The Fracture-control Plan for Steel Bridges

Robert J. Connor, PE
Jack And Kay Hockema Professor of Civil Engineering
Purdue University

Central Ohio Chapter of ABCD
November 2020

150 YEARS OF GIANT LEAPS
PURDUE UNIVERSITY

New & Improved

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National Steel Bridge Alliance
Virginia Tech
Michael Baker International

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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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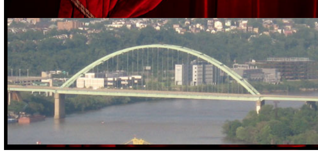
FIRST… SET THE STAGE

- 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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Current Fracture Control Plan

- Today the FCP is fragmented in the US Bridge industry
  - Material & Design are independent of…
  - Fabrication/shop inspection which is independent of…
  - 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 performance
    - 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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Bl

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In-service performance following fracture of an FCM is contrary to assumptions

Lafayette Bridge (1975)
Neville Island Bridge (1976)
Dan Ryan Transit Str (1978)
Green River Bridge (1992)
Hoan Bridge (2000)
US 422 over Schuylkill River (2003)
Diefenbaker Bridge (2011)
Mathews Bridge (2013)
I-276 PA Turnpike Bridge (2017)

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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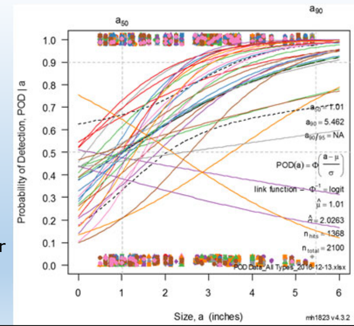
Actual POD Might Surprise You

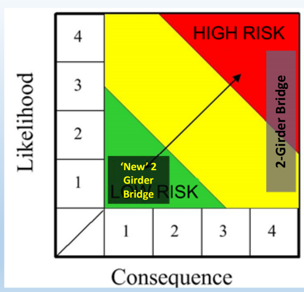
- Best detection rate: 86%
- Lowest detection rate: 31%
- Average rate: 65%

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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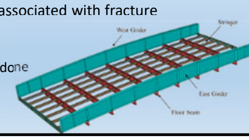
Todays objective?

It is Time to 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
  - Following speakers will show how this can be done



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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 presentations, we will focus on two new AASHTO Guide Specifications:
  - Internal Redundancy (Built-up Members)
  - System analysis per NCHRP Report 883

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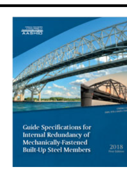

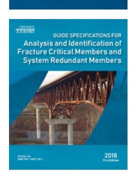

Member-level Redundancy

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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 was that it works
  - AASHTO IRM Guide Specifications are focused on provided rational approach to evaluating such redundancy

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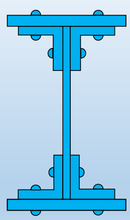
Research Objectives

- 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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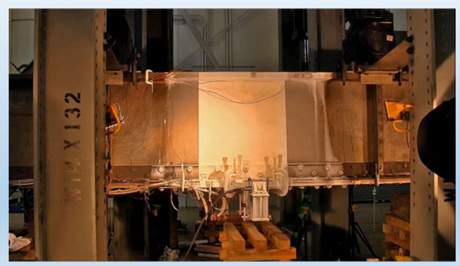
Poorly Proportioned Girder



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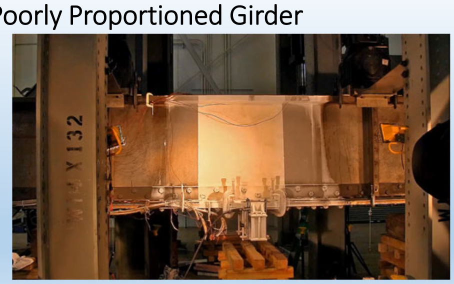
Poorly Proportioned Girder



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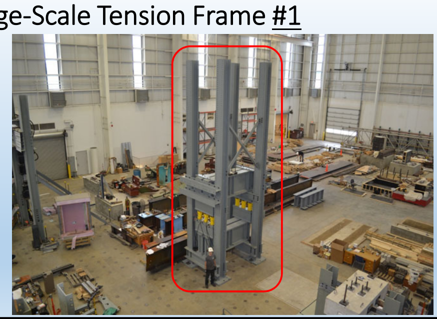
Large-Scale Tension Frame <u>#1</u>



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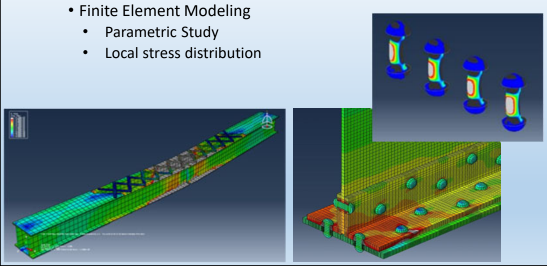
Phase II - Analytical Evaluations

- Finite Element Modeling
  - Parametric Study
  - Local stress distribution



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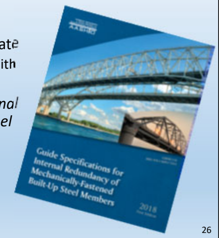
Results of Experimental and Analytical Studies?

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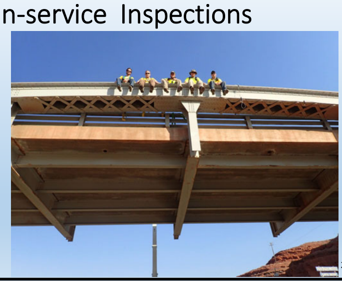
Biggest Impact of IRM Guide Spec. is Related to Future In-service Inspections



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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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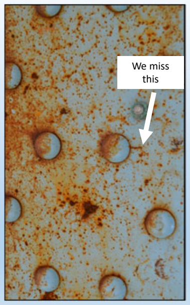

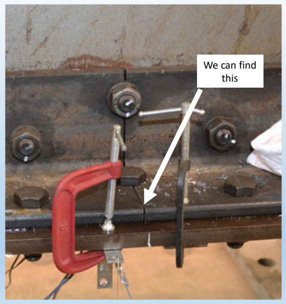

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Advantages of this Approach

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

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What about cases in which complete member failure is feasible?

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What about cases in which complete member failure is feasible?

- i.e., full member failure
- 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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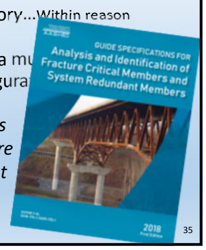
Scope & Results of NCHRP Project 12-87a

- Cover existing and 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, configura… 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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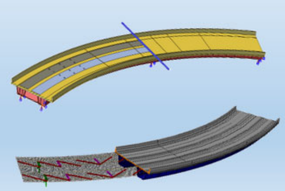
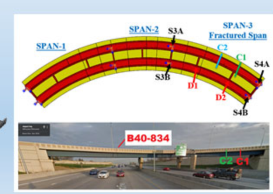
Example Application of NCRHP 883

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





Results of the Study?

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

CONCLUSIONS?

- THE GIRDERS ARE NOT FCMs!!!
- A SIMPLIFIED APPROACH IS VIABLE

What is Included in Proposed Simplified Method?

- Geometric limitations and configurations to which the proposed criteria apply included:
  - e.g., full-depth intermediate plate diaphragms or "equivalent", span limitations, etc.
- How to design and detail such bridges in order to meet the criteria and satisfy:
  - Minimum strength in faulted state
  - Minimum serviceability in faulted state
- AASHTO-ready proposed language developed:
  - Insert as new articles in the AASHTO SRM Guide Specifications (2018)

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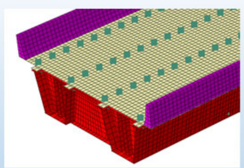
Limitations of Applicability:



- *Geometric limitations for applicability:*
  - Minimum two span continuous
  - Composite section with properly detailed studs
  - Max deck width: 50 ft.
  - Max center to center girder spacing: 25 ft.
  - 60" ≤ Web height ≤ 90"
  - 70 ft. ≤ Interior span length ≤ 250 ft.
  - 100 ft. ≤ End span length ≤ 200 ft.
  - 0.60 ≤ Adjacent span length / Fractured span length ≤ 1.70
  - Max skew < 10 deg.
  - 1.85 ≤ Radius of Curvature / Longest span length
  - Maximum number of design lanes: 3 (# that can fit)
  - Estimated the geometry limits include over 80% of existing bridges
- *Two to three full-depth & full-width intermediate diaphragms:*
  - Locations of diaphragms
  - Section details of diaphragms must meet certain requirements

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When satisfied…

- All loading and failure criteria of the AASHTO Guide Spec. for SRM are satisfied under complete girder fracture
  - Shear stud pull-out and shear failure;
  - Flexural and shear failure of intermediate diaphragms;
  - Local bottom flange buckling of the girder in compression;
  - Positive moment flexural failure (girder and deck);
  - Web shear buckling in the girder;
  - Excessive torsional cracking in the deck according to ACI 318-14 Section 22.7.6 *Torsional Strength* [11];
  - Excessive concrete cracking in the deck due to flexure or shear;
  - Excessive support reaction increases & unacceptable horizontal displacements;
  - Vertical deflection of the fractured girder is less than L/50.

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Glimpse of Verbiage for SRM Guide Specs.

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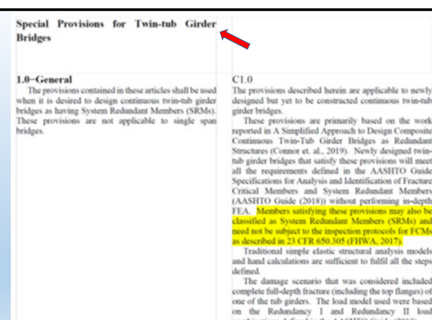

Special Provisions for Twin-tub Girder Bridges

1.0−General The provisions contained in these articles shall be used when it is desired to design continuous twin-tub girder bridges as having System Redundant Members (SRMs). These provisions are not applicable to single span bridges.	C1.0 The provisions described herein are applicable to newly designed but yet to be constructed continuous twin-tub girder bridges. These provisions are primarily based on the work reported in A Simplified Approach to Design Composite Continuous Twin-Tub Girder Bridges as Redundant Structures (Connor et. al., 2019). Newly designed twin-tub girder bridges that satisfy these provisions will meet all the requirements defined in the AASHTO Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members (AASHTO Guide (2018)) without performing in-depth FEA. Members satisfying these provisions may also be classified as System Redundant Members (SRMs) and need not be subject to the inspection protocols for FCMs as described in 23 CFR 650.305 (FHWA, 2017). Traditional simple elastic structural analysis models and hand calculations are sufficient to fulfil all the steps defined. The damage scenario that was considered included complete full-depth fracture (including the top flanges) of one of the tub girders. The load model used were based on the Redundancy I and Redundancy II load combinations defined in the AASHTO Guide (2018).

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2.1−Screening Criteria

The provisions shall be satisfied in order to use the provisions contained herein:

2.1.1) There shall be a minimum of two or more continuous spans;
2.1.2) Composite section with shear stud details as defined in Article 3.2;
2.1.3) Maximum out-to-out deck width ≤ 50 feet;
2.1.4) Maximum center-to-center girder spacing ≤ 25 feet;
2.1.5) 60 inches ≤ web depth ≤ 90 inches;
2.1.6) 70 feet ≤ interior span length ≤ 250 feet;
2.1.7) 100 feet ≤ exterior span length ≤ 200 feet
2.1.8) The ratio of the unfractured adjacent span length to the fractured span length with in 0.6 and 1.7.

C2.1

Geometric limitations were developed to ensure that post-fracture behavior is predicted accurately and to ensure there are no unexpected failure modes. These limitations are based on the wide range of types and geometry of bridges analyzed in the study of Analytical Evaluation of the Post-fracture System Performance of Typical Steel Twin-Tub Girder Bridges in the State of Wisconsin Phase I" (Korkmaz et. al 2017). The results of that and other research were used to develop the simplified methodology summarized in "A Simplified Approach to Design Composite Continuous Twin-tub Girder Bridges as Redundant Structures" (Connor et al., 2019). The requirements were developed to be 1) easy to use and 2) ensure behavior that satisfies the Guide Specifications (2018) in the *faulted* without the need for detailed nonlinear FEA.

The criteria in Articles 2.1.1 through 2.1.12 were developed based on the parameters studied during the development of these criteria (Connor et. al., 2019).

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3.0−Design Methodology

3.1−General

The requirements specified herein shall be considered applicable to steel bridges that satisfy Article 2.1.

The following twin-tub girder members and/or components shall be designed as a minimum to satisfy:

(1) The shear stud provisions specified in Article 3.2.
(2) The provisions for intermediate diaphragms specified in Article 3.3.
(3) The bottom flange buckling resistance provisions specified in Article 3.3.
(4) The maximum positive moment flexural resistance specified in Article 3.4.

C3.1

The requirements of Article 3 were developed according to detailed FE analysis results, section details, and demand/capacity ratios of 18 multi-span twin-tub girder bridge units (in total 2.4 miles and 70 spans) that were studied in detail using the procedures outlined in the AASHTO Guide (2018) as performed by (Korkmaz et al., 2017). The FE analysis results were used to obtain post-fracture demand/capacity ratios under the Redundancy load combinations and compared to the demand/capacity ratios under the familiar Strength I load combination. Many ratios using the Redundancy load factors were equal to, insignificantly higher, or in most cases less than ratios for the Strength I limit state in the *unfaulted* state. The study revealed that when the requirements of Article 3 are satisfied, the following failure modes need not be considered under the Redundancy load factors in the *faulted* state.

(1) Web shear buckling;
(2) Deck related failure modes due to flexure, shear and torsion;
(3) Support bearing failure due to excessive reactions and excessive horizontal displacements;
(4) Excessive vertical displacement in the faulted state;
(5) Brace failures.

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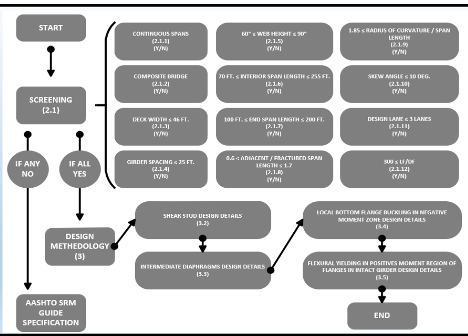

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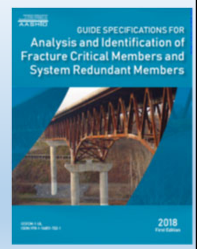
Summary:

- Twin tub girder bridges can be easily and reliably designed as redundant structures satisfying AASHTO SRM Guide Specs. (2018) without need for FEA.
- If the bridge does not meet the criteria defined above, then..
  - Alter the design as needed
  -or-
  - Follow: The AASHTO SRM Guide Specs. (2018)



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CLOSING THOUGHTS

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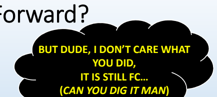
Overall Objectives Moving Forward?

- 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 <u>views</u> regarding "FCMs" of most bridges engineers have not advanced



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The Biggest Hurdle?

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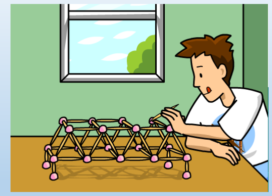
The Biggest Hurdle?

The FC Emotional Factors



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

50

DAD, IS IT REALLY TRUE THERE USED TO BE BRIDGES THAT WERE CALLED "FRACTURE CRITICAL"?

YES SON, BUT THAT WAS A LONG TIME AGO… YOU DON'T HAVE TO BE AFRAID OF THEM ANYMORE

150 YEARS OF GIANT LEAPS PURDUE UNIVERSITY