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Towards an Integrated Fracture-Control Plan for Steel Bridges
April 23, 2019

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Course Description

Towards an Integrated Fracture-Control Plan for Steel Bridges
April 23, 2019

There has been considerable research and interest in the topic of fracture-critical members (FCMs) during the past decade. As a result, the entire concept of what constitutes an FCM is being revisited and many long-standing ideas and opinions related to this classification of members is being shown to be overly conservative. Significant advances in the understanding of fracture mechanics, material and structural behavior, fatigue crack initiation, fatigue crack growth, fabrication technology and inspection technology have allowed other industries to address fracture in a more integrated manner. After years of research, new stand-alone AASHTO-ready guide specifications that give codified direction on how to perform 3D system analysis to verify system redundancy, as well as guide specifications to evaluate internal member-level redundancy of mechanically fastened built-up members, have been proposed. Additional research demonstrating the benefits of exploiting the improved toughness of modern HPS grades of steel has been completed. Through these advances, it is now possible to create an integrated FCP, combining the original intent of the 1978 FCP with modern materials, design, fabrication and inspection methodologies. Further, an integrated FCP will provide economic benefits and improved safety to owners by allowing for a better allocation of resources by setting inspection intervals and scope based on sound engineering rather than based simply on the calendar. In summary, an integrated FCP encompassing material, design, fabrication and inspection can make fracture no more likely than any other limit state, ultimately allowing for a better allocation of owner resources and increased steel bridge safety.

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Learning Objectives

- Describe how 3D system analysis can be used to ensure a safe and code compliant design.
- Describe how an integrated fracture-control plan (FCP) can improve safety and provide economic benefits.
- Describe what is meant by fracture-critical members (FCMs).
- Describe the benefits of using modern HPS grades of steel.

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Towards an Integrated Fracture-control Plan for Steel Bridges

Robert J. Connor, PhD
Professor of Civil Engineering
Director of the S-BRITE Center
Purdue University

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Towards an Integrated Fracture-control Plan for Steel Bridges

2018 AISC
Theodore R. Higgins Lecture

Robert J. Connor
Purdue University

150 YEARS OF GIANT LEAPS
PURDUE UNIVERSITY

FIRST… SET THE STAGE

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FIRST… SET THE STAGE

- Overall, historical performance of "FC" bridges is excellent
- Two-part statement
  1. Fractures rarely occur
     - Even in those bridges built prior to modern fatigue provisions
     - Even in those bridge prior to FCP
     - None that can be identified when member built to modern FCP
  2. Even when a has fracture occurred
     - Except for Silver Bridge and Mianus River
       - Both truly had FCMs

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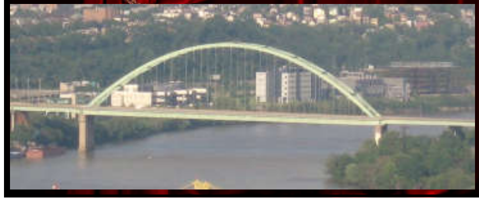
FIRST… SET THE STAGE

- Despite overwhelming excellent service record, a few bad experiences resulted in strong reaction
- This is unfortunate as many systems traditionally classified as non-redundant systems are very efficient



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FIRST… SET THE STAGE

- Despite overwhelming excellent service record, a few bad experiences resulted in strong reaction
- This is unfortunate as many systems traditionally classified as non-redundant systems are very efficient
- Other industries have figured this out

VS

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FIRST… SET THE STAGE

It is a good thing these bridges
don't know we call them
Fracture Critical
behind their back

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Current Fracture Control Plan

- Today the FCP is fragmented in the US Bridge industry
  - Material & Design
  - Fabrication/shop inspection
  - Field Inspection

- In a "True" FCP these are integrated
  - Shortfalls in one area can be made up in others
  - e.g., 24 month interval is not linked to crack tolerance
    - What if something bad happens after the inspector leaves?

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Current Fracture Control Plan

- Further, meeting the modern Fracture Control Plan offers no relief
  - i.e., In-service inspection unaffected

1950s field welded steel bridge carrying ADTT 15,000 with E' flange details ≠ New bridge w/ HPS, HOV, bridge highly fatigue resistance fabricated to FCP

≠

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Then Versus Now…

1960s

- Manual or Simple Computer Structural Analysis
- No Explicit Fatigue Design Provisions
- No Special Fabrication QA/QC
- High Toughness Materials Not Economically Feasible
- No Knowledge of Constraint Induced Fracture
- Limited Shop Inspection

2000s

- 3D Non-Linear Finite Element Analysis
- In-plane & Distortional Fatigue Problem Solved
- Fracture Critical Fabrication per AASHTO/AWS
- High Performance Steels Readily Available
- Know to Avoid Intersecting Welds and CIF Details
- Significant Advances in NDT

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BRIDGES WHERE FRACTURES OCCURRED

BRIDGE	CAUSE	DO WE ALLOW THIS TODAY?	WOULD FIELD INSP. HAVE PREVENTED
SILVER BRIDGE	BRITTLE HIGH STRENGTH STEEL	**NO**	**NO**
NEVILLE ISLAND (I-79)	POOR REPAIR WELD PROCEDURES	**NO**	**NO**
LAFAYETTE ST.	POOR QUALITY INTERSECTING WELD	**NO**	**MAYBE**
HOAN BRIDGE	CONSTRAINT INDUCED FRACTURE (CIF)	**NO**	**NO**
DELAWARE RIVER TRUSS	MIS-DRILLED HOLES FILLED WITH WELD	**NO**	**NO**

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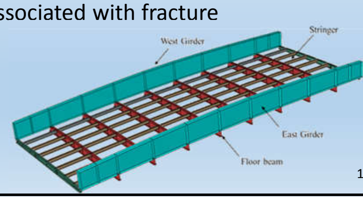
THE GOAL?:
Change how we think about the concept of FCMs

- If the fracture limit state is adequately addressed in some rational way, the term "FCM" has no meaning
- For example, since we design for buckling, a non-redundant compression member is not referred to as "buckling critical"
  - Why? We "believe" in design methods to address this limit state
- Today, using state-of-the-practice, the risk associated with fracture can be treated like any other limit state
  - Minimize risk and achieve desired reliability



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More things to keep in mind…

- We perform hands-on inspection for safety…or so we think
- Recent INDOT study found the following:
  - The congested crash rate on all Indiana interstates in 2014 was found to be 24 times greater after 5 min. of queue
  - What about highway worker safety?
- We hope to find cracks before they are an issue
  - What about POD?
    - Existing data not very encouraging
    - Are we able to find what we think we can find?

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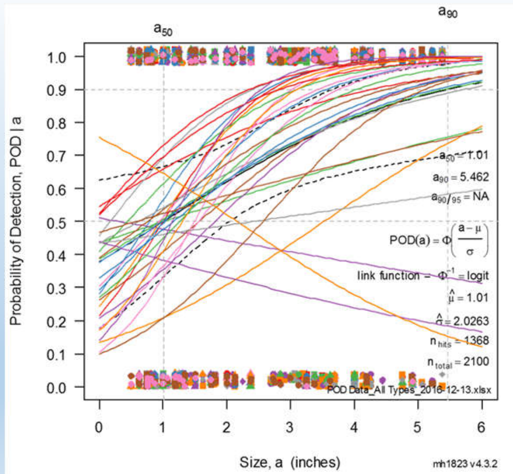
Actual POD Might Surprise You

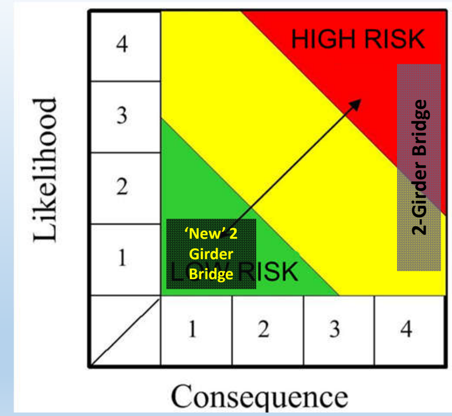
- Best detection rate: 86%
- Lowest detection rate: 31%
- Average rate: 65%

Crack tolerance of member should be linked to inspection capability… (seems like a good idea)



Risk-based Approach Would be More Rational

K_{IC}, Detailing, S_R, etc.



Collapse, Loss of service, Loss of life, etc.

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Alternative Methods to Address FCM "Concerns" without Simply adding Girder Lines

- Exploiting internal redundancy – TPF-5(253)
- Exploiting advanced system analysis – NCHRP Report 883
- Exploiting superior toughness of HPS – TPF-5(238)

- Today, we will focus on:
  - Internal Redundancy (Built-up Members)
  - System analysis per NCHRP Report 883
    - Focus on twin tub girders

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Member-level Redundancy

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Member-level Redundancy

- Built-up members
  - Consist of several individual and isolated components
    - Might prevent cracks from propagating through entire member
  - Common strategy in other industries to reduce susceptibility to complete member fracture
  - Not explicitly accounted for in highway bridges
    - But, the general perception is that it works

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- North Fork Mollala River Bridge, OR
  - Fracture in bottom flange of riveted built-up two-girder bridge

Lovejoy, 2001

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- Diggelmann, Connor, & Sherman, 2013
  - Milton Madison Bridge, IN
  - Partially severed bottom chord of truss

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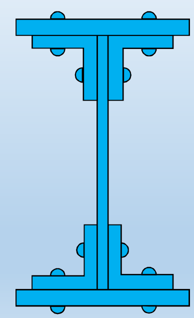
Research Objectives

- Determine how to assess internal redundancy of built-up members
- Can partially failed built-up members support design loads at some target reliability?
- Evaluate remaining fatigue life in faulted state
  - How long until <u>next</u> component fails?
  - Critical for setting future inspection interval



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Experimental Program – Fracture Testing

- 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 → ensured lower shelf behavior
  - Warmest was -60F….some as cold as -120F
  - Eliminates "but you had good steel" comment
- Apply load to induce a fracture
  - And then….nothing happened
  - Needed to drive a "wedge" into the crack!!

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Specimen Matrix – Flexural Members

Specimen Height	Failed 1st Component	Bolted		Riveted	
		Friction	Low-Friction	Friction	Low-Friction
23 in.	Cover Plate				23-1D
	Flange Angle				23-2D 23-3D
30 in.	Cover Plate	30-1D			
36 in.	Middle Cover Plate	36-1P			
	Bottom Cover Plate	36-2D 36-5D 36-6D		36-3D 36-4D	
	Flange Angle				
46 in.	Cover Plate	46-2P 46-4D	46-1P	46-3P	
	Flange Angle			46-5D	

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Experimental Testing

TPF 5(253)
Member-level Redundancy of Built-up Steel Girders

Purdue University

PI - Robert Connor
Graduate Research Assistant - Matt Hebdon

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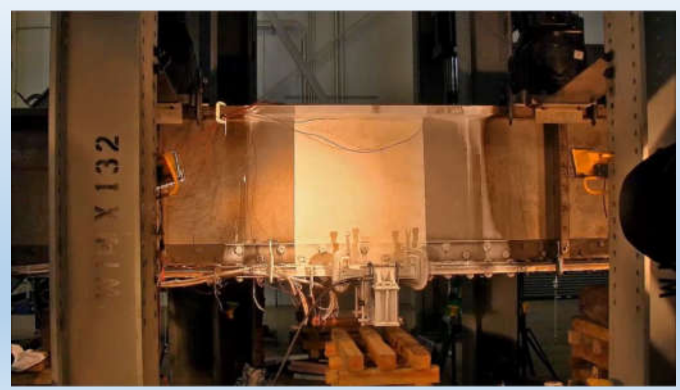
Poorly Proportioned Girder



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Specimen Matrix – <u>Axially</u> Loaded Members

Specimen ID	Targeted Parameter	Fractured Component	Redundancy Components	Fastener Type	Fracture Jumped?
1	Fracture resistance	Center plate	2 plates	Snug A325	No
2	Fracture resistance	Center plate	2 plates	Snug A325	No
3	Fracture resistance	Center plate	2 plates	Loose A307	No
4	Fracture resistance	Center plate	2 plates	Snug A325	No
5	Fracture resistance **with tack weld**	Center plate	4 angles	Snug A325	No

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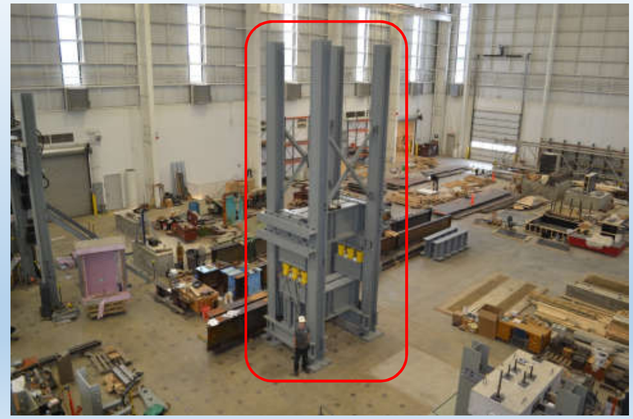
Large-Scale Tension Frame <u>#1</u>



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Large-Scale Tension Frame <u>#2</u>

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Some Members Very Poorly Proportioned

- 1.5” center plate
- (2) 0.5” redundancy plates
- Center plate = 66% of total cross-section area
- All materials were “modern” steels
  - Cooled to “single digit” ft-lb
- 2 Sets of Redundancy plates
  - Set 1 used for Specimen 1
  - Set 2 used for Specimens 2, 3, & 4

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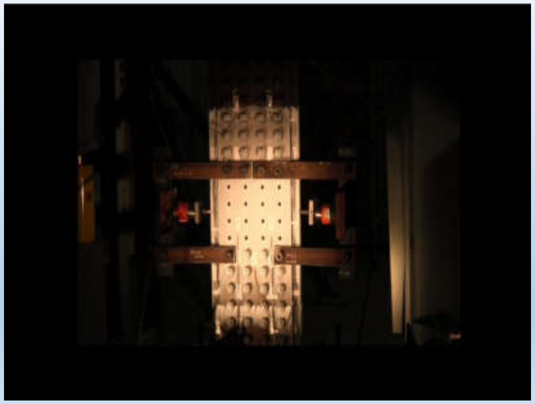
Axial Member Fracture Tests



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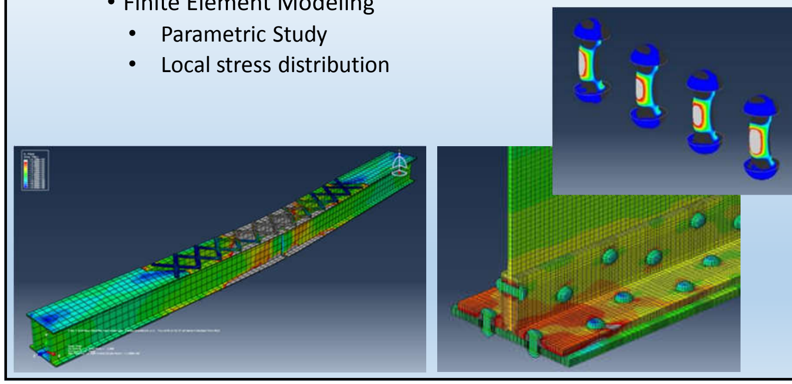
Phase II - Analytical Evaluations

- Finite Element Modeling
  - Parametric Study
  - Local stress distribution



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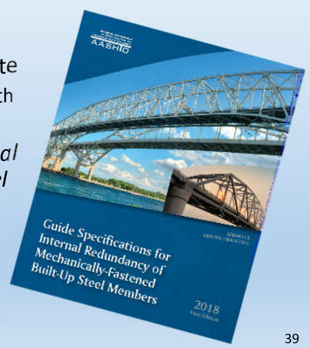
Results of Experimental and Analytical Studies?

- Confirmed internal redundancy can be utilized
  - Fractures do not "jump"
    - Cross-boundary Fracture Resistance (CBFR)
  - Reliable fatigue resistance in the faulted state
    - Can use current nominal stress approach with simple modification factors
- Developed *"AASHTO Guide Specifications for Internal Redundancy of Mechanically-fastened Built-up Steel Members"*
  - Approved by AASHTO SCOBS June 2018
  - Applicable to:
    - Flexural and axial members
    - New and existing members



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Biggest Impact of IRM Guide Spec. is Related to Future In-service Inspections

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Inspection Implications

- Traditional FC Hands-on replaced with "Special Inspection for IRMs"
  - Existing definition of a "Special Inspection" is included in the CFRs
  - Per 23 CFR 650.305 – Definitions:
    An inspection scheduled <u>at the discretion of the bridge owner</u>, <u>used to monitor a particular known or suspected deficiency</u>.
- The objective of this inspection is defined in the Guide Specifications
  - Specifically <u>NOT</u> a hands-on inspection
- Routine inspections continue unaffected

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Inspection Intervals Calculated in the Spec.

Table 3-1 – Maximum Interval between Special Inspections for Case I Members

Calculated Estimated Remaining Minimum Fatigue Life, N_f (Years)	Maximum Permitted Interval (Years)
$N_f < 20$	Larger of 2 years or $0.5N_f$*
$N_f \geq 20$	10

*The calculated inspection interval may be rounded up to the next even-year interval.

Table 3-2 – Maximum Interval between Special Inspections for Case II Members

Calculated Estimated Remaining Minimum Fatigue Life, N_f (Years)	Maximum Permitted Interval (Years)
$N_f \leq 5$	Smaller of 2 years or $0.5N_f$*
$5 < N_f < 20$	$0.5N_f$**
$N_f \geq 20$	10

*The calculated inspection interval may be rounded up to the next half-year interval.
**The calculated inspection interval may be rounded up to the next even-year interval.

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Advantages of this Approach?

- IRM inspection objectives different than FCM
  - Member is capable of carrying specified level of load in a faulted state that is assumed to have occurred
  - Objective is to find completely broken component, not a small crack

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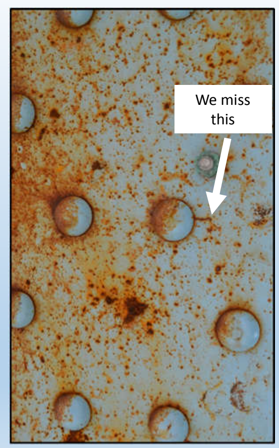

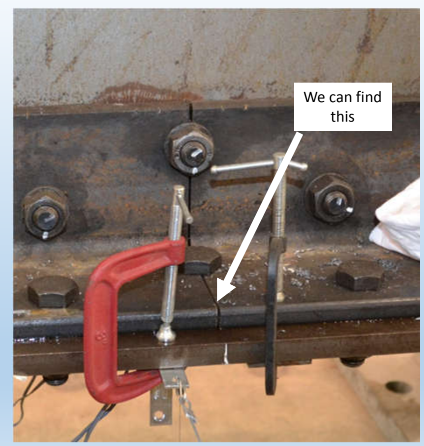

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Advantages of this Approach

- First Integrated Fracture Control Plan
  - Inspection interval, member tolerance and inspector capability are all linked

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What other Criteria are needed for Classifying a Member as FCM, SRM, or IRM?

- For example:
  - What are the minimum damage scenarios?
  - What is/defines failure?
    - i.e., the bridge should be classified as having FCMs if….
  - What loading should be applied in the faulted state?
    - One HS-20….All lanes loaded with HL-93
  - What level of “refinement” in the refined analysis?

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NCHRP Project 12-87a Initiated to Develop such Criteria (NCHRP Report 883)

- Objectives:
  - Develop a methodology to establish whether a member is an FCM or an SRM
  - Codify the methodology into AASHTO-ready specifications
  - Must recognize that the outcome is to remove or alter hands-on inspection interval associated with FCMs

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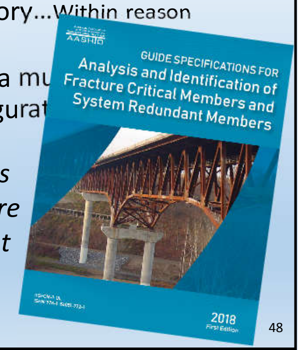
Scope & Results of NCHRP Project 12-87a

- Cover existing <u>and</u> structures under design (i.e., new)
  - Applicable to entire steel bridge inventory…Within reason
  - Analysis, load model, and failure criteria mu to wide-range of structure types, configurat modes
- *Resulted in AASHTO Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members*

  Approved June 2018 by AASHTO SCOBS



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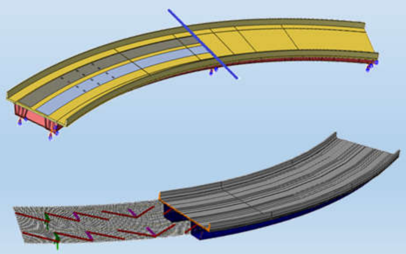
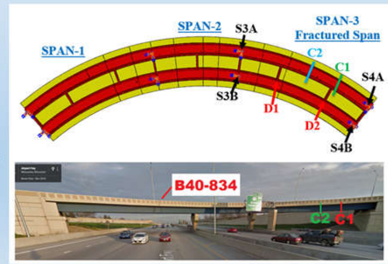
Example Application of NCRHP 883

- 21 different continuous twin tub bridges evaluated using NCHRP 883 criteria for the State of Wisconsin





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Results of the Study?

- ALL 21 bridges found to possess significant reserve strength with an entire tub girder fractured
  - "Satisfied" NCHRP 883 criteria

- CONCLUSION?
- THE GIRDERS ARE NOT FCMs!!!

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CLOSING THOUGHTS

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Overall Objectives Moving Forward?

- First look back
  - FCP in place for nearly 40 years
    - No fractures since introduction
      - Modern fatigue design, fabrication, inspection, etc.

- Need to recognize that there have been many significant improvements made in the past 40 years, yet views on FCMs have not advanced

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The Biggest Hurdle?

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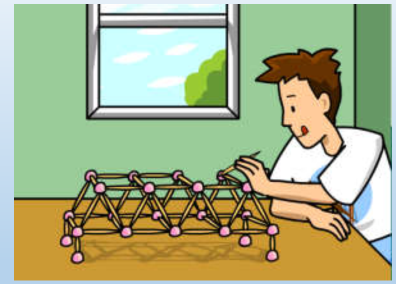
The Biggest Hurdle?

The FC
Emotional
Factors



LITTLE DID BILLY KNOW HE WOULD BE LAUGHED OUT OF THE BRIDGE COMPETITION SINCE HIS DESIGN USED <u>"FRACTURE CRITICAL MEMBERS"</u>

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Back to the Aircraft Comparison…

- Two-winged aircraft are acceptable as RISK associated with failure is low
  - Consequence high
  - Likelihood low
- Modern steel bridges?
  - Likelihood low (FCP)
  - Consequence low (IRM/SRM)

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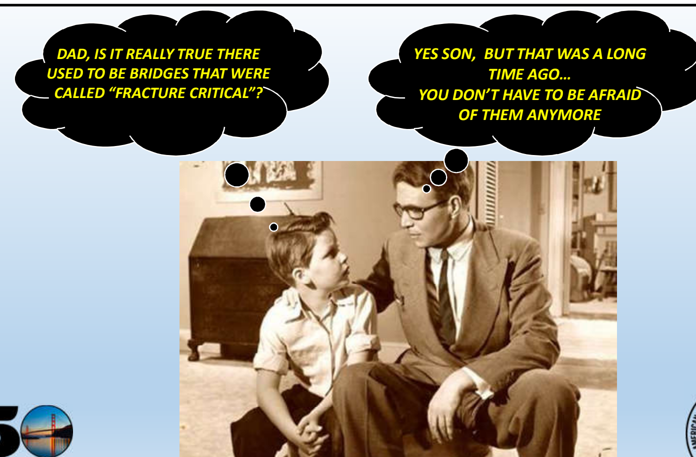

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