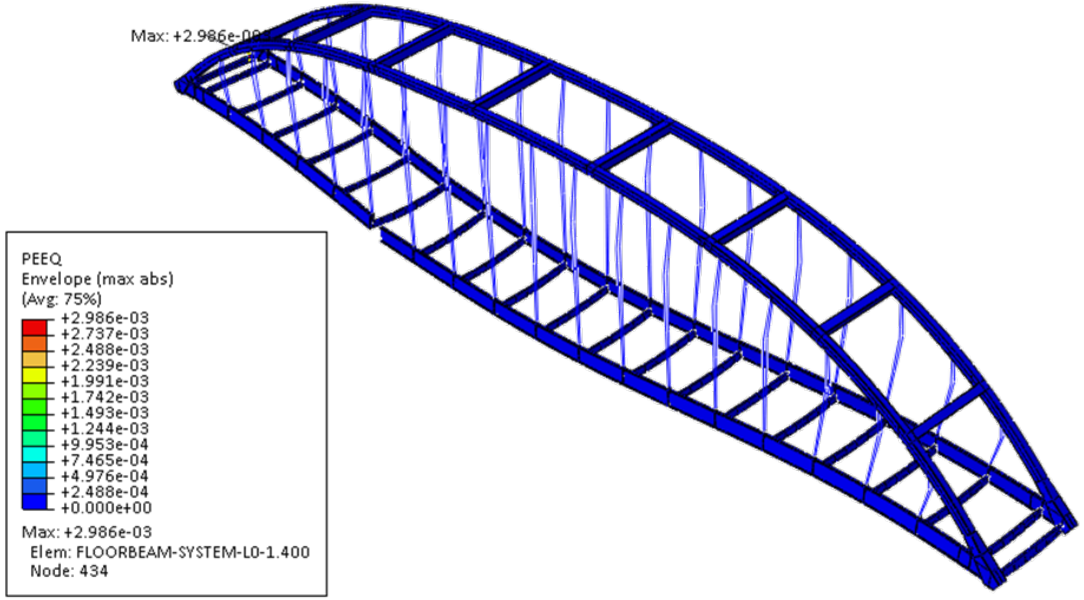
System Redundancy: Results

- 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

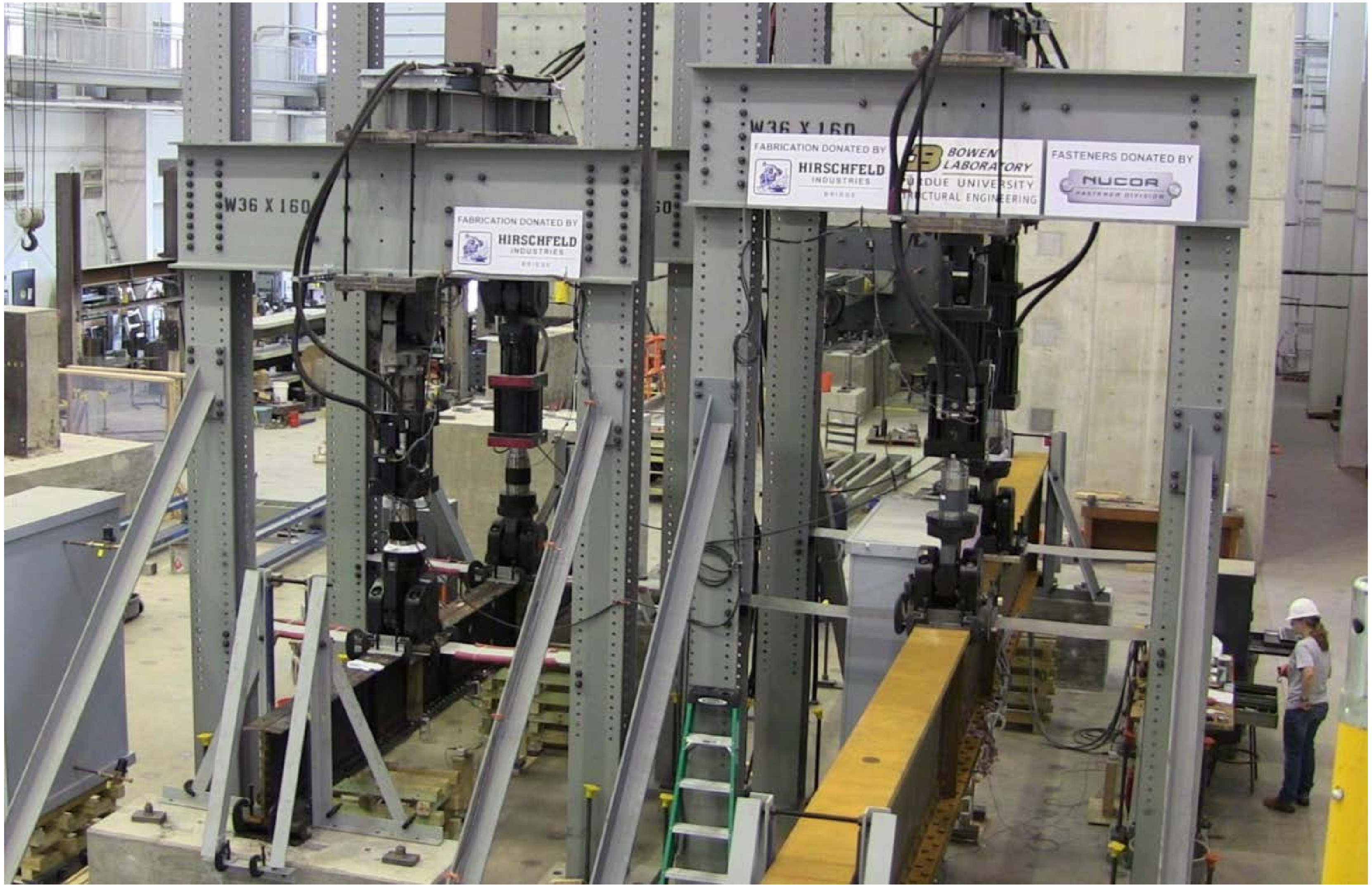
System Redundancy: Implementation

- Proposed analysis has been used by Wisconsin DOT for tub girder
- A guide specification is being discussed at AASHTO
- Application examples developed





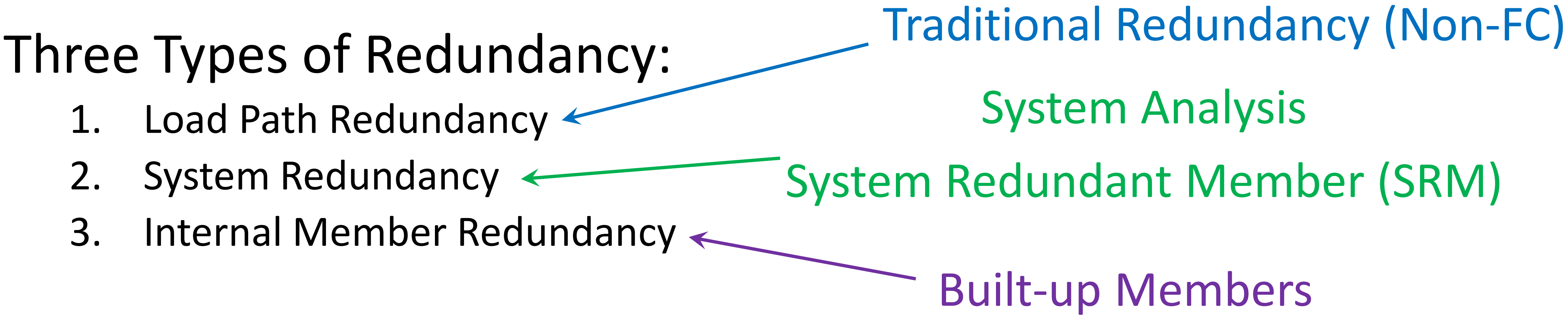
TPF-5(253): Member-level Redundancy in Built-up Steel Members



R. Connor, M. Hebdon

Member-level Redundancy

Member-level Redundancy



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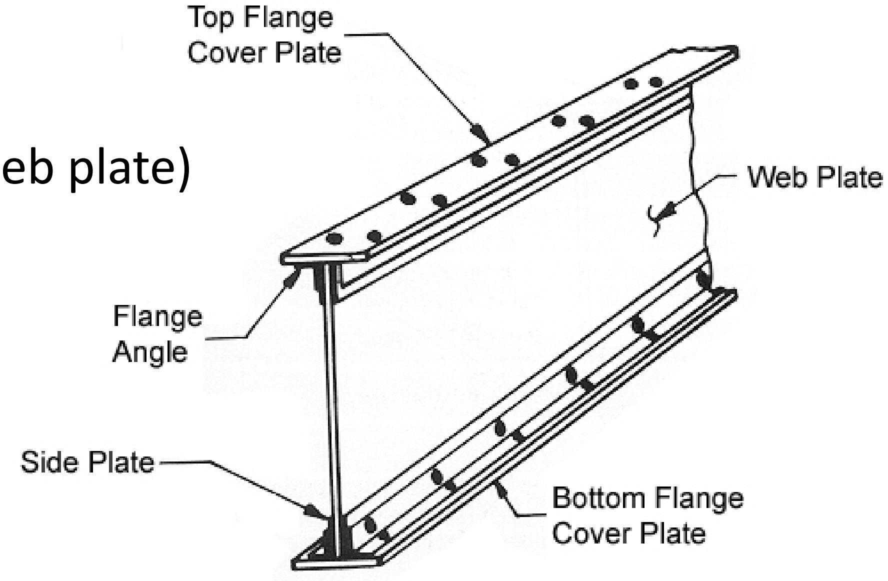
System Redundant Member (SRM)

Built-up Members

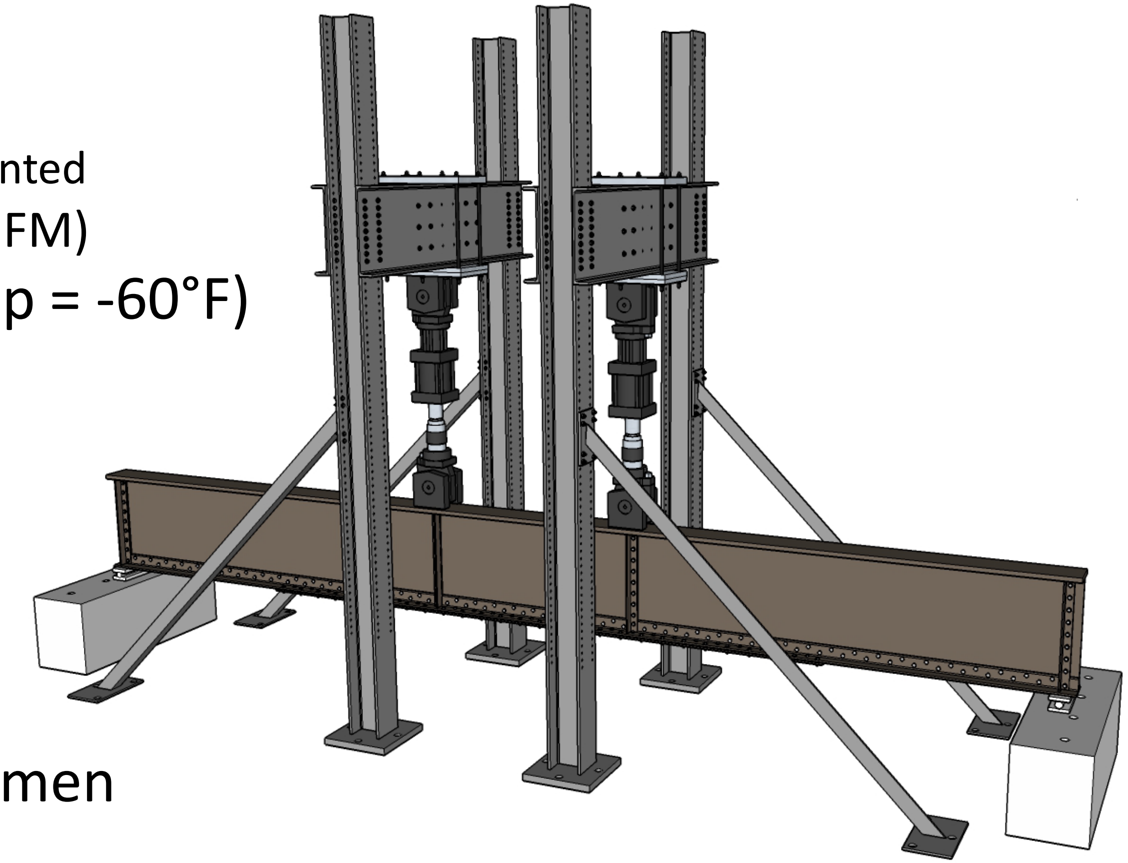
Member-level Redundancy: Objectives

- 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)

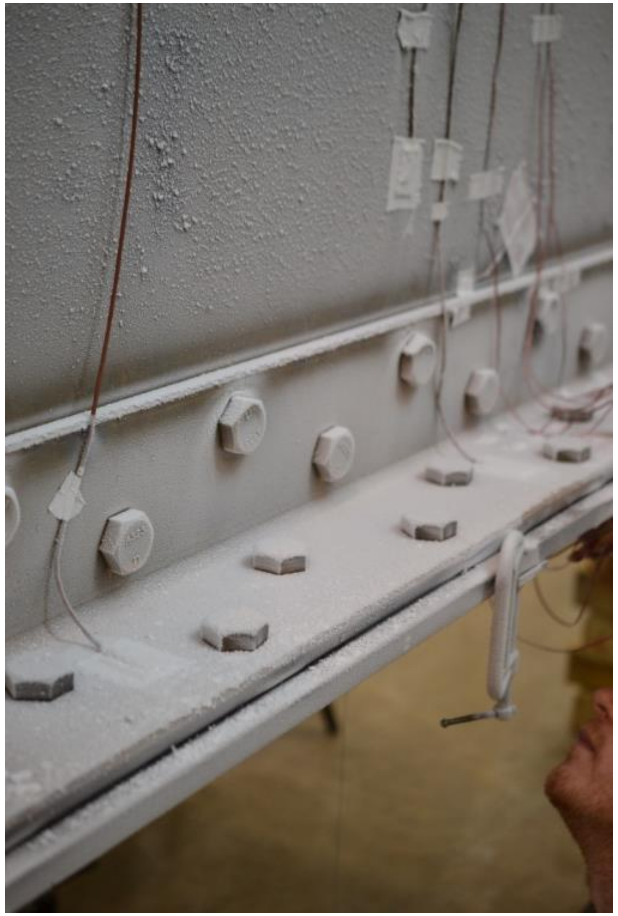


Member-level Redundancy: Testing

- 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



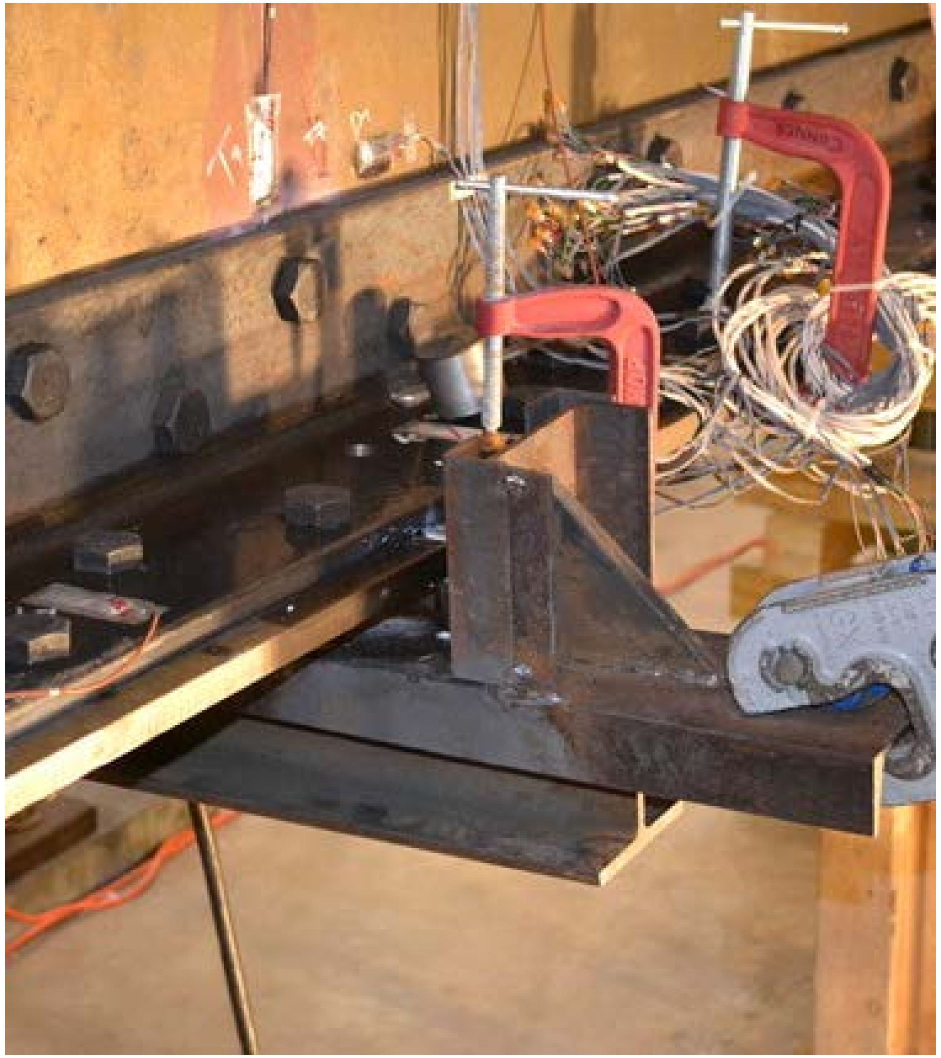
Member-level Redundancy: Testing



- 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

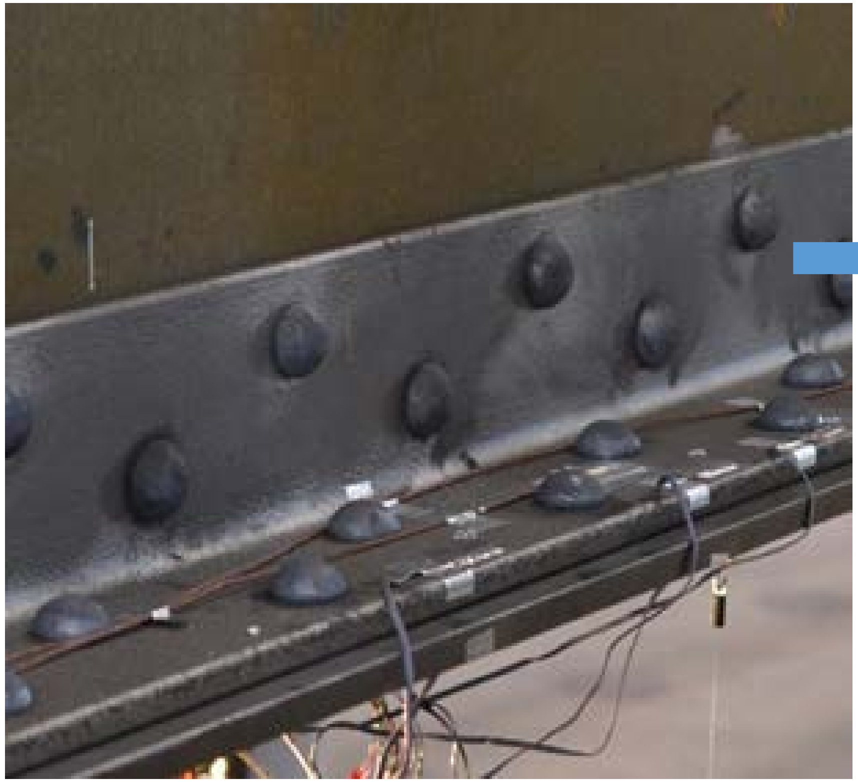


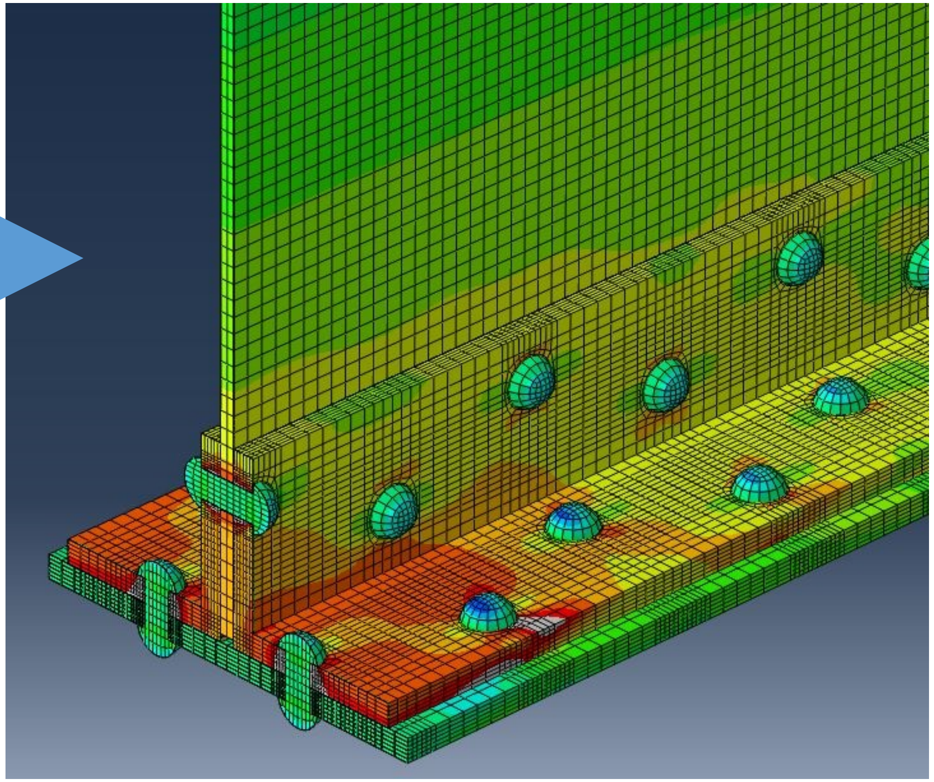
Member-level Redundancy: Testing

- Fracture resilience

Member-level Redundancy: Analytical Evaluation

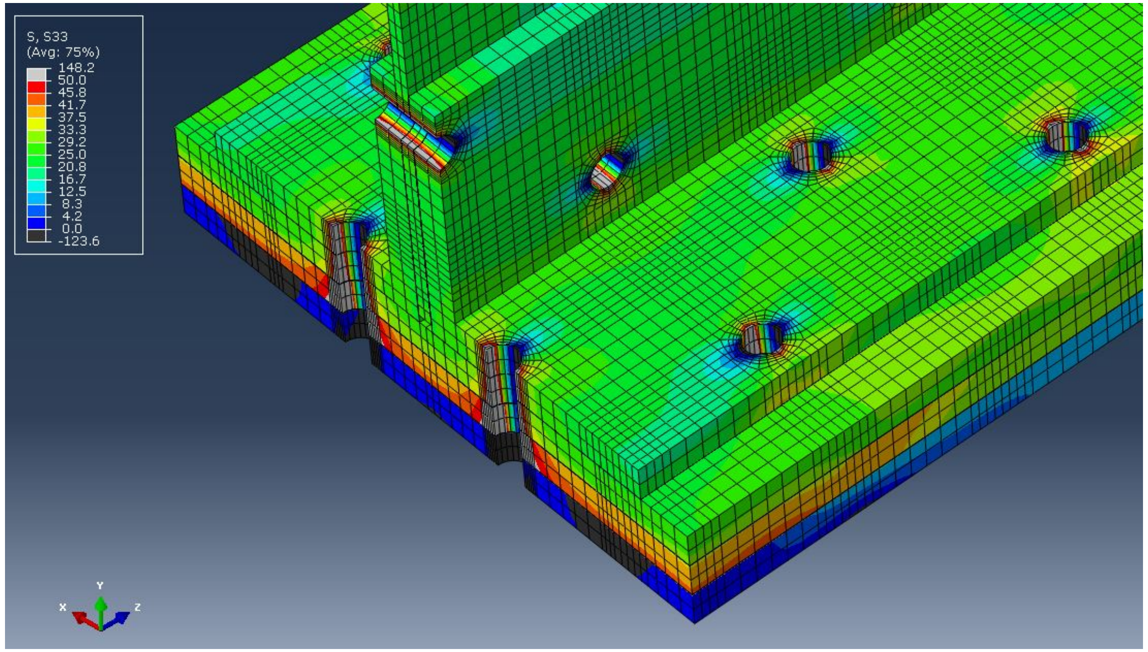
- 3D Finite Element Modeling
  - Parametric study
  - Local stress distribution

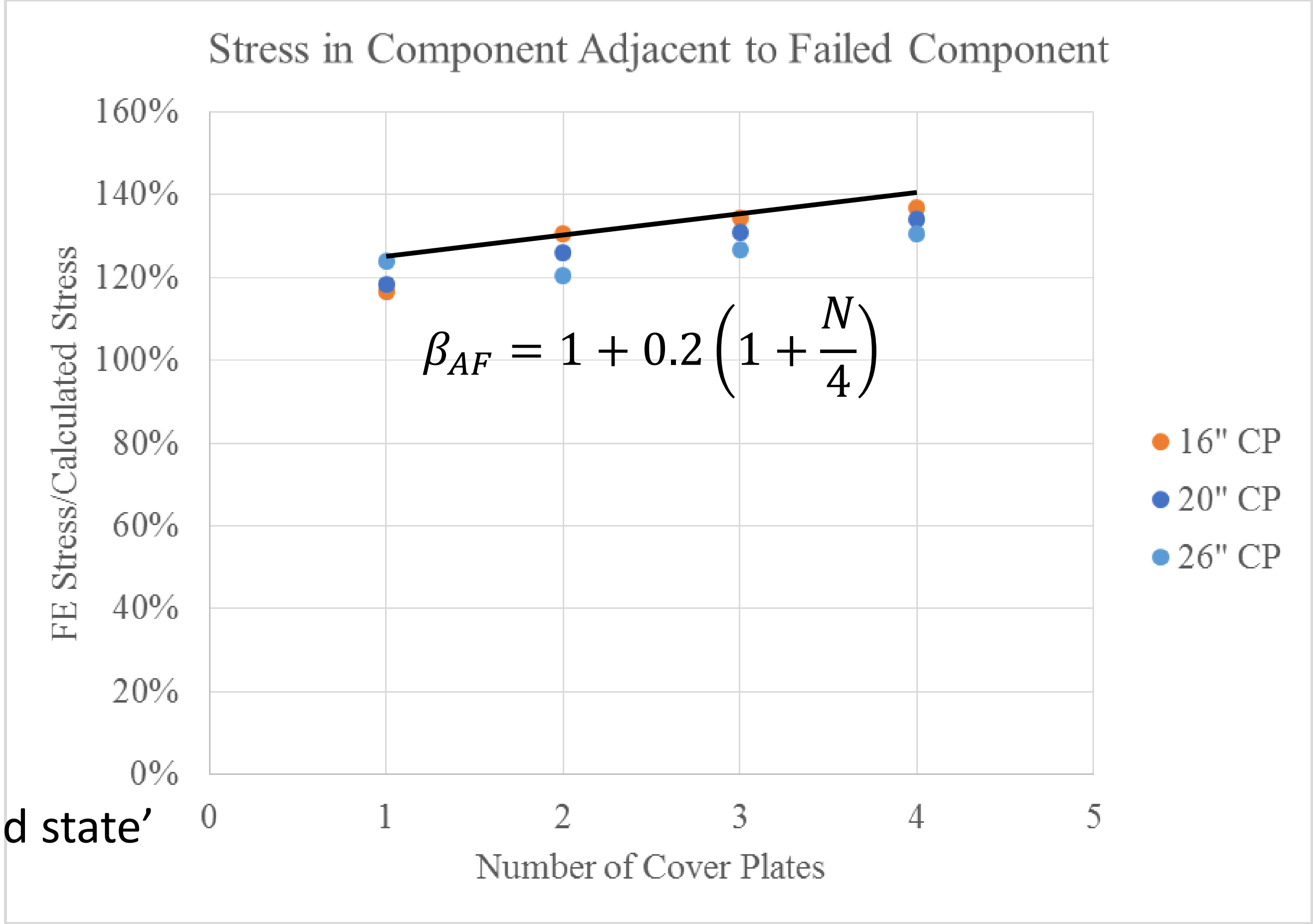




Member-level Redundancy: Analytical Evaluation

- Parametric Study: Number of cover plates

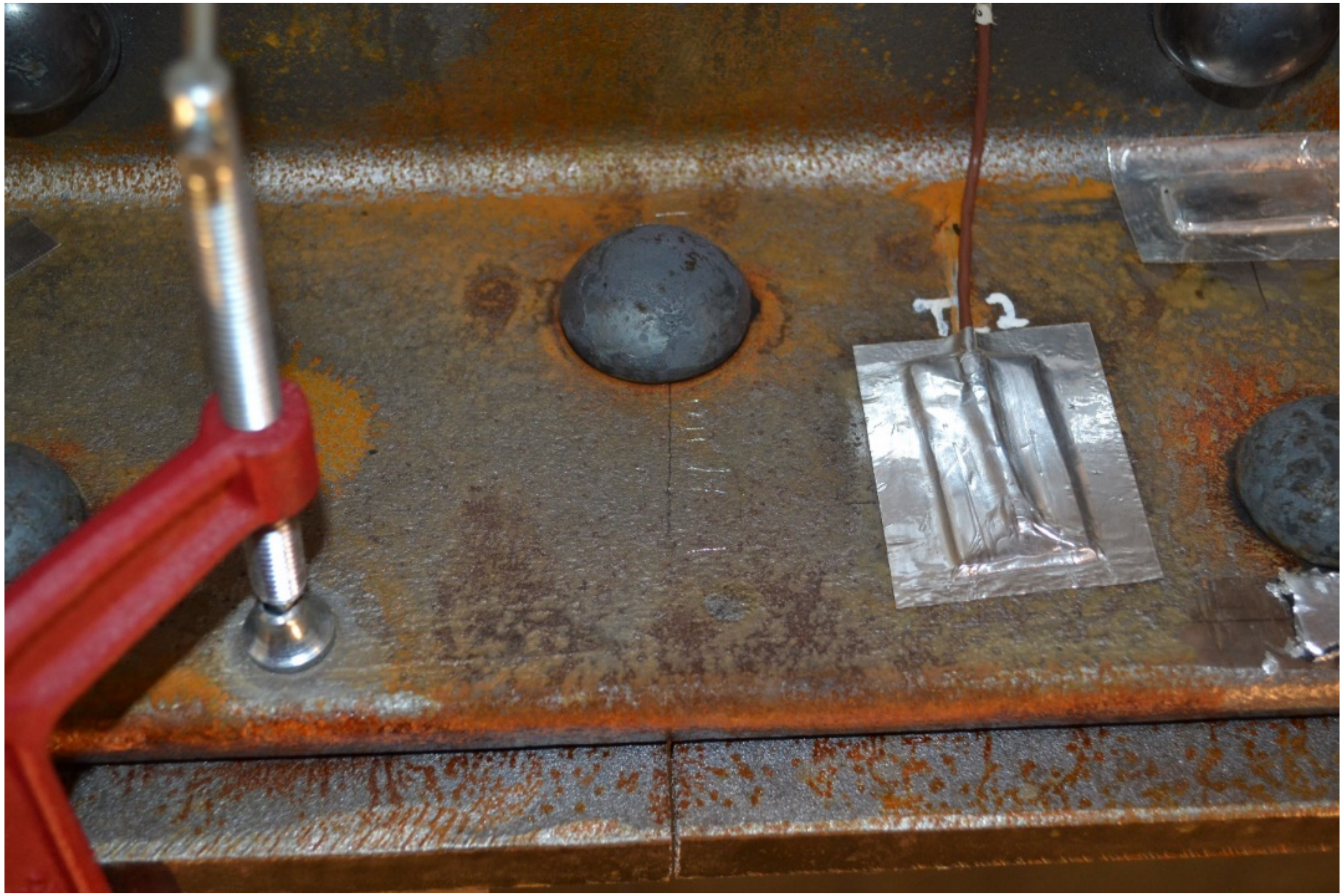




- $\sigma_{AF} = \beta_{AF} \dfrac{M_u}{S_{x-AF}}$
  - Where:
    - σ_{AF} = Stress in critical component in the ‘faulted state’
    - M_u = Applied moment
    - S_{x-AF} = Section modulus in the ‘faulted state’
    - $\beta_{AF} = 1 + 0.2\left(1 + \frac{N}{4}\right)$ Stress adjustment factor
    - N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

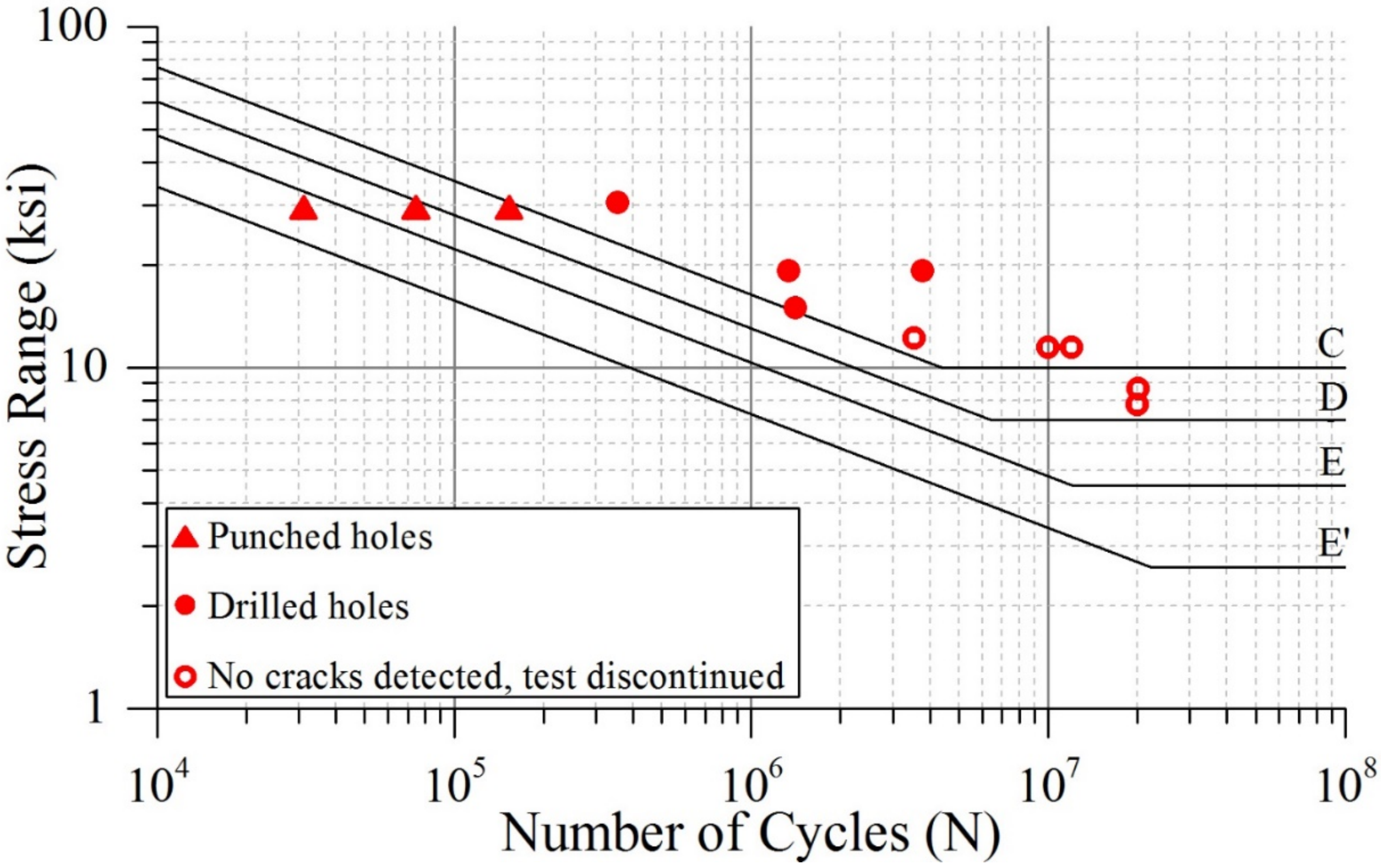
Member-level Redundancy: Testing Phase 2

- Fatigue life of partially failed cross-sections
  - How long until 2nd 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

Member-level Redundancy: Implementation

- Guide Specification integrate methodology for setting <u>maximum</u> 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

~~HPS Toughness~~

~~High Toughness~~

Integrated Fracture Control Plan

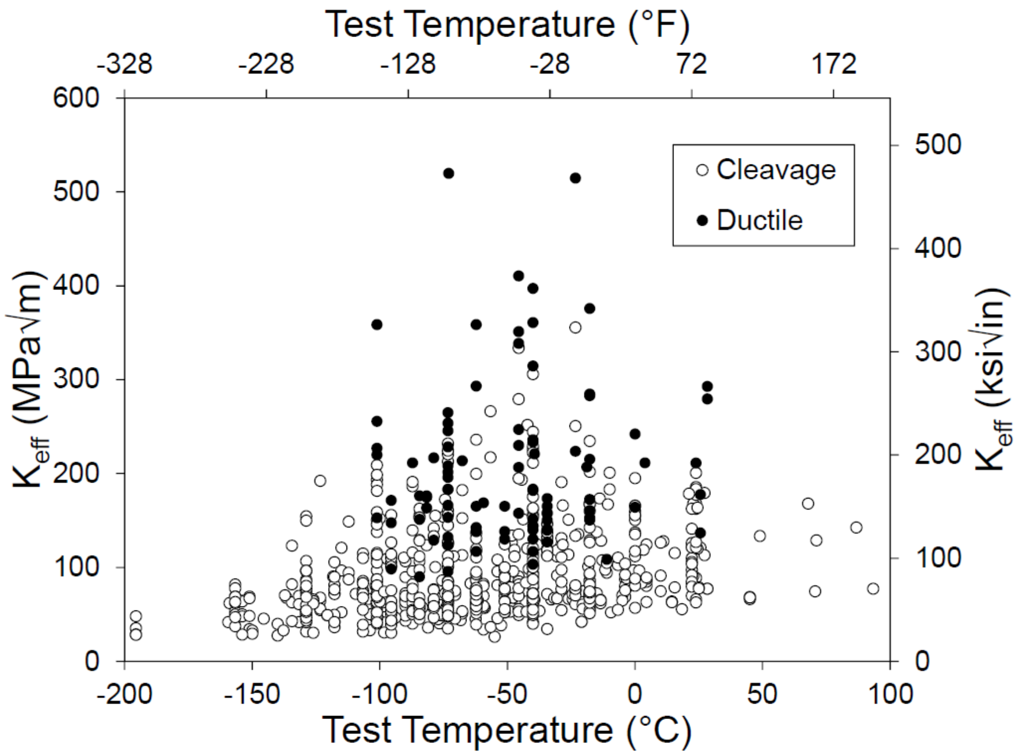
R. Connor, W. Collins, R. Sherman

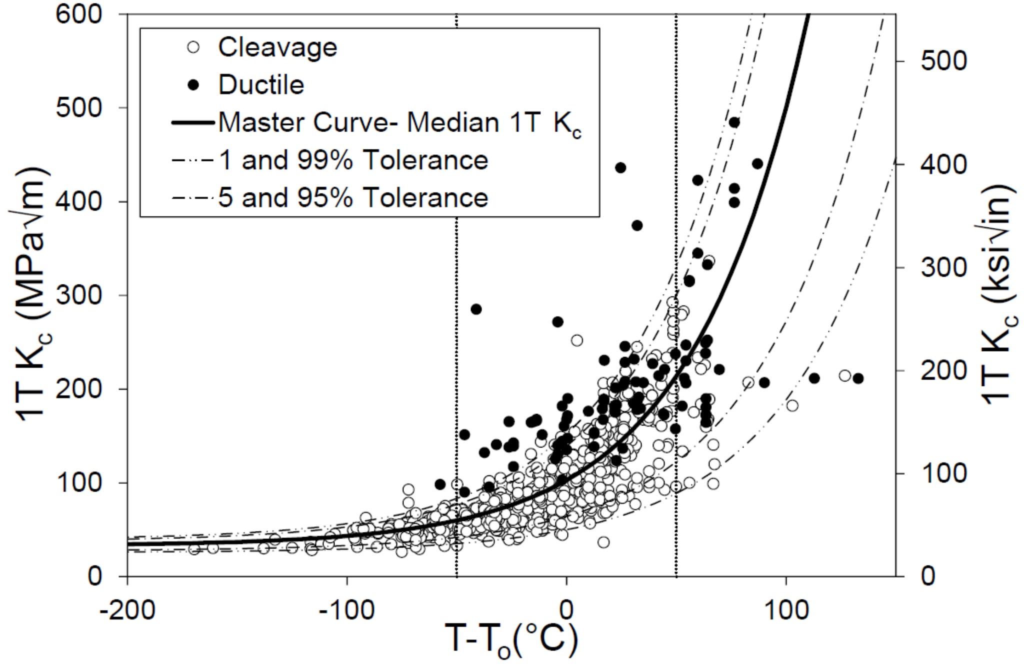
Integrated FCP

- High-performance steel (HPS)
    - High-strength
    - Improved weldability
    - Corrosion resistance
    - Increased fracture resistance
- Achieved through
    - Chemical composition
    - Processing

Integrated FCP: Overview

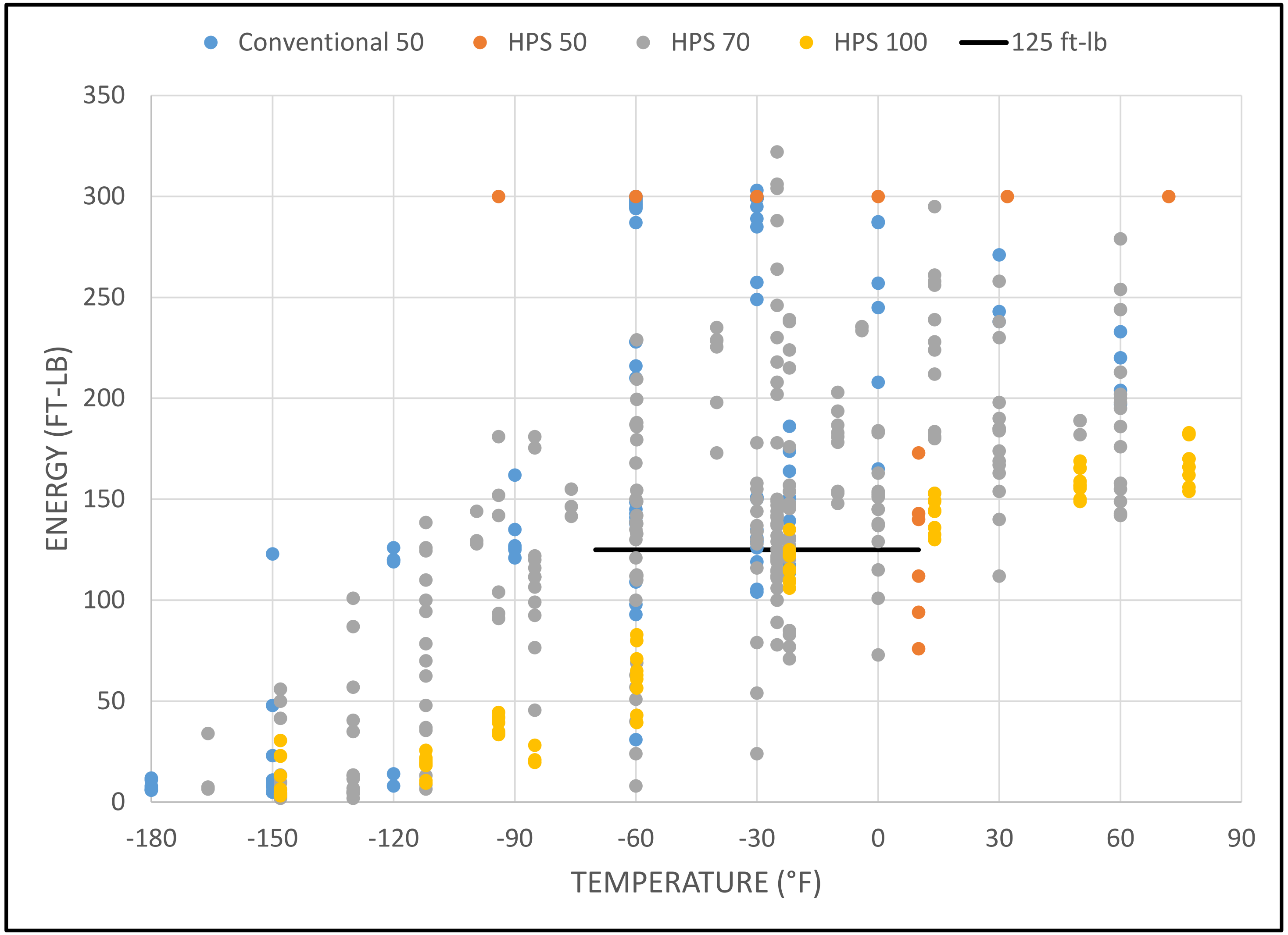
- Experimental testing
    - Small-scale
    - Large-scale
- FE modeling
    - Fracture toughness
- Framework
    - Material toughness
    - Inspection interval





Integrated FCP: Material Requirement

- CVN energy: 125 ft-lbf



Integrated FCP: Large-scale Test Matrix

Plate Designation	Specimen	Type	F_y	t_f	b_f	h_w	L
			(ksi)	(in.)	(in.)	(in.)	(ft.)
E	50_2-5_1B	Bending	50	2.5	14	33	46
	50_2-5_2B	Bending	50	2.5	14	33	46
	50_2-5_1A	Axial	50	2.5	14	N/A	16
H	70_1-5_1B	Bending	70	1.5	18	33	50
	70_1-5_2B	Bending	70	1.5	18	33	50
	70_1-5_1A	Axial	70	1.5	18	N/A	16
	70_1-5_2A	Axial	70	1.5	18	N/A	16
I	50_2-0_1B	Bending	50	2.0	14	33	40
	50_2-0_2B	Bending	50	2.0	14	33	40
J	50_1-5_1A	Axial	50	1.5	22	N/A	16
	50_1-5_2A	Axial	50	1.5	22	N/A	16

Integrated FCP: Experimental Testing

Test process

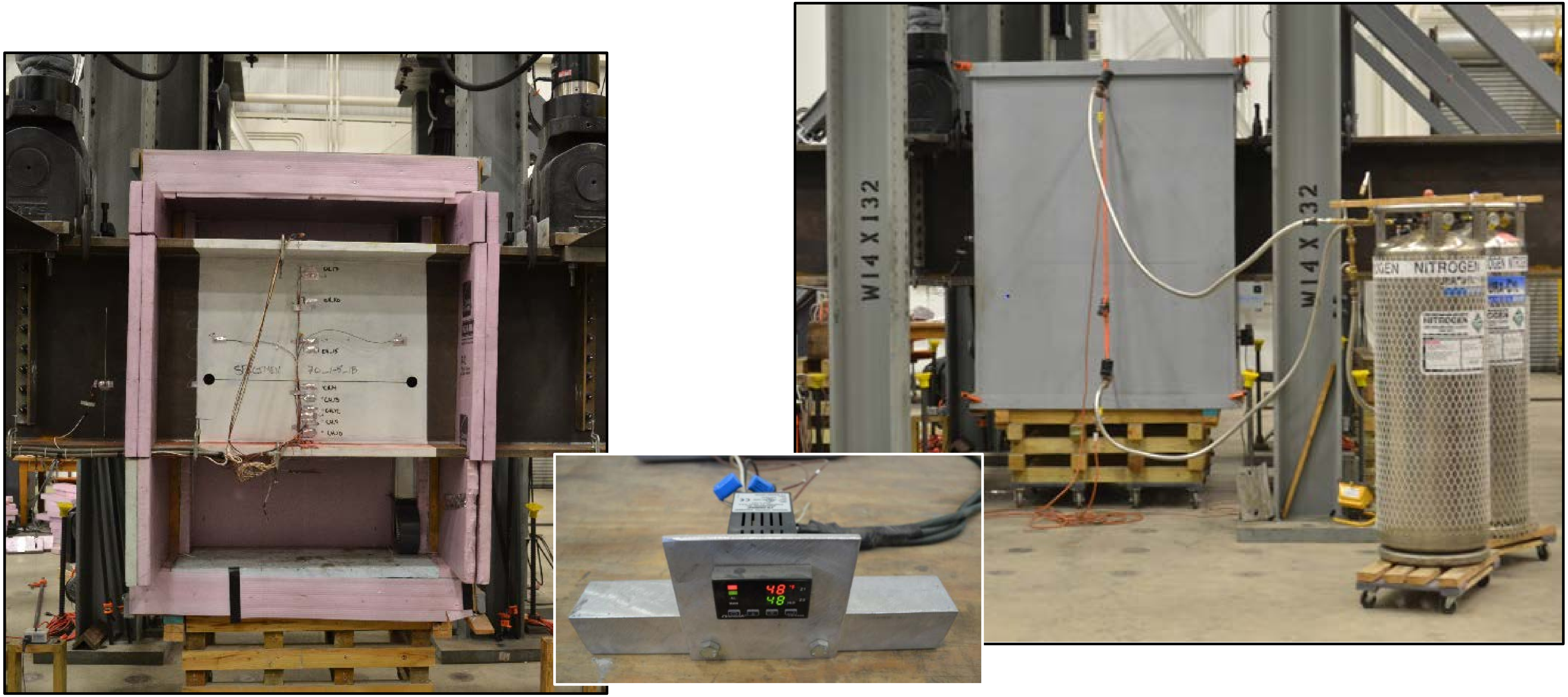
- Incremental growth
  - Notch specimen
  - Crack growth through fatigue
  - Cool to desired behavior
  - Load to induce fracture
  - Repeat until fracture achieved
- Grow to fracture length

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

Integrated FCP: Experimental Testing

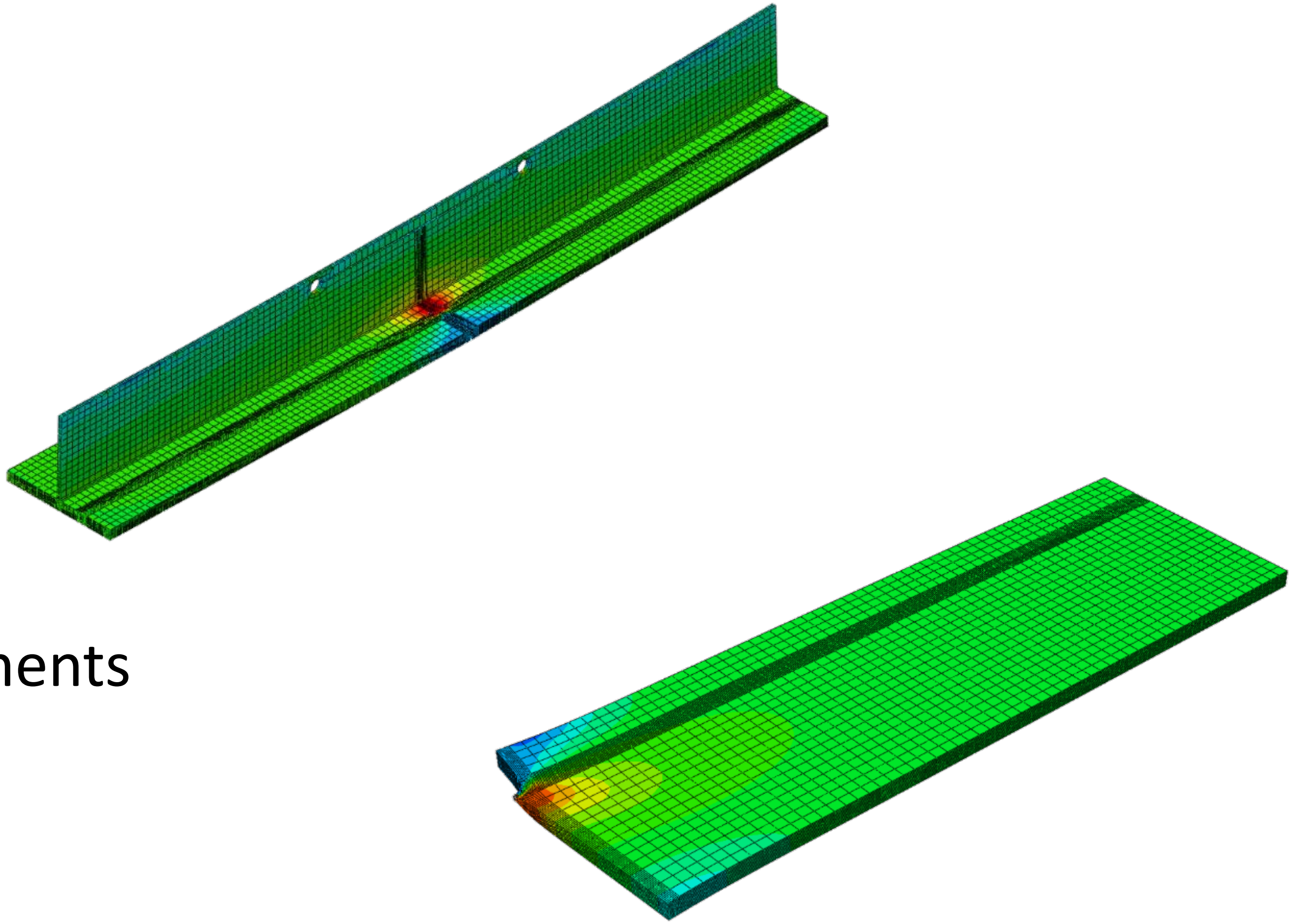
Test Results

Plate Designation	Specimen	Type	Final Crack (in.)	Fracture Load (kip)	Fracture Stress (ksi)	Deflection (in.)
E	50_2-5_1B	Bending	5.00	104.6	18.7	0.96
	50_2-5_2B	Bending	4.38	163.3	29.2	1.52
	50_2-5_1A	Axial	4.94	581.7	16.6	N/A
H	70_1-5_1B	Bending	5.06	160.4	40.4	2.52
	70_1-5_2B	Bending	7.50	164.6	41.5	2.66
	70_1-5_1A	Axial	4.88	859.1	26.0	N/A
	70_1-5_2A	Axial	6.94	728.3	22.1	N/A
I	50_2-0_1B	Bending	1.69	149.2	26.3	1.09
	50_2-0_2B	Bending	1.06	128.6	22.6	0.94
J	50_1-5_1A	Axial	6.00	424.4	15.7	N/A
	50_1-5_2A	Axial	4.63	871.0	32.3	N/A

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



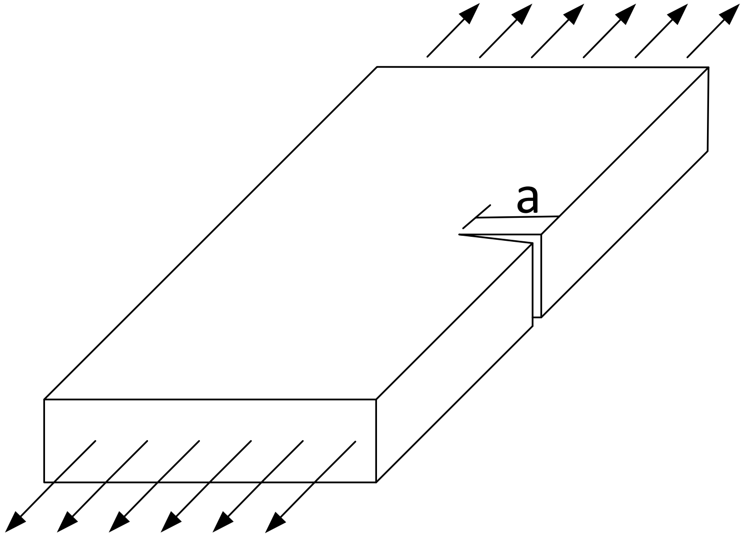
Integrated FCP: Analytical Evaluation

Results

Plate Designation	Specimen	FEA Model J	FEA Model K_J	FEA $K_{J(1T)}$
		(ksi*in.)	(ksi√in.)	(ksi√in.)
E	50_2-5_1B	0.52	128.3	156.6
	50_2-5_2B	1.28	200.1	246.9
	50_2-5_1A	0.64	142.7	174.8
H	70_1-5_1B	2.76*	295.8*	325.4*
	70_1-5_2B	6.63*	458.2*	505.1*
	70_1-5_1A	0.58	135.5	148.0
	70_1-5_2A	1.88	244.0	268.1
I	50_2-0_1B	0.17*	74.2*	84.8*
	50_2-0_2B	0.08	49.0	54.8
J	50_1-5_1A	1.27	200.2	219.6
	50_1-5_2A	2.29	269.4	296.2

Integrated FCP: Rational Inspection Interval

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

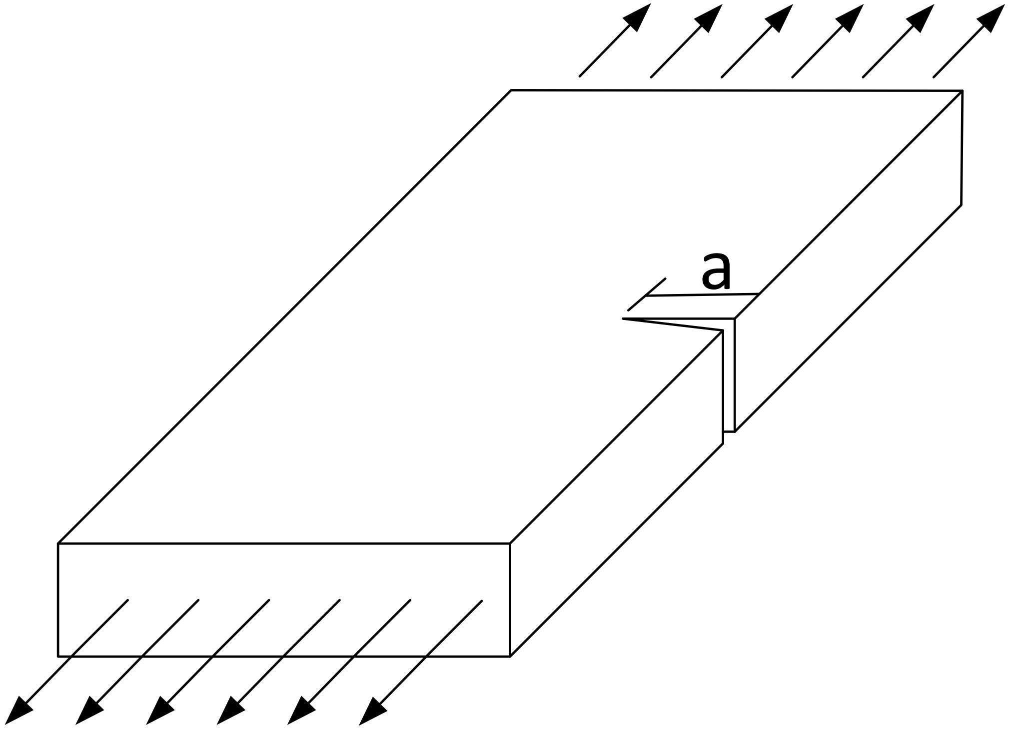
Critical Flaw Size

CURRENT SPECIFICATION					
Grade	**Thickness (in.)**	**Minimum Test Value Energy (ft.-lb.)**	**Minimum Average Energy (ft.-lb.)**		
			Zone 1	**Zone 2**	**Zone 3**
HPS 50 WF	to 4	24	30 @ 10 °F	30 @ 10 °F	30 @ 10 °F
HPS 70 WF	to 4	28	35 @ -10 °F	35 @ -10 °F	35 @ -10 °F
HPS 100 WF	to 2.5	28	35 @ -30 °F	35 @ -30 °F	35 @ -30 °F
	2.5 - 4	N/A	N/A	N/A	N/A
POTENTIAL SPECIFICATION					
Grade	**Thickness (in.)**	**Minimum Test Value Energy (ft.-lb.)**	**Minimum Average Energy (ft.-lb.)**		
			Zone 1	**Zone 2**	**Zone 3**
Damage Tolerant	TBD	TBD	125 @ 0 °F	125 @ -30 °F	125 @ -60 °F

Integrated FCP: Rational Inspection Interval

Critical Flaw Size

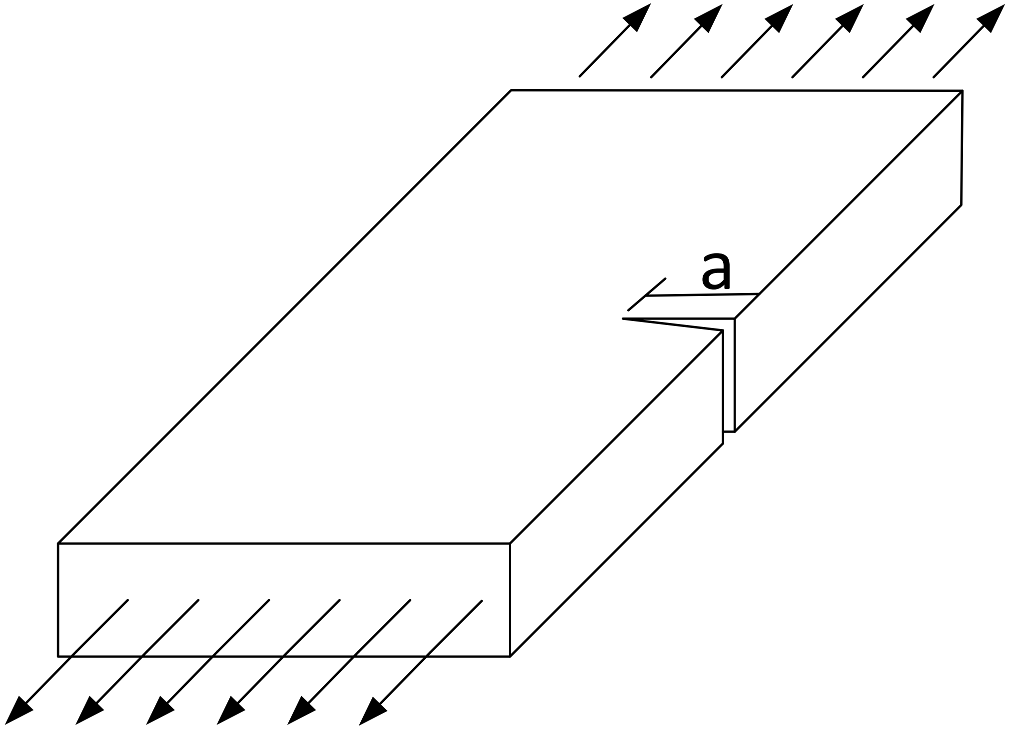
Tolerable Crack Sizes			
Grade	**Applied Stress**	**K_{new}**	**Edge**
			a
(ksi)	**(ksi)**	**(ksi√in.)**	**(in.)**
50	37.5	122	
70	52.5	122	
100	75	122	



Integrated FCP: Rational Inspection Interval

Critical Flaw Size

Tolerable Crack Sizes			
Grade	**Applied Stress**	**K_{new}**	**Edge** **a**
(ksi)	**(ksi)**	**(ksi√in.)**	**(in.)**
50	37.5	122	1.3
70	52.5	122	0.8
100	75	122	0.5



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 $0.75F_y$
- Same crack growth rate

Grade	**Initial a**	**Cycles**
(ksi)	**(in.)**	**(millions)**
50	0.125	30.6
70		28.9
100		26.0

Integrated FCP: Rational Inspection Interval

Calculate Interval

- 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

Grade	**Initial a**	**Years**	**Final Crack**
(ksi)	**(in.)**		**(in.)**
50	0.125	83.9	
70		79.2	
100		71.2	

Integrated FCP: Rational Inspection Interval

Summary

Grade	Initial a	Years	Final Crack
(ksi)	(in.)		(in.)
50	0.125	83.9	1.3
70		79.2	0.8
100		71.2	0.5

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

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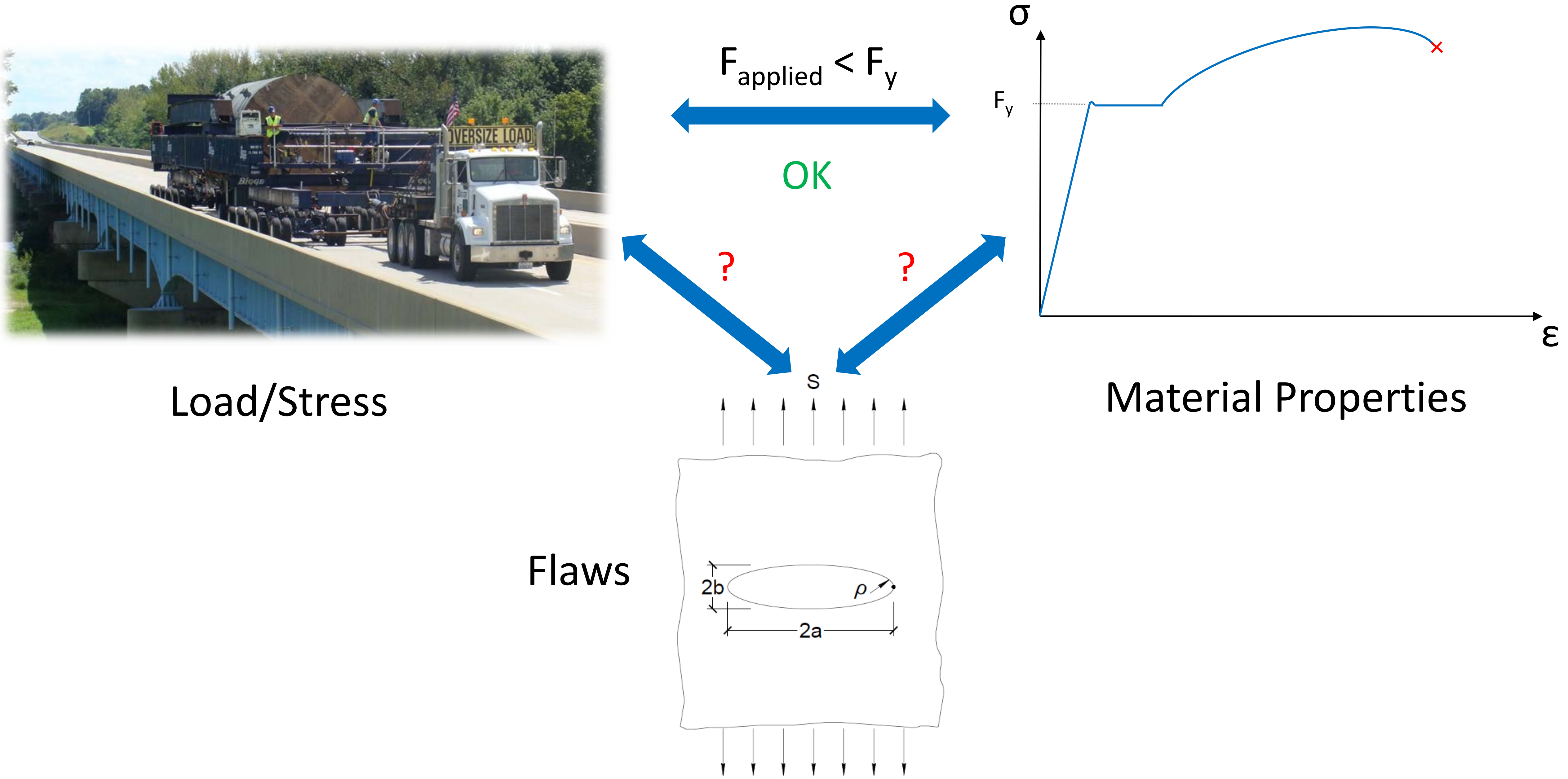
Additional Material

Fracture Mechanics Introduction

Fracture Mechanics Introduction



$F_{applied} < F_y$

OK

?

?

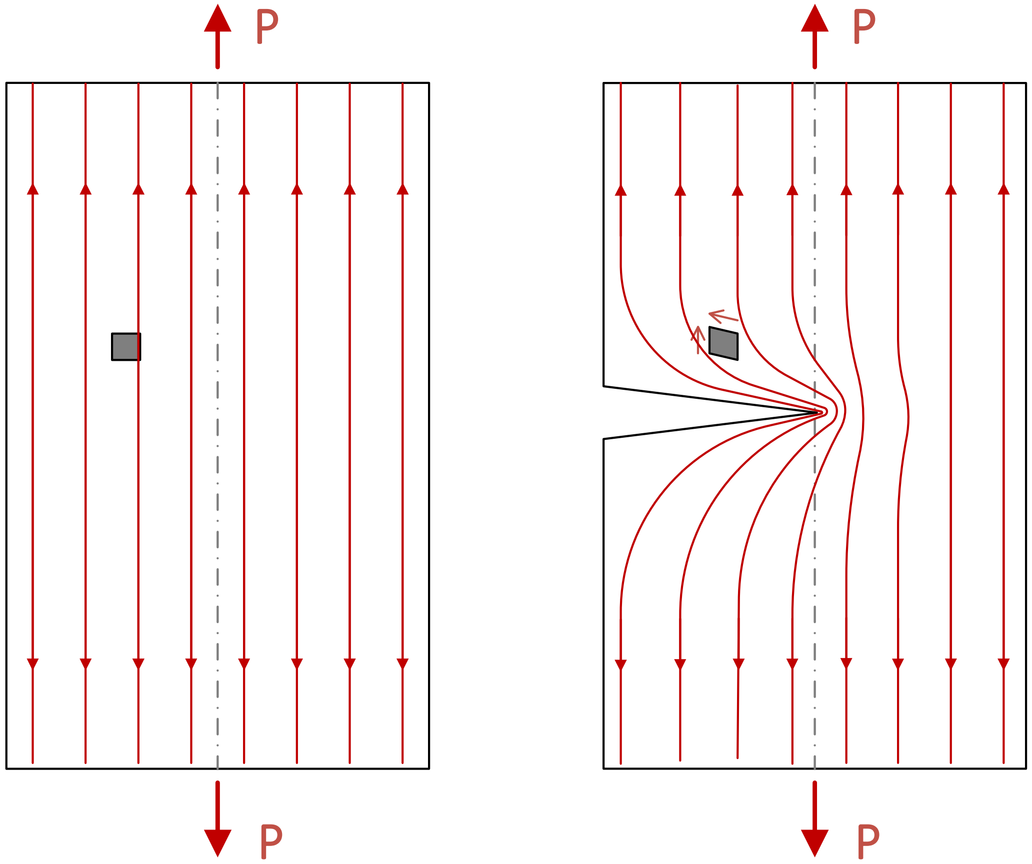
Load/Stress

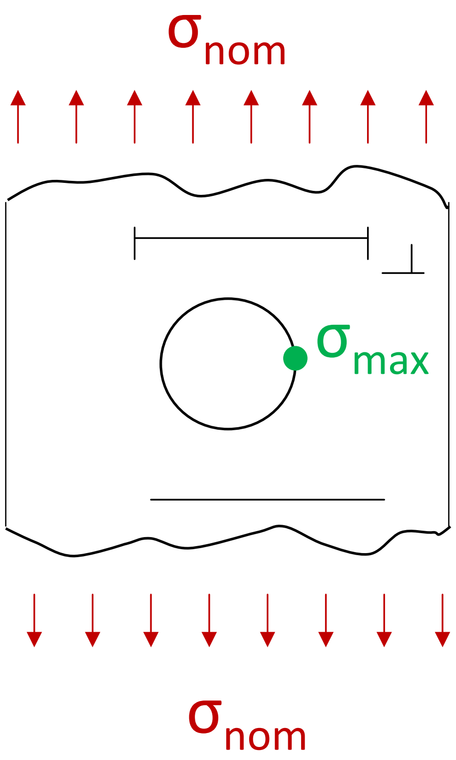
Material Properties

Flaws

Fracture Mechanics Introduction

Why do flaws matter?

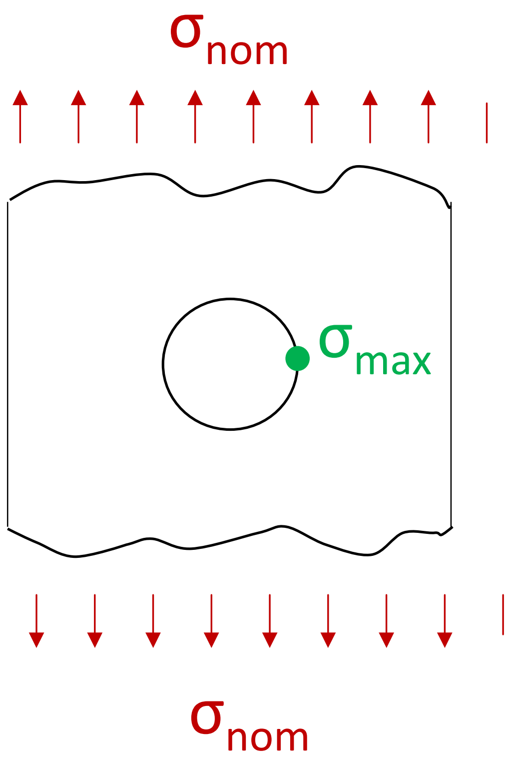




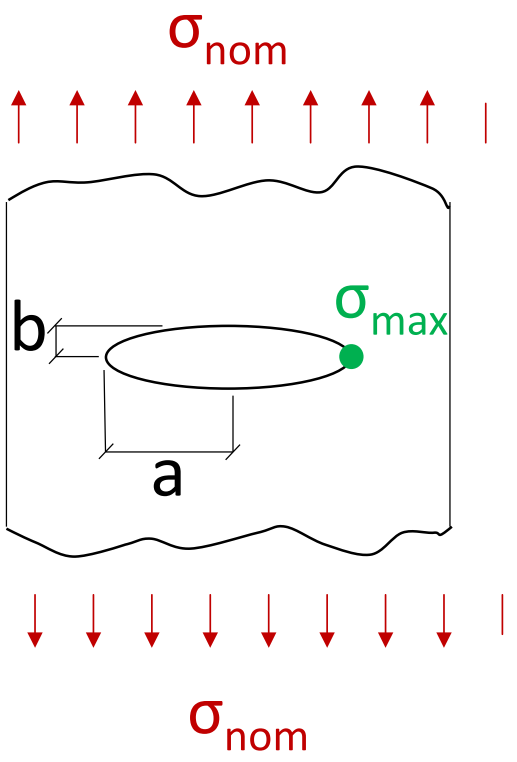
$$\sigma_{max} = k_t \times \sigma_{nom}$$

Stress Concentration Factor, k_t

Fracture Mechanics Introduction



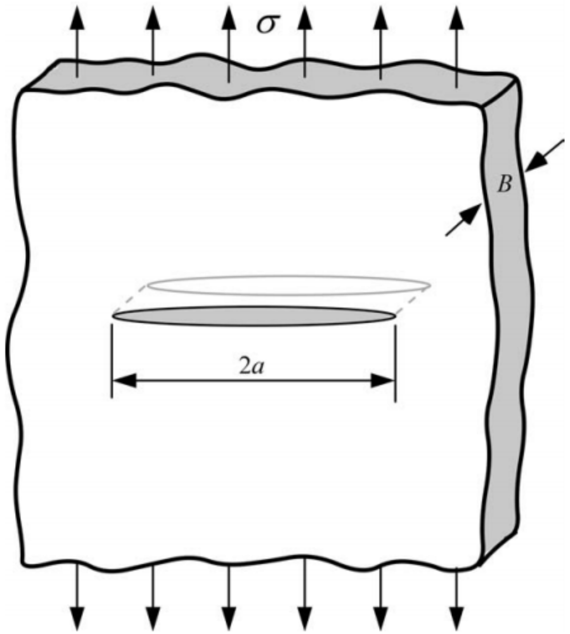
$k_t = 3$



$k_t = 1 + 2a/b$

Stress concentration factors cannot be used for infinitely sharp cracks

Fracture Mechanics Introduction



Stress Intensity Factor, K

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

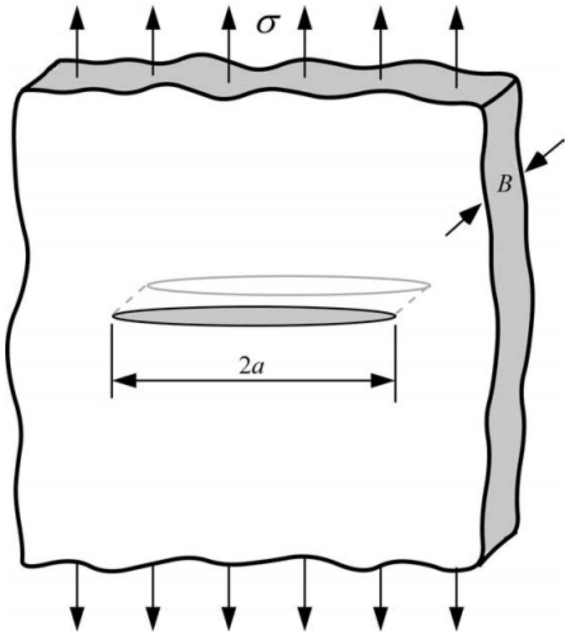
Crack size (CAUTION!)

Applied Stress

Function of geometry

Load/Stress/Stress Intensity		Material Properties
Applied Stress	$F_{applied} < F_y$	Yield Strength
Applied Stress Intensity	$K_I < K_c$	Fracture Toughness

Fracture Mechanics Introduction



Stress Intensity Factor, K

- Material property- ASTM test methods
- Evaluate for specific:
  - Temperature
  - Constraint
  - Loading rate

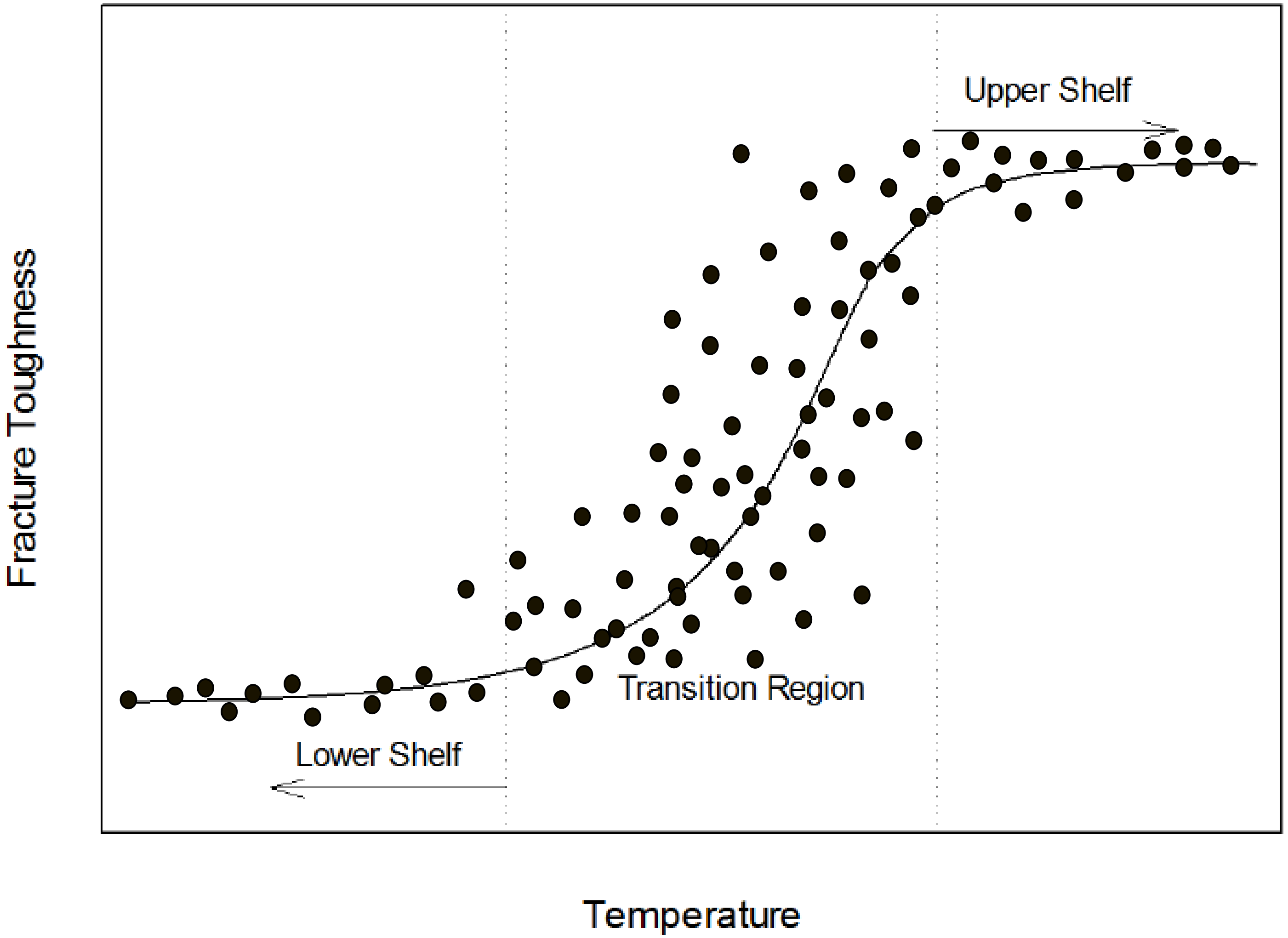
Additional Material

Weakest Link Behavior

and

Master Curve

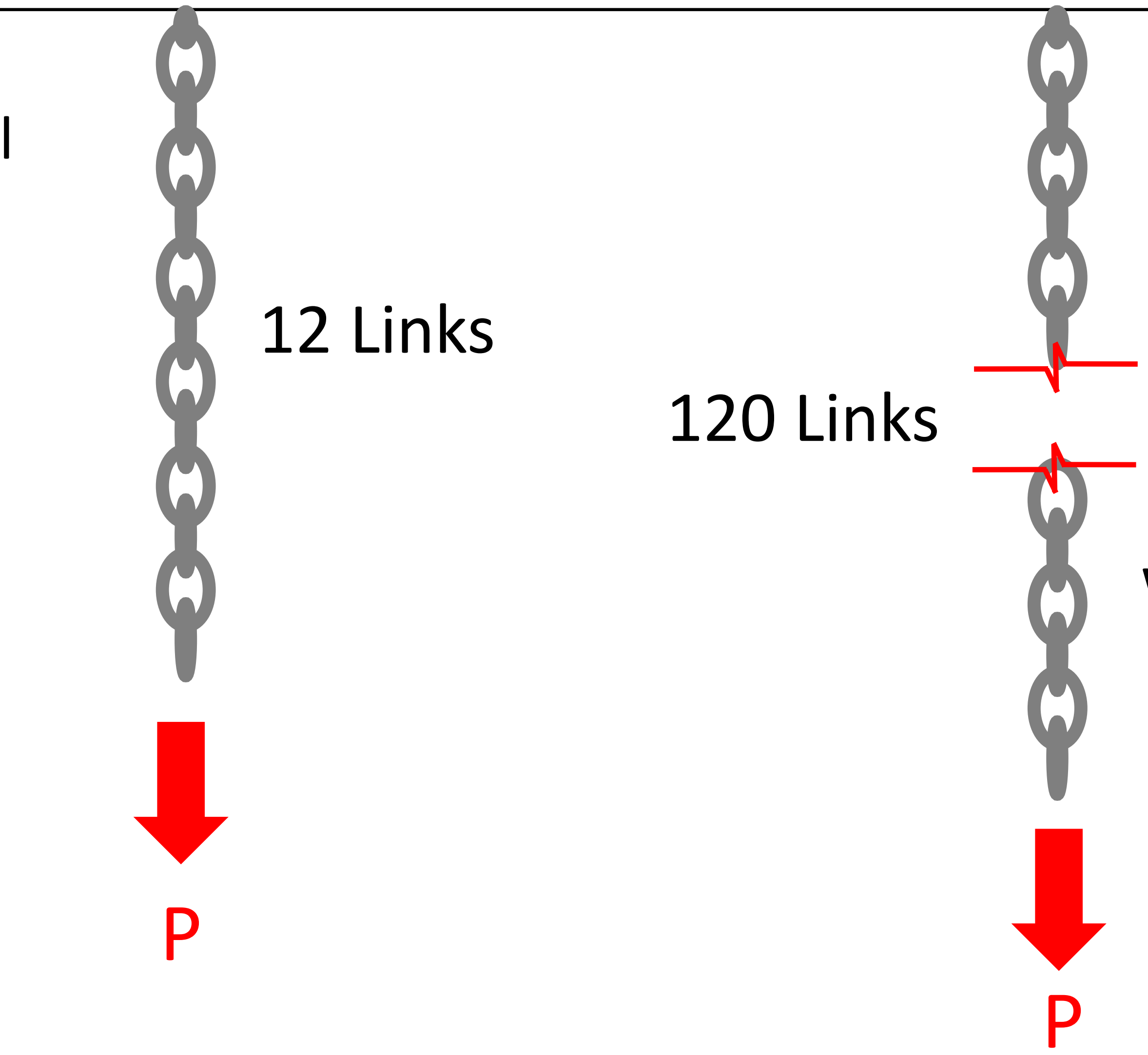
Fracture Mechanics- Behavior



Fracture Mechanics- Behavior

Thought exercise…

- Same Material
- Same Size
- Same Load



Which one will break first?

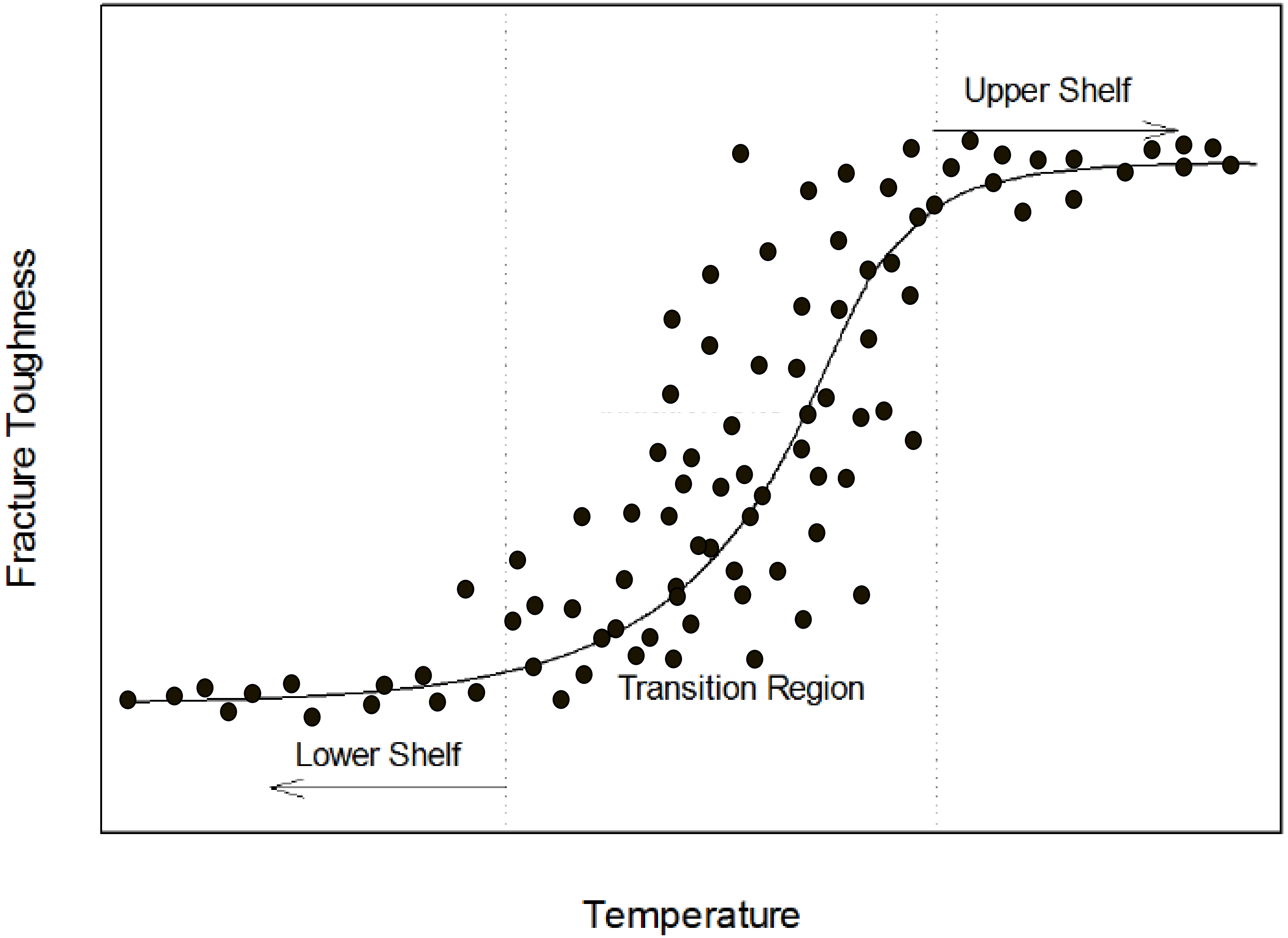
The one with more links!
Weakest Link Theory!

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

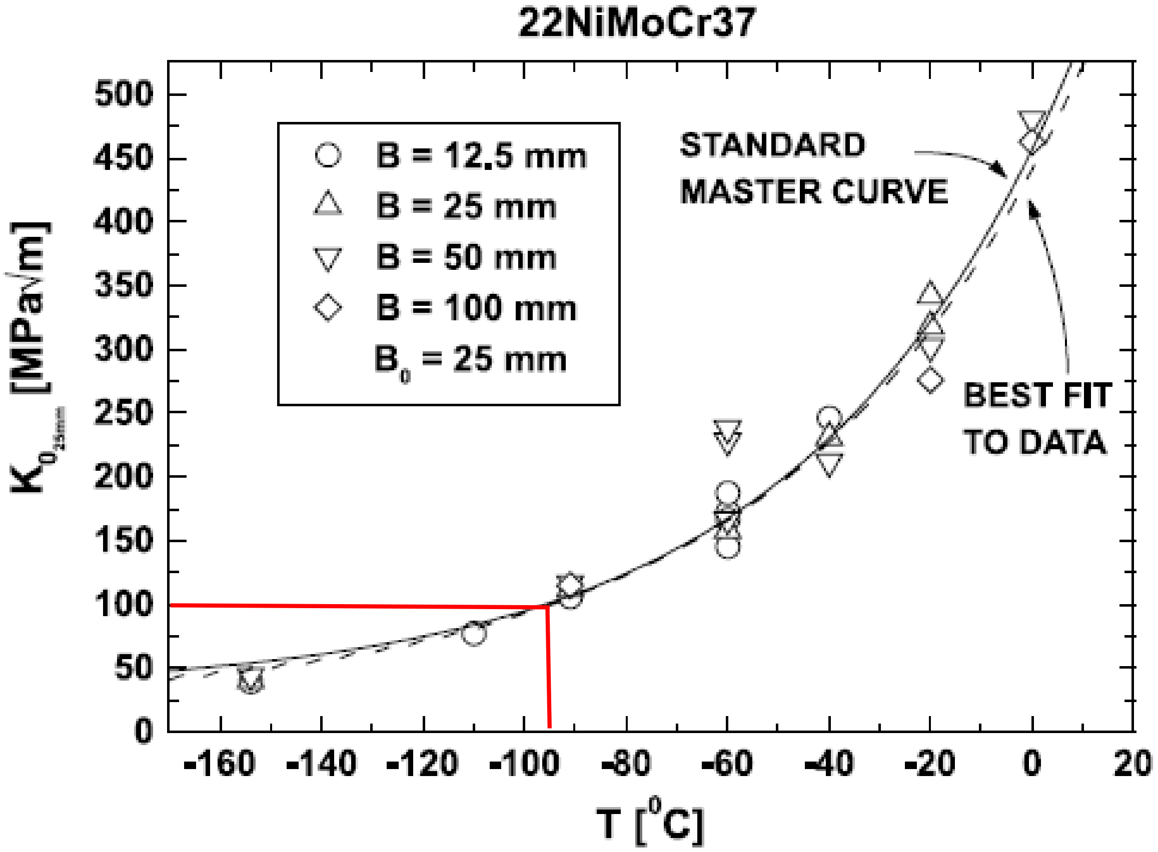


Future of Fracture Critical- Advances

Fracture Behavior Characterization

Master Curve

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



Wallin, Kim, (2000) "Master curve analysis of the "Euro" fracture toughness dataset," Engineering Fracture Mechanics, 69, p. 451-481.

Future of Fracture Critical- Advances

Fracture Behavior Characterization

<u>Master Curve</u>

- 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

<u>Master Curve</u>

- Median Toughness vs Temperature
  - Single Value Characterization, T_o

$$K_{Jc(med)} = 30 + 70\exp[0.019(T - T_o)]$$

- 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

$$P_f = 1 - \exp\left\{-\left[\frac{K_{Jc} - 20}{K_o - K_{min}}\right]^4\right\}$$

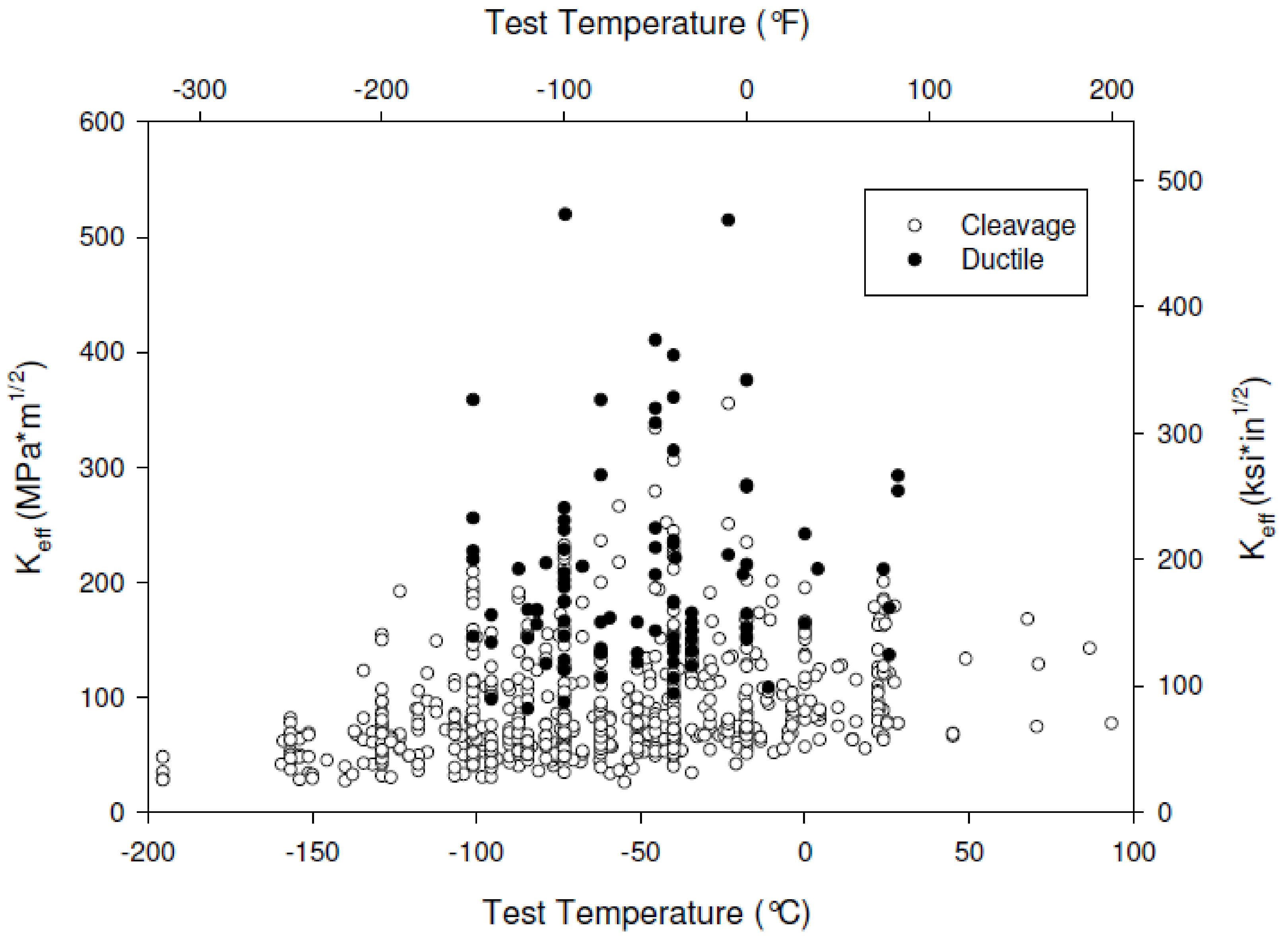
Future of Fracture Critical- Advances

Fracture Behavior Characterization

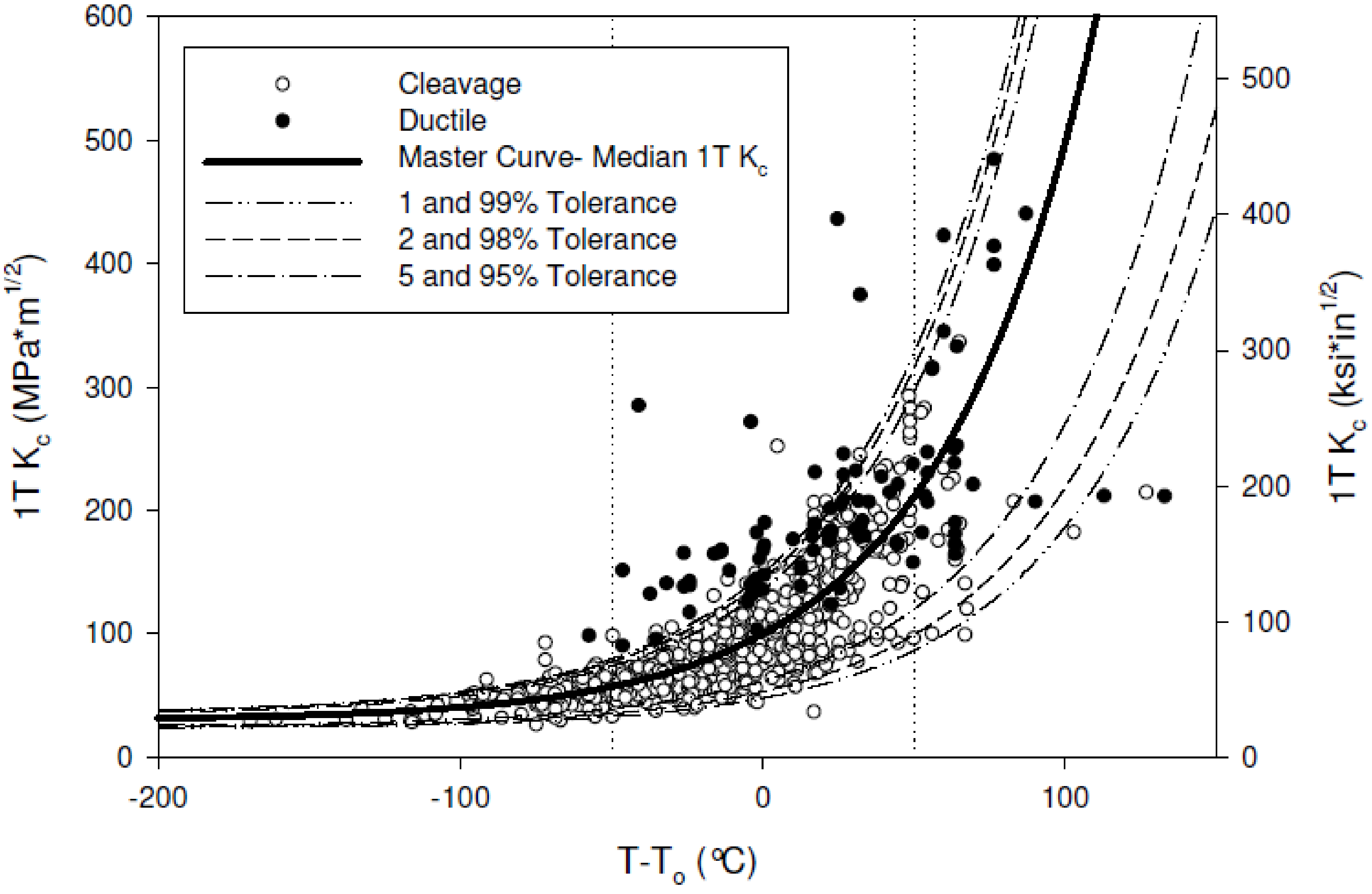
Master Curve: Applied to “Legacy” Data

- 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

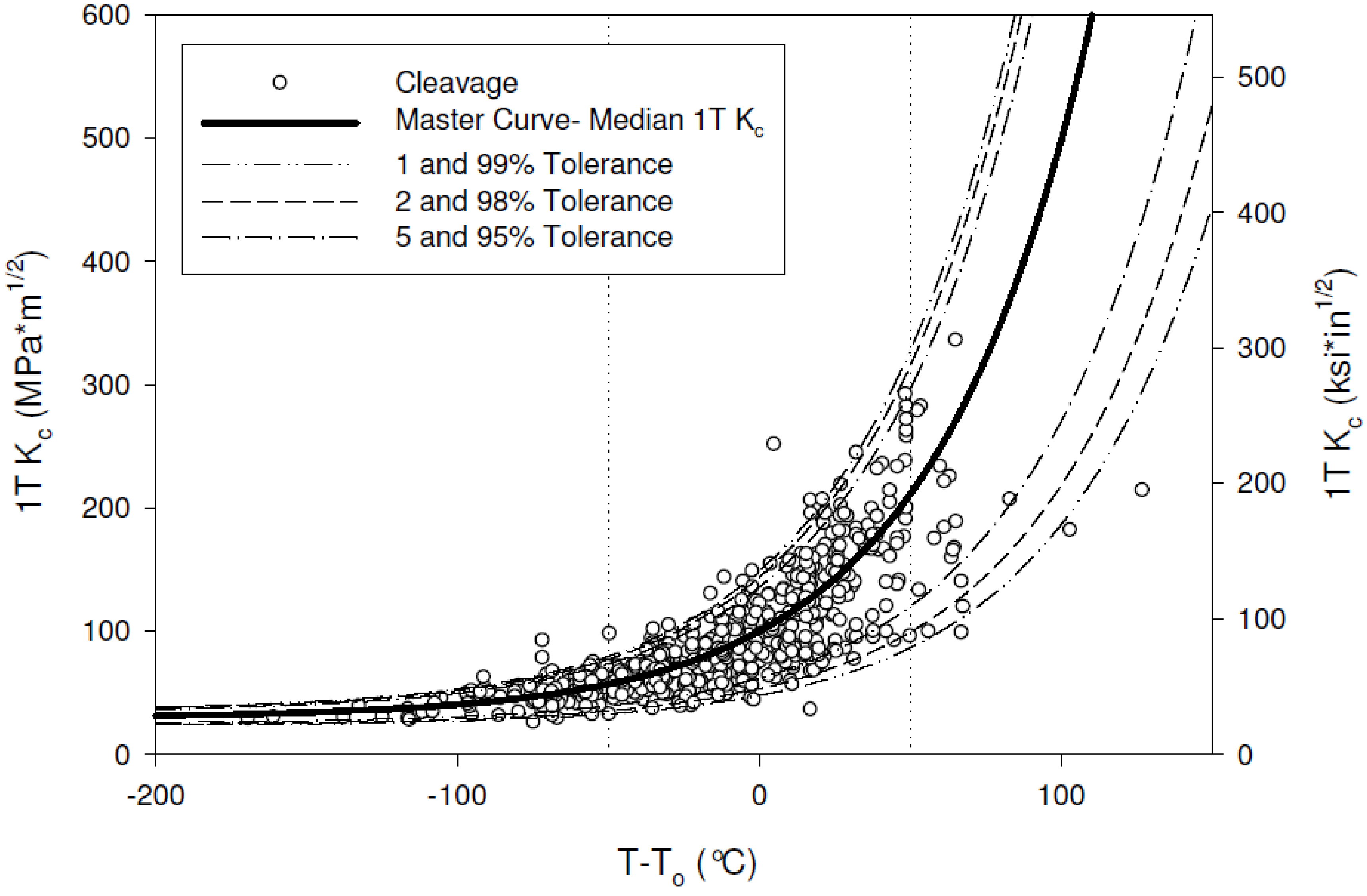
Future of Fracture Critical- Advances



Future of Fracture Critical- Advances



Future of Fracture Critical- Advances



Future of Fracture Critical- Advances

Tolerance Bound	Total Fracture Database (801)		Ductile Failure Excluded (681)	
	Data Count Below	Percentage Below	Data Count Below	Percentage Below
10%	100	12.5	94	13.8
5%	48	6.0	45	6.6
2%	21	2.6	19	2.8
1%	10	1.2	8	1.2

Future of Fracture Critical- Advances

Tolerance Bound	Total Fracture Database (801)		Ductile Failure Excluded (681)	
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2%	21	2.6	19	2.8
1%	10	1.2	8	1.2

Additional Material

FFS and FADs

Future of Fracture Critical- Existing Structures

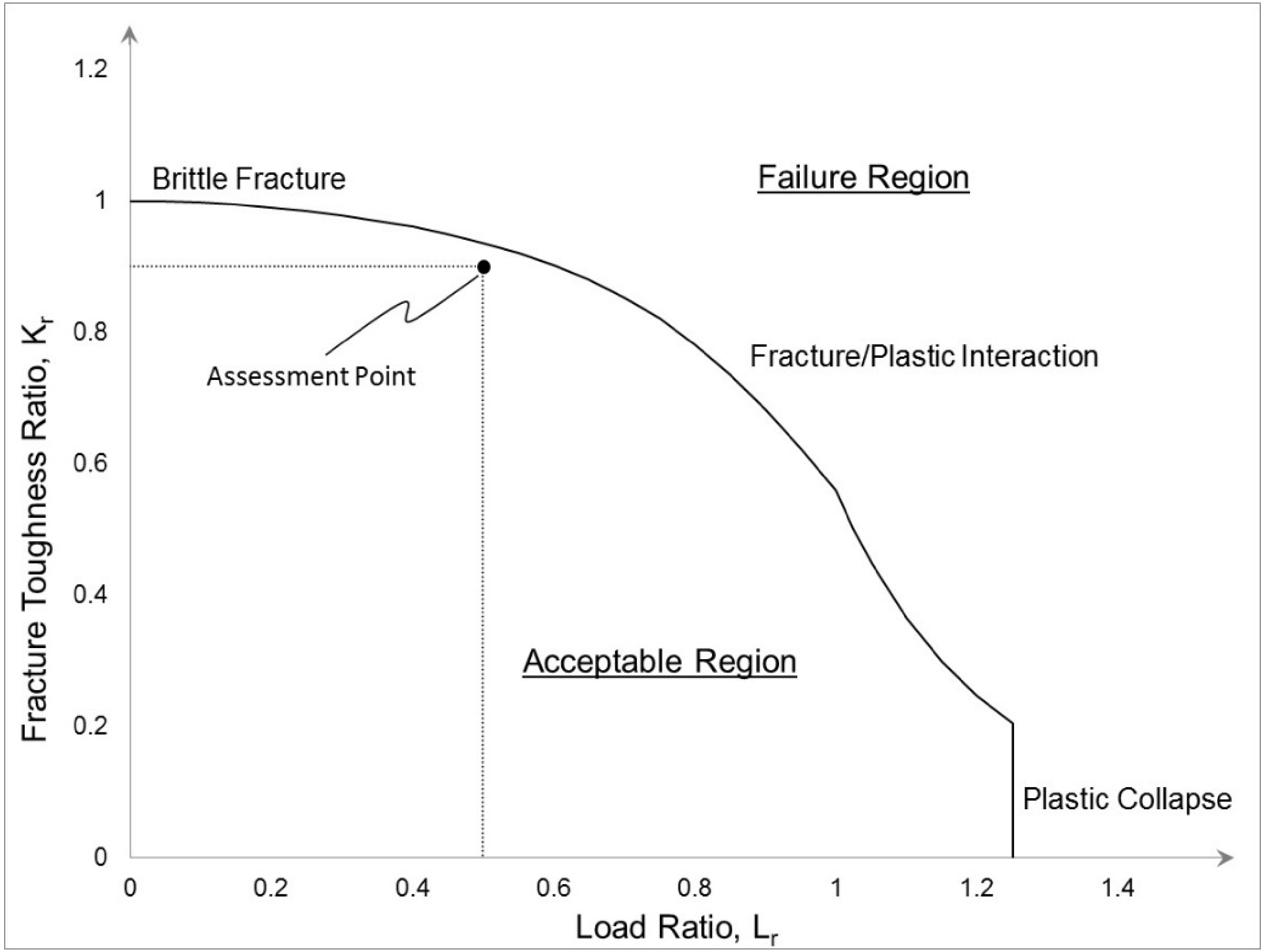
Fitness for Service (FFS) Evaluation

- 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

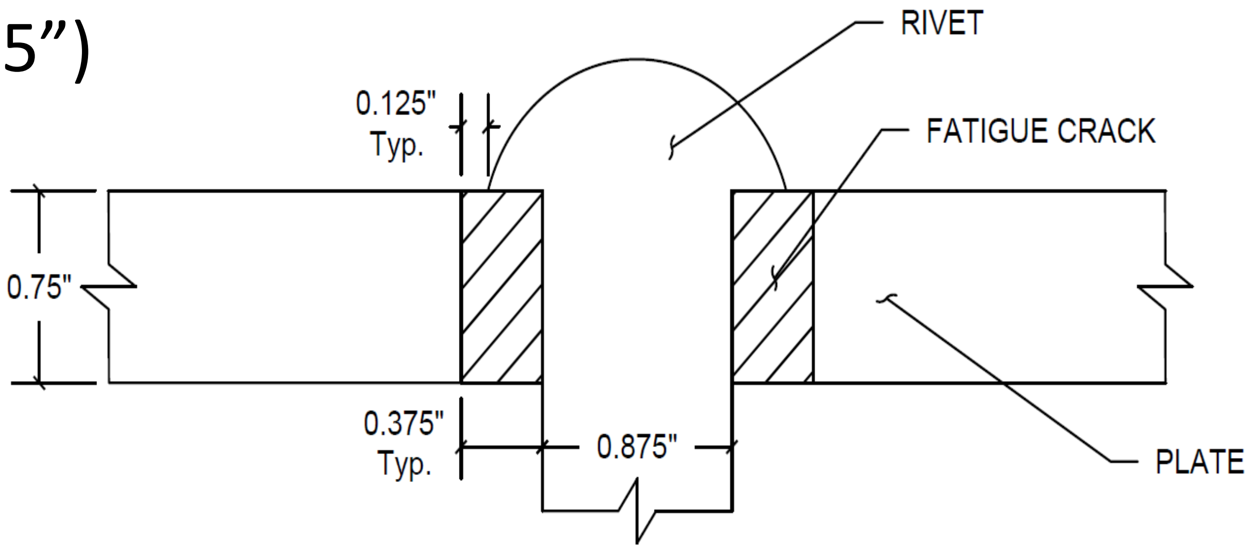


Future of Fracture Critical- Existing Structures

Riveted Bridge

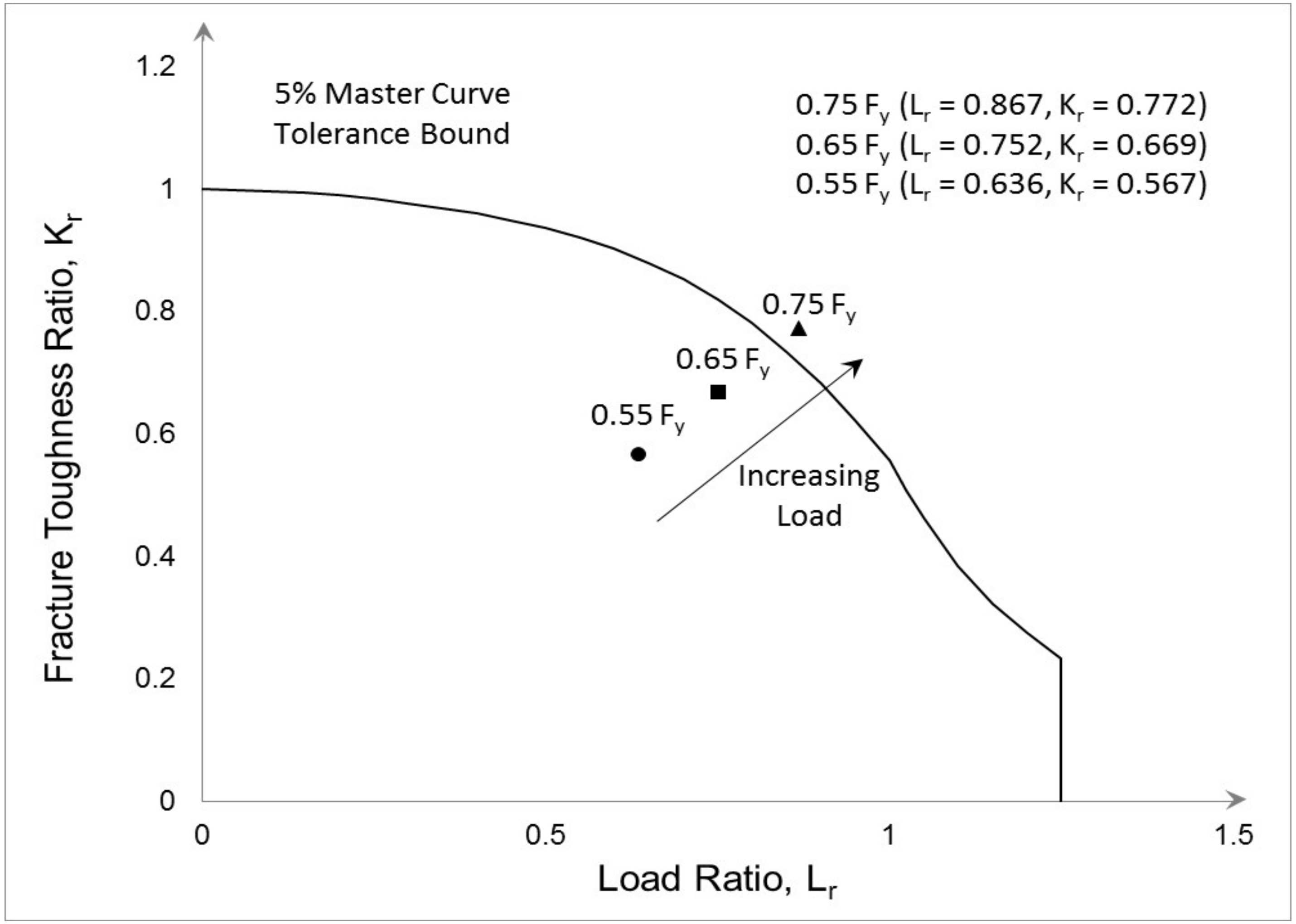
- Inspection for fatigue cracks (0.125”)
- 0.55 F_y and 0.75 F_y
- CVN values known

Bridge Posting? Permit Loads?



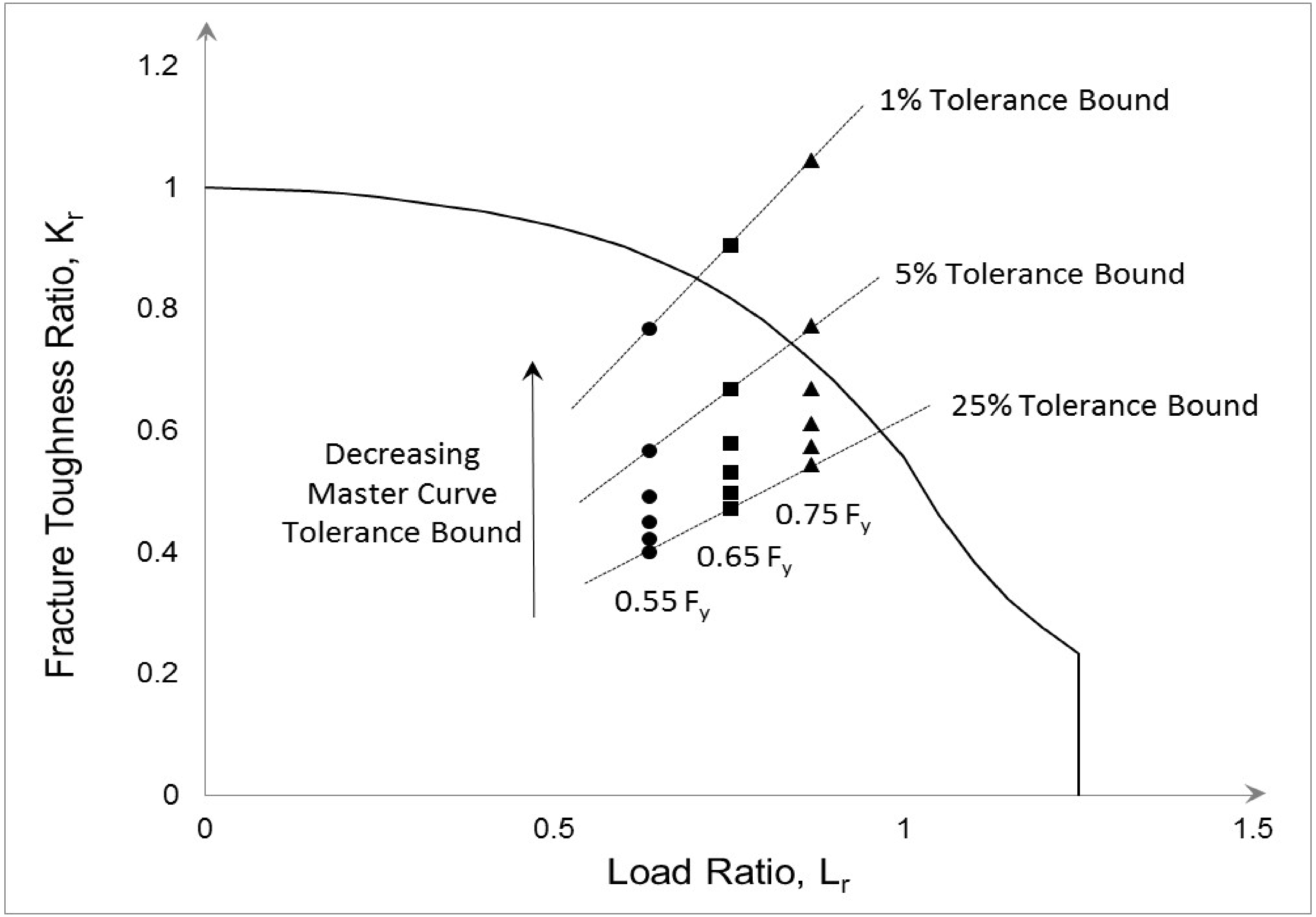
Future of Fracture Critical- Existing Structures

Riveted Bridge



Future of Fracture Critical- Existing Structures

Riveted Bridge



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)

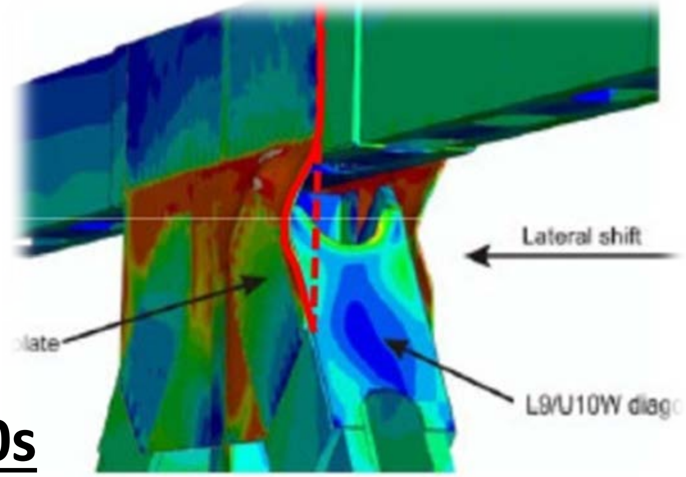
from the AAHSTO/AWS Commentary:

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

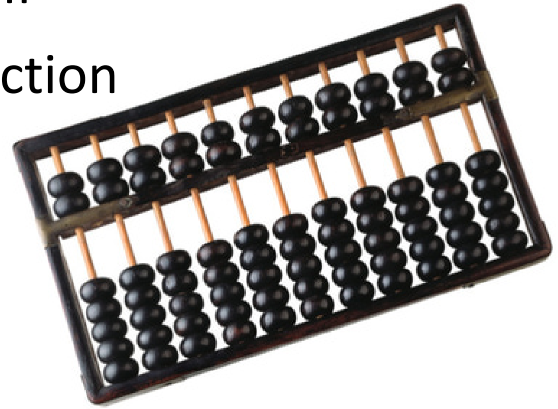
Future of Fracture Critical- Advances



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