STANDARDS TO CONTROL FRACTURE IN STEEL BRIDGES THROUGH THE USE OF HIGH-TOUGHNESS STEEL AND RATIONAL INSPECTION INTERVALS

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Research Team

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Project Partners

- Federal Highway Administration
- US Army Corps of Engineers
- Idaho DOT
- Indiana DOT
- Iowa DOT
- Minnesota DOT
- North Carolina DOT
- Oregon DOT
- Virginia DOT
- Wisconsin DOT

Project Contributors

- Fabricators
  - Hirschfeld Industries
  - High Steel Structures
- Steel mills
  - Steel Dynamics, Inc.
  - Nucor Corporation
  - SSAB

HIRSCHFELD INDUSTRIES
BRIDGE

HIGH STEEL STRUCTURES LLC
An Affiliate of High Industries Inc.

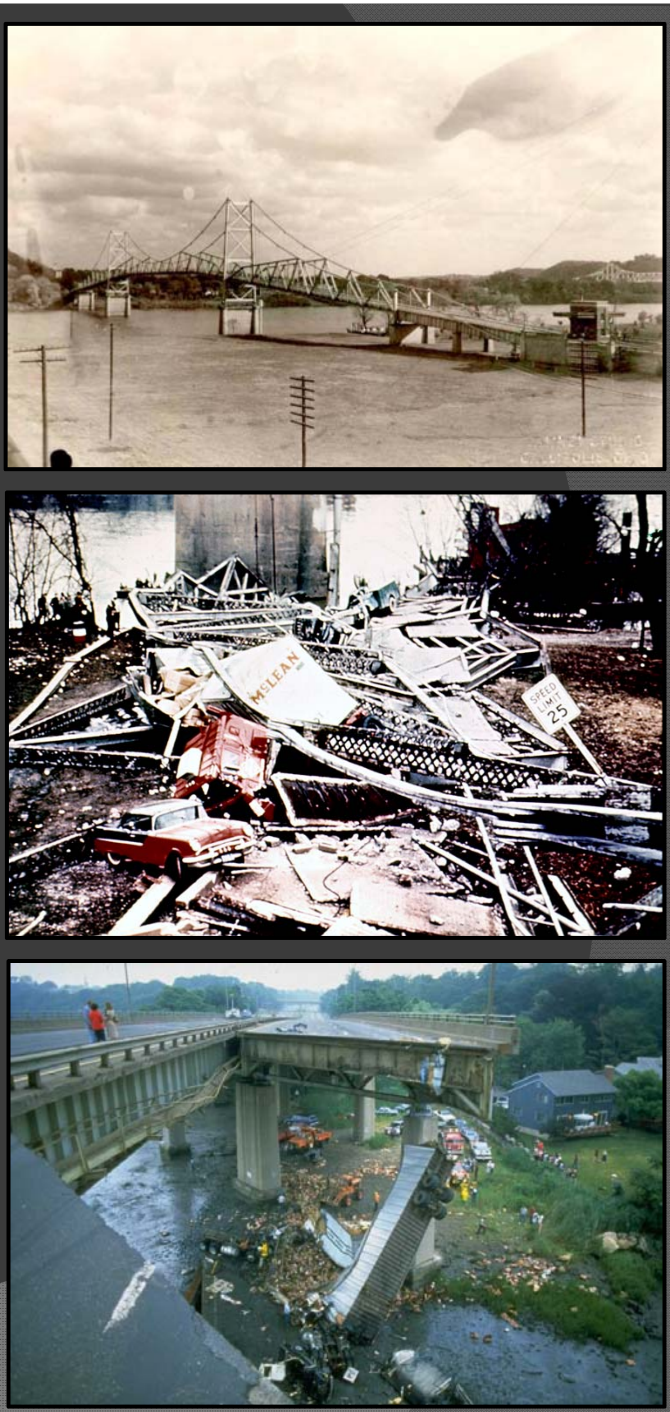
SDI Steel Dynamics, Inc.®
Structural and Rail Division • Columbia City, Indiana

NUCOR®

SSAB

History

- Point Pleasant Bridge
  - Collapsed Dec. 1967
  - 46 fatalities
  - Result: Fracture control plan
- Mianus River Bridge
  - Collapsed June 1983
  - 3 fatalities
  - Result: Hands-on inspection
- 2005 – NBIS updated
  - Result: 24-month interval



Improved Bridge Steel

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

Motivation

- Advances in past 40 years
  - Material
  - Design
  - Fabrication
  - Inspection
- 24 month hands-on inspection
  - Cost
  - Time
  - Safety

Integrated fracture control plan

Rational inspection intervals

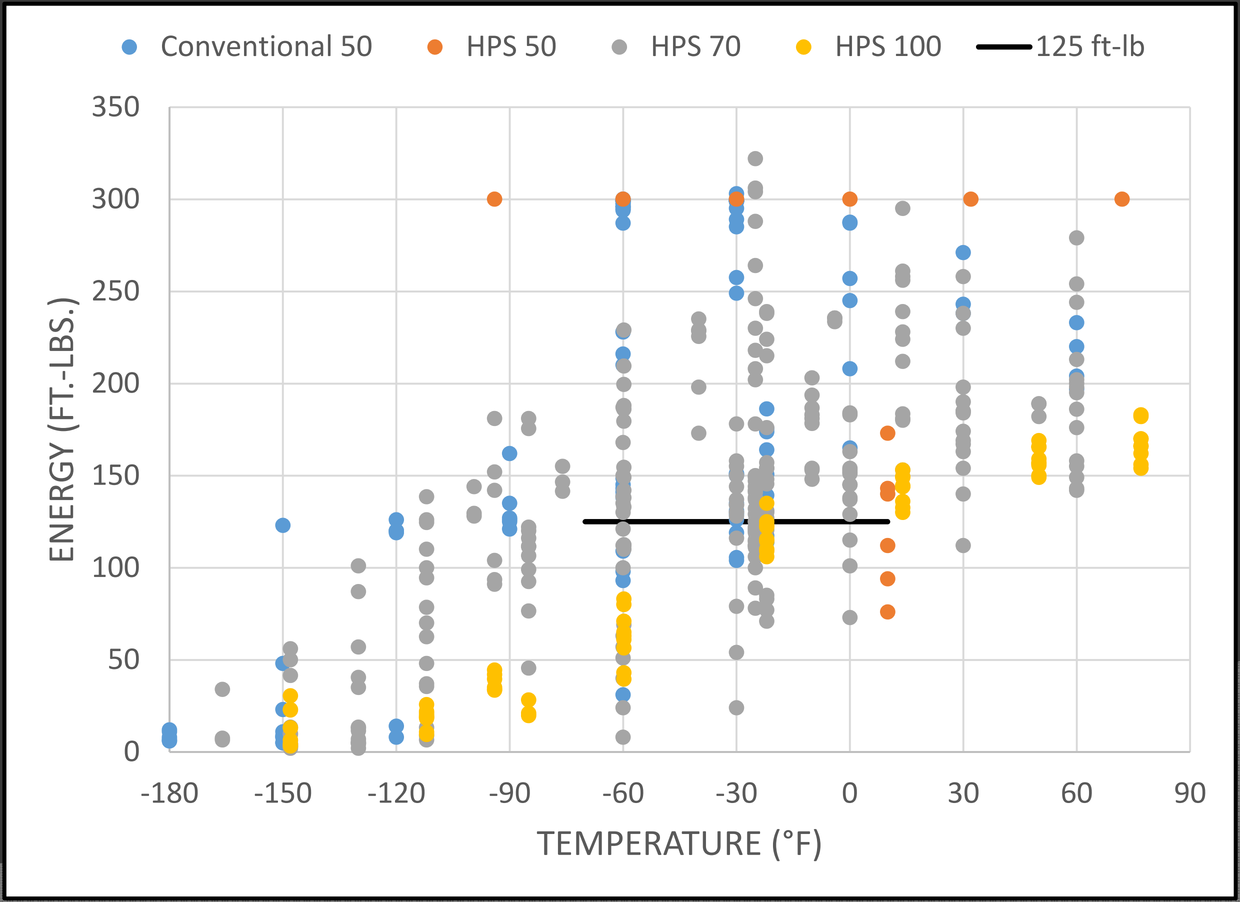
Overview of Process

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

Experimental Testing

Material Requirement

- CVN energy: 125 ft.-lbf



Experimental Testing

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

Experimental Testing

Test process

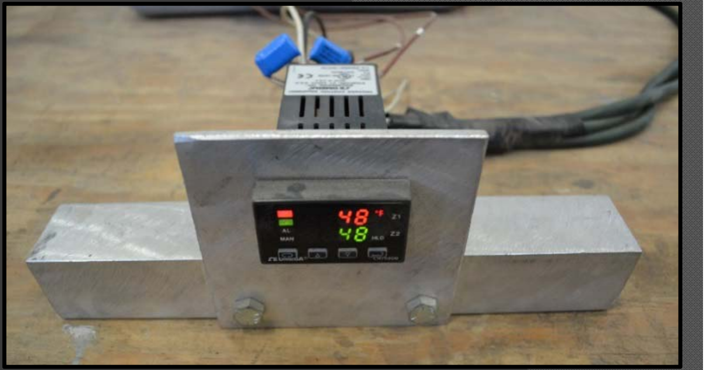
- Incremental growth
  - Notch specimen
  - Crack growth through fatigue
  - Cool to desired behavior
  - Load to induce fracture
  - Repeat until fracture achieved
- Grow to fracture length

Experimental Testing

Bending Test Setup

Experimental Testing

Temperature Chamber



Experimental Testing

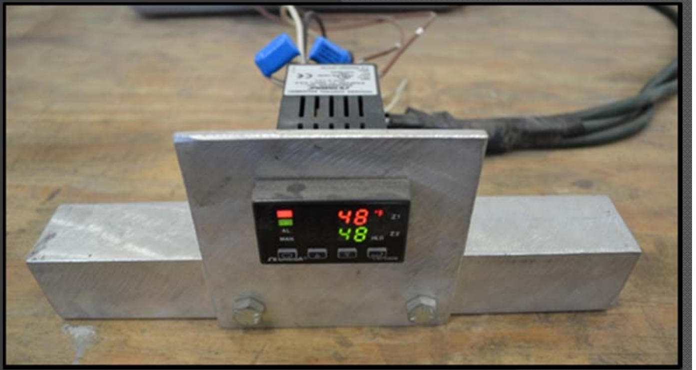
Bending Fracture Test

Experimental Testing

Axial Test Setup

Experimental Testing

Temperature Chamber



Experimental Testing

Axial Fracture Test

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

Finite Element Analysis

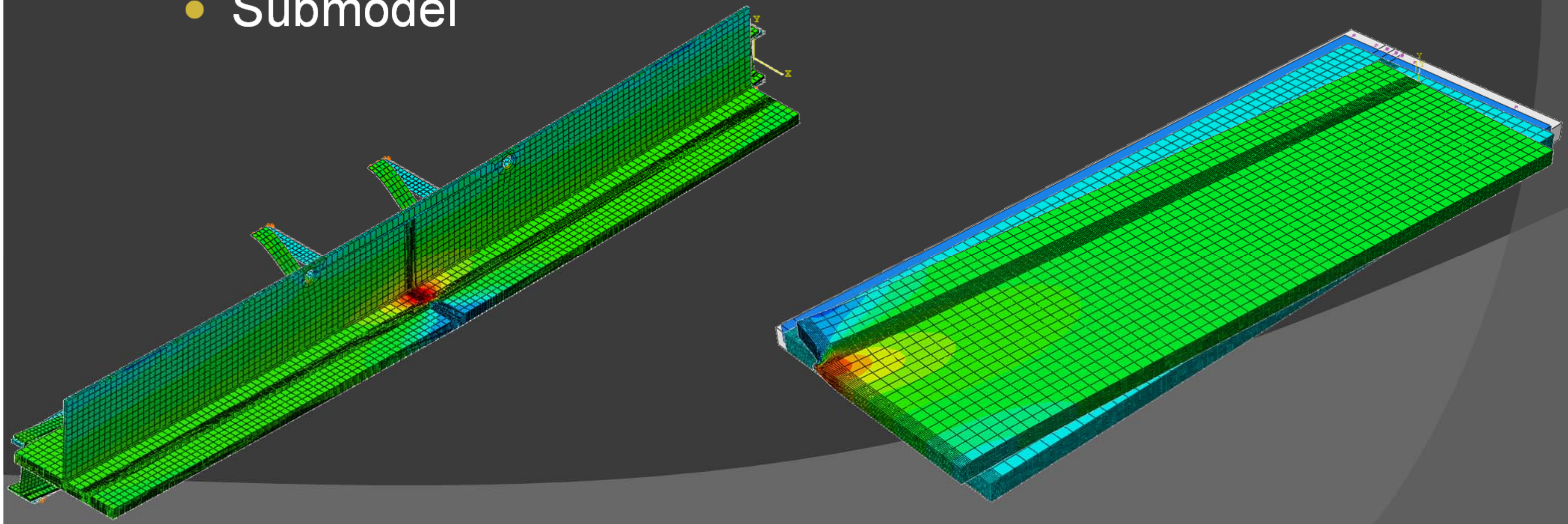
General Parameters

- Load at failure
- Crack length at failure
- Material model
  - Grade 50 and 70
  - Elastic properties
  - Plastic properties
- Solid (continuum) elements

Finite Element Analysis

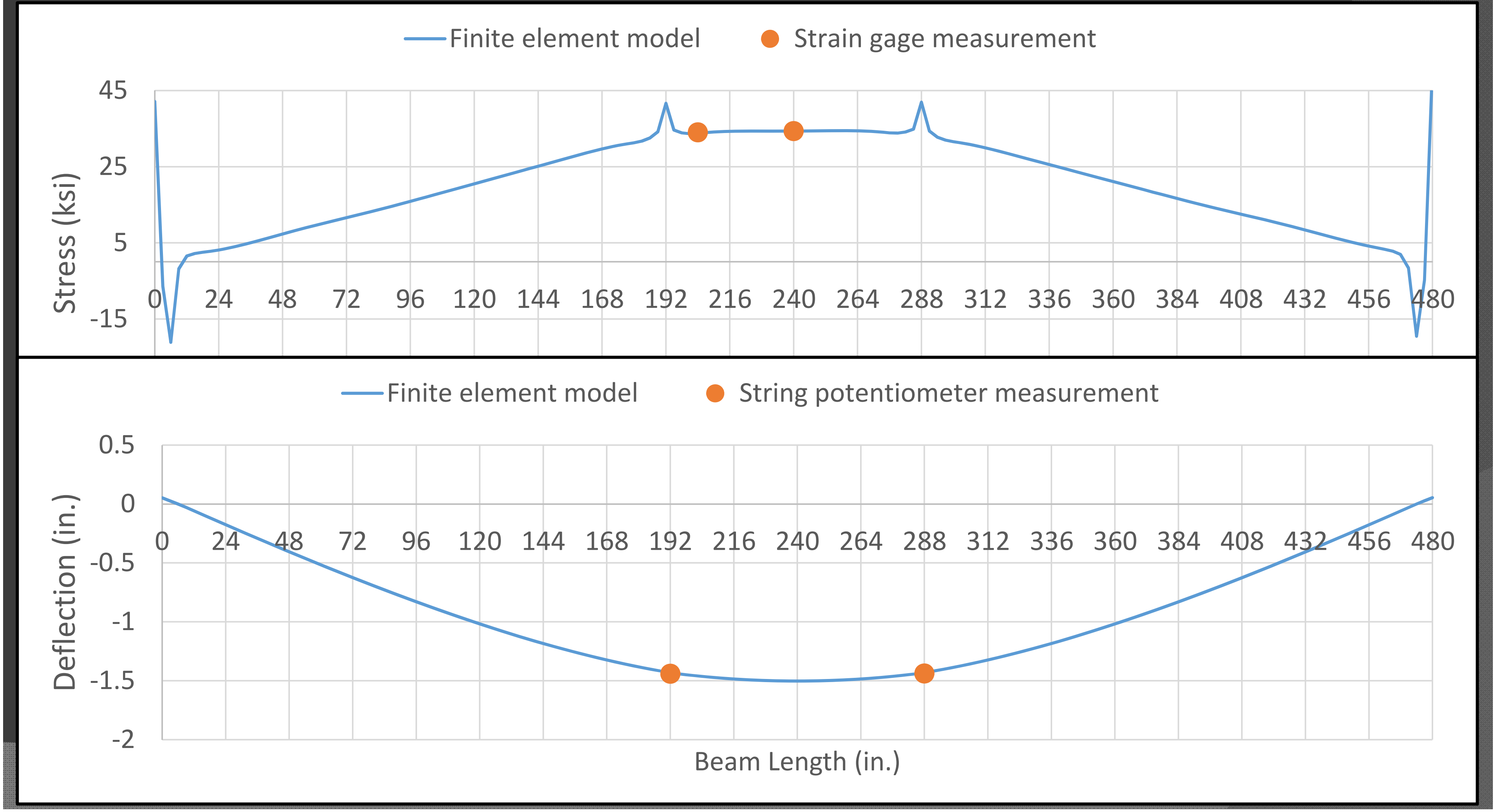
Bending vs Axial Specimens

- Bending
  - Point load
  - Pin and roller
  - LTB bracing
  - Submodel
- Axial
  - Surface traction
  - Simplified geometry
  - ½ symmetry



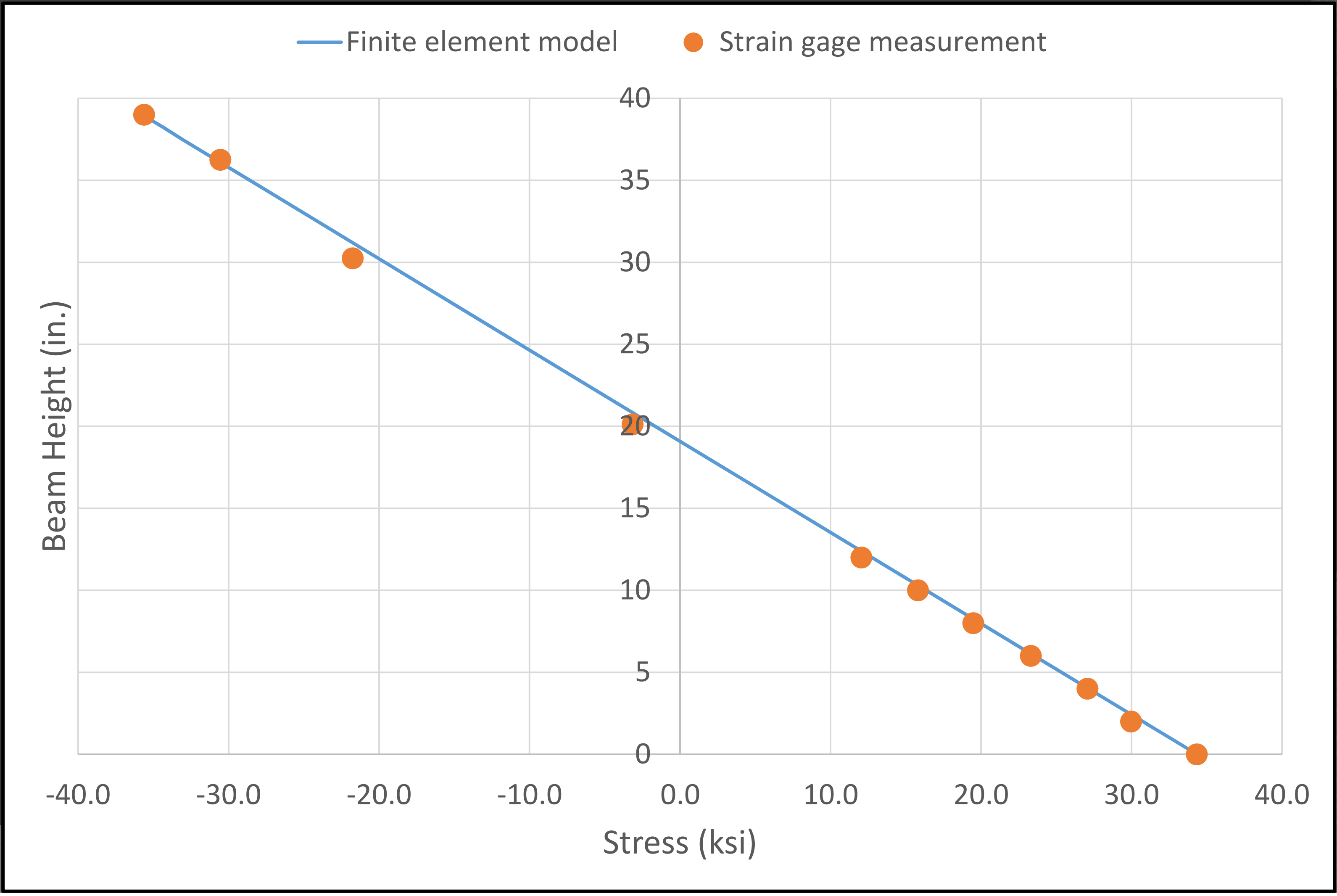
Finite Element Analysis

Representative Results



Finite Element Analysis

Representative Results



Finite Element Modeling

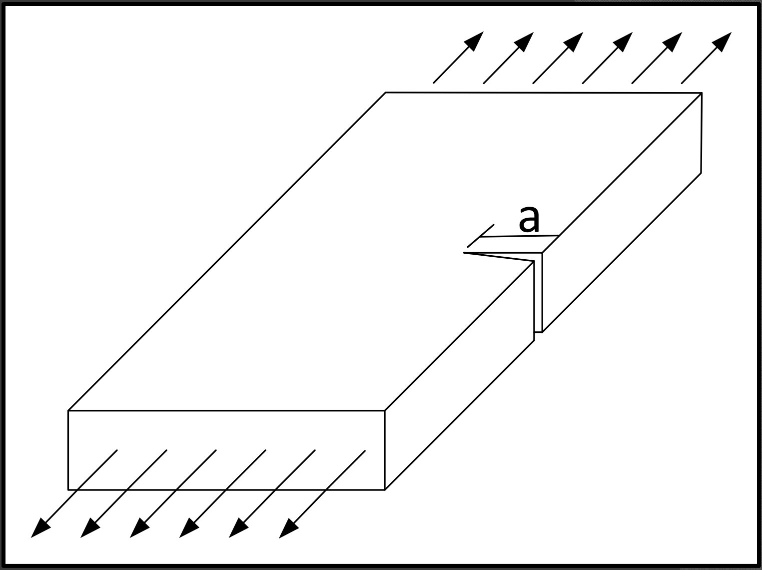
Results

Plate Designation	Specimen	FEA Model J (ksi*in.)	FEA Model K_J (ksi√in.)	FEA $K_{J(1T)}$ (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

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)
  - $0.75F_y$



Rational Inspection Interval

Critical Flaw Size

CURRENT SPECIFICATION

Grade	Thickness (in.)	Minimum Test Value Energy (ft.-lbf)	Minimum Average Energy (ft.-lbf)		
			Zone 1	Zone 2	Zone 3
HPS 50 WF	≤ 4	24	30 @ 10 °F	30 @ 10 °F	30 @ 10 °F
HPS 70 WF	≤ 4	28	35 @ -10 °F	35 @ -10 °F	35 @ -10 °F
HPS 100 WF	≤ 2.5	28	35 @ -30 °F	35 @ -30 °F	35 @ -30 °F
	2.5 ≤ 4	N/A	N/A	N/A	N/A

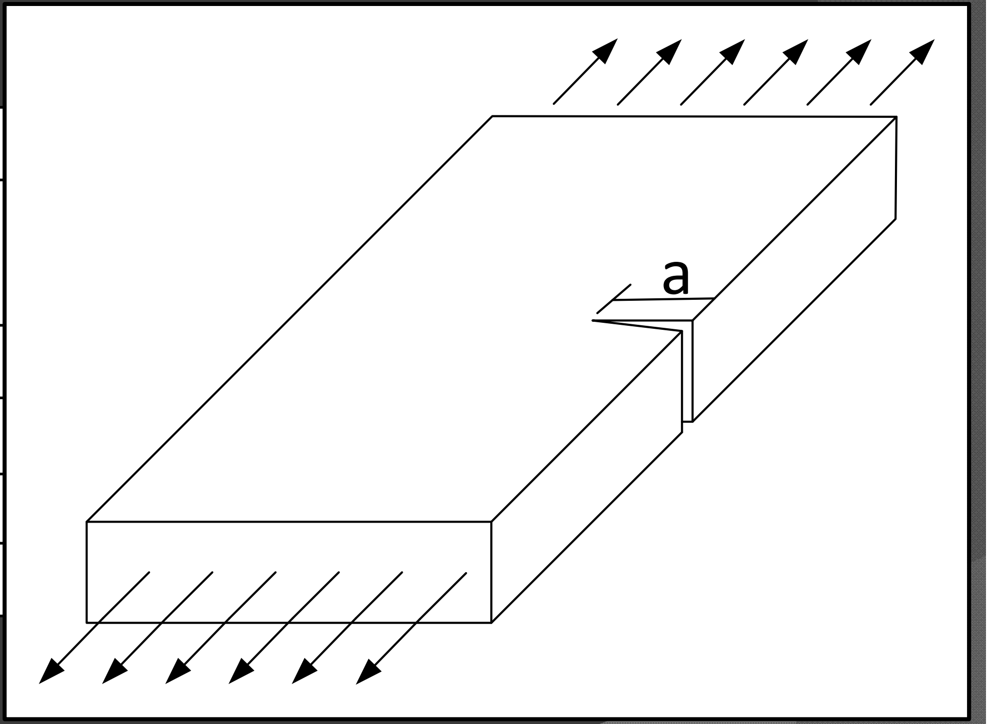
POTENTIAL SPECIFICATION

Grade	Thickness (in.)	Minimum Test Value Energy (ft.-lbf)	Minimum Average Energy (ft.-lbf)		
			Zone 1	Zone 2	Zone 3
Damage Tolerant Steel	TBD	TBD	125 @ 0 °F	125 @ -30 °F	125 @ -60 °F

Rational Inspection Interval

Critical Flaw Size

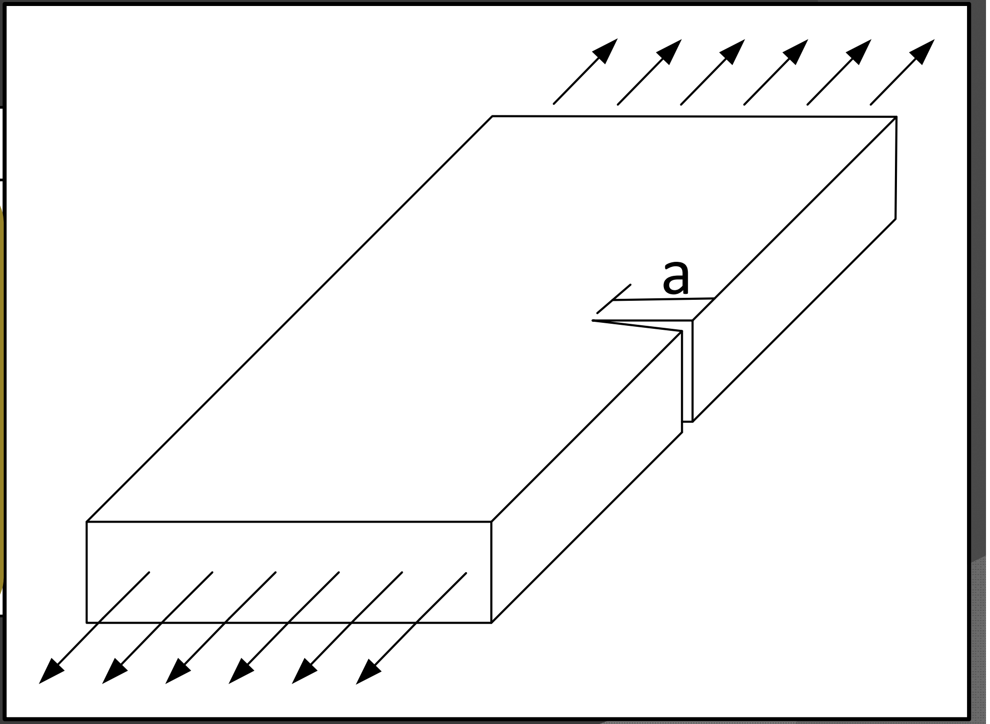
Tolerable Crack Sizes			
Grade	Applied Stress	K_{new}	a
(ksi)	(ksi)	(ksi$\sqrt{\text{in.}}$)	(in.)
50	37.5	122	
70	52.5	122	
100	75	122	



Rational Inspection Interval

Critical Flaw Size

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



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

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

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	

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

Parametric Study

- Parameters
- CVN impact energy
  - 100 ft.-lbf to 200 ft.-lbf
- Plate thickness
  - 1”, 2”, and 3”
- Plate width
  - 18” and 24”

Parametric Study Results

- Grade 50 and 70
  - 75+ year interval for all analyses
  - Critical flaw > 0.7”
- Grade 100
  - 75+ year interval for 1” thickness
  - 70+ year interval for 2” thickness
  - 65+ year interval for 3” thickness

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

Questions?