The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

Classifying Fracture Critical Members

Thursday, June 7, 2018
2:00-4:00 PM ET

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Purpose

Discuss the concept of fracture critical members (FCMs) in steel bridges.

Learning Objectives

At the end of this webinar, you will be able to:

- Identify the history, issues, and current research on the topic of FCMs
- Evaluate if a member should or should not be classified as an FCM
- Describe the proposed American Association of State Highway and Transportation Officials (AASHTO) guide specifications and their objectives, use, and limitations
- Design and detail main girders of twin tub bridges such that they need not be classified as FCMs

Need for This Webinar?

- Considerable research has been completed focused on topic of FCMs over the past few years

- The objective of this work has been to:
  - Rationalize the concept of classifying FCM
    - Not just count girders to determine if FCM
    - Rather use quantitative “engineering” to determine if a member should or should not be classified as an FCM
  - Develop an “Integrated” fracture control plan (FCP)

Current Fracture Control Plan

- First, advances made appear to be working
  - No fractures since introduction of the FCP

- But 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?

Redundancy, Redundancy, Redundancy…

- In bridge engineering, the focus is almost always on redundancy

Translation: ADD GIRDER LINES!!!!

(That addresses Consequence)

- But what is important is the ability to control or mitigate the RISK associated with fracture
  - i.e., a Fracture Control Plan (FCP)
  - Risk = Likelihood x Consequence

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

≠

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

BRIDGES WHERE FRACTURES OCCURRED

BRIDGE	CAUSE	DO WE ALLOW THIS TODAY?	WOULD FIELD INSP. HAVE PREVENTED

Many ways to “control” fracture

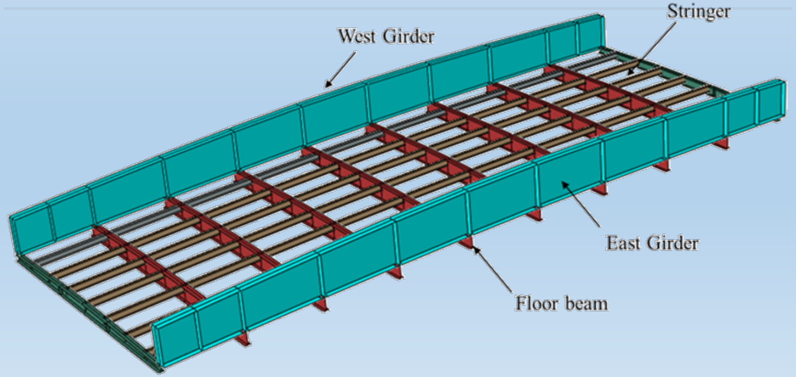
- Simply providing “redundancy” does NOT prevent fracture or guarantee it is “controlled”
  - Fractures can occur in multi-girder bridges
  - Redundancy is a strategy *believed* and *assumed* to mitigate the *consequence* of fracture

- Hands-on inspection every 24 months does NOT “control” fracture
  - Hopefully find a crack before it is “critical”
  - Find a broken component

TODAYS 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



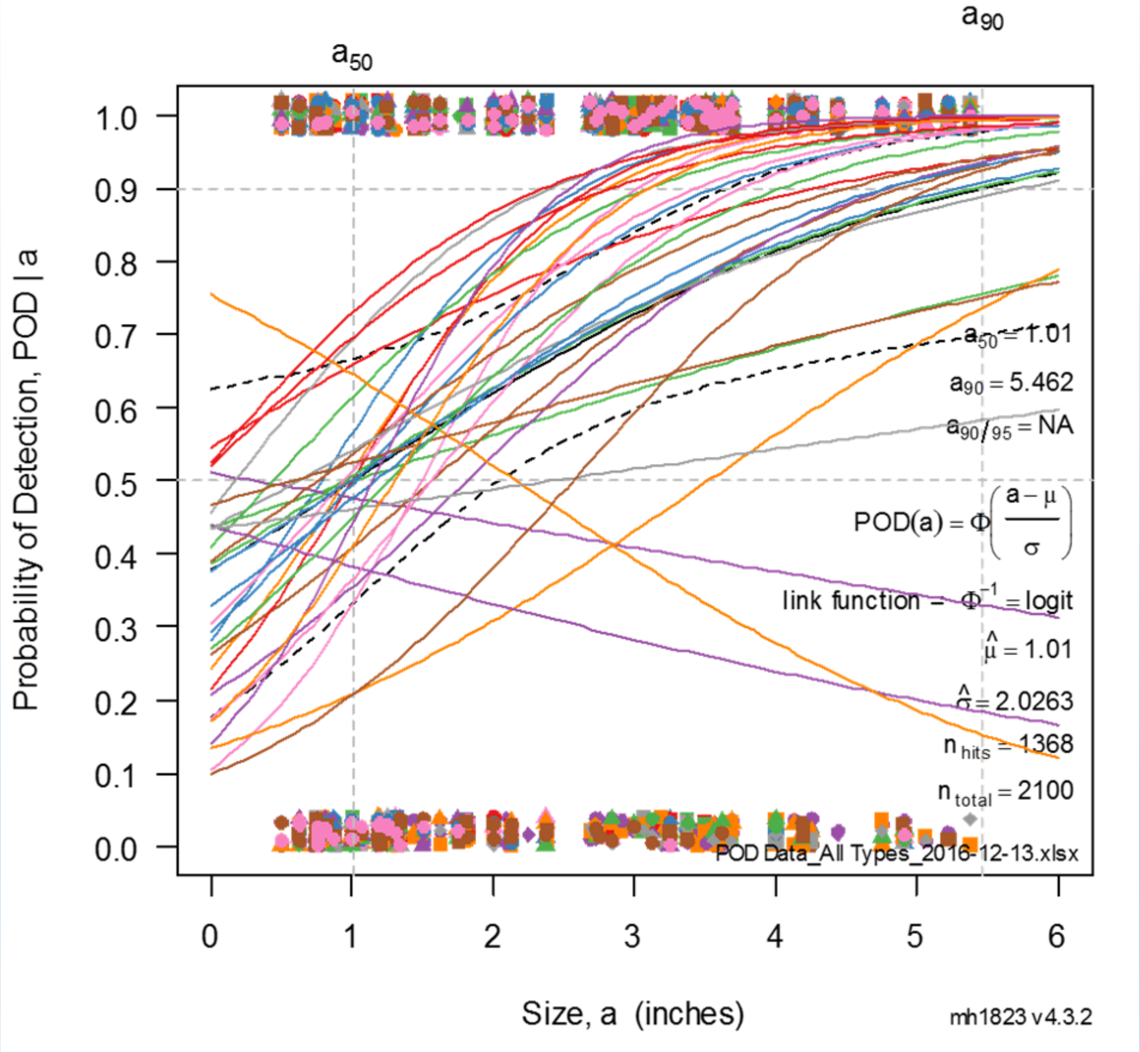
More things to keep in mind…

- 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?

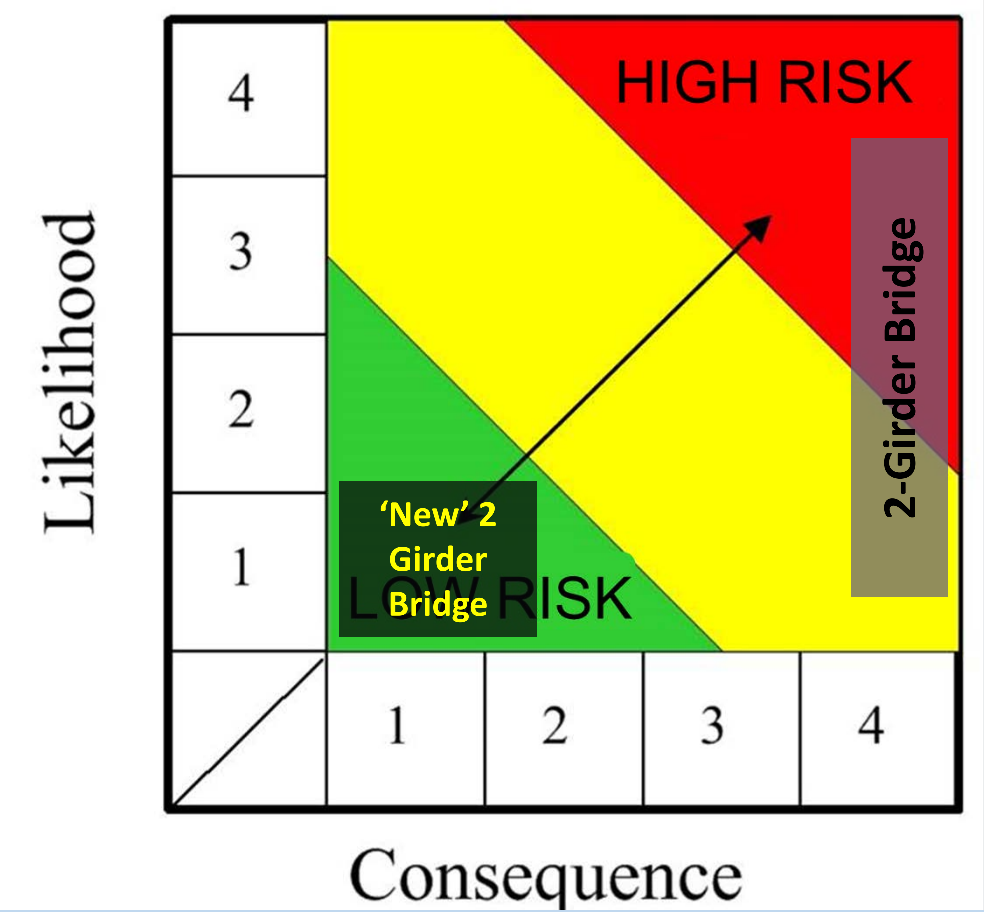
Actual POD Might Surprise You

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.

Alternative Methods to Address FCM “Concerns” without Simply adding Girder Lines

- Exploiting internal redundancy – TPF-5(253)
- Exploiting advanced system analysis – NCHRP 12-87a
- Exploiting superior toughness of HPS – TPF-5(238)

- Today, we will focus on:
  - Internal Redundancy (Built-up Members)
  - Mention system analysis of NCHRP 12-87a
    - Focus on twin tub girders

Member-level Redundancy

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

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
- Develop proposed *“AASHTO Guide Specifications for Internal Redundancy of Mechanically-fastened Built-up Steel Members”….applicable to:*
  - Flexural and axial members
  - New and Existing members

Basic Components of the Proposed IRM Specs?

- Strength and fatigue criteria to demonstrate member possesses adequate internal redundancy
  - Failure of entire member due to a small crack not a failure mode that needs to be considered

- Provisions “keep you in a box” in terms of:
  - General criteria, Member proportions, Conditions, etc.
  - Must have remaining fatigue life in “unfaulted condition”
    - Faulted condition = one component failed

Other Factors to Keep in Mind

- Not all members will meet the provisions
  - Can tailor inspection needs
- Results in a new member classification
  - “Internally Redundant Member” (IRM)
- Easily implemented with an Excel Spreadsheet!

Biggest Impact is Related to Future In-service Inspections

Inspection Interval Tables

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

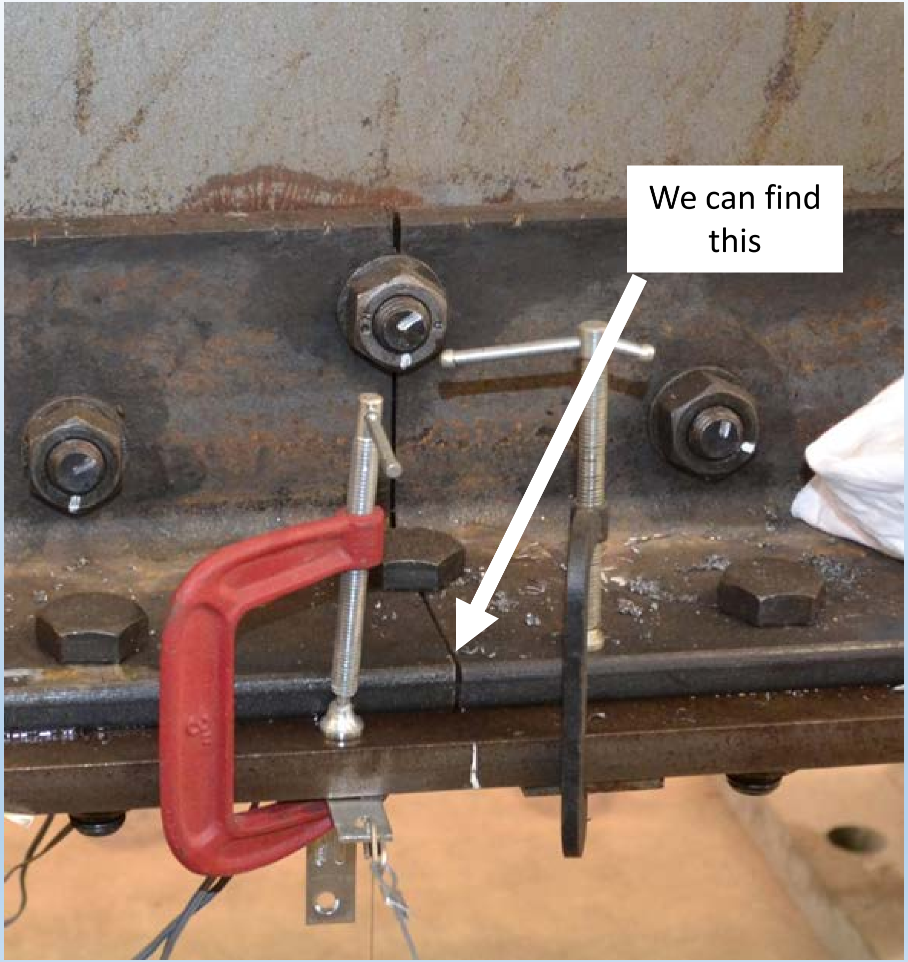
Calculated Estimated Remaining Minimum Fatigue Life, N_f (Years)	Maximum Permitted Interval (Years)
$N_f \leq 5$	Smaller of 2 years or $0.5N_f$*
$5 < N_f < 20$	$0.5N_f$**
$N_f \geq 20$	10

*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.

Advantages of this Approach?

- IRM inspection objectives different than FCM
  - Member is capable of carrying specified level of load in a faulted state
  - Thus, the objective is to find completely broken component, not a small crack

We miss this



We can find this

Advantages of this Approach

- Much higher Probability of Detection (POD)
  - Very low POD finding small cracks at any one of tens of thousands of rivets

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

Summary of IRM Research

- Internal Redundancy of built-up members can be reliably quantified and exploited
  - Similar to what other industries already do!
- Easy-to-use AASHTO ready provisions for built-up members developed
  - 2018 AASHTO ballot item
- First attempt at an integrated FCP
- Result is increased reliability for fatigue and fracture limit state w.r.t. inspection for IRMs

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?

NCHRP 12-87a Initiated to Develop such Criteria

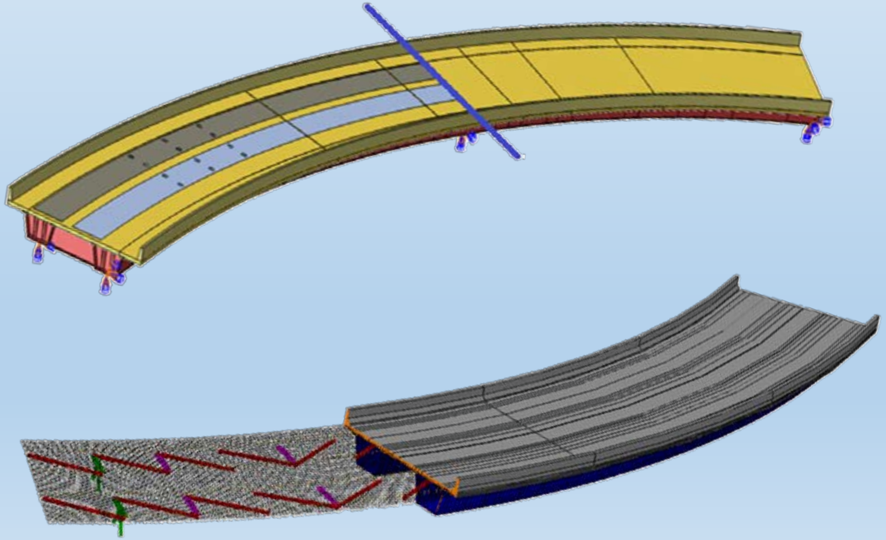
- Objectives:
  - Develop a methodology to establish whether a member is an FCM or an SRM
    - Loading, failure, and analytical requirements developed

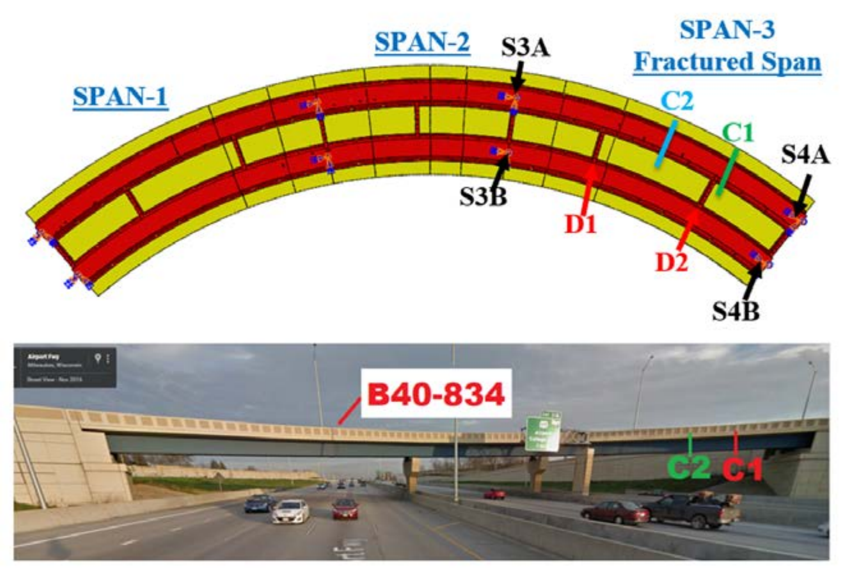
  - Codify the methodology into AASHTO-ready specifications
    - Being balloted at June 2018 SCOBS meeting

  - Must recognize that the outcome is to remove or alter hands-on inspection interval associated with FCMs

Example Application of NCRHP 12-87a

- 21 continuous twin tub bridges evaluated using NCHRP 12-87a criteria for the State of Wisconsin





Characteristics of the WisDOT Bridges

1) End span lengths: 100 ft. to 210 ft.

2) Continuous spans (2 to 7)

3) Composite design

4) Full-depth full-width diaphragms

5) Number of traffic lanes: one to two

6) Web height: 60 in. to 86 in.

7) Girder spacing: 16 ft. to 25 ft.

- Between the center of the bottom flanges)

8) Clear distance: 8 ft. to 13.875 ft.

- Between the center of the interior top flanges)

Results of the Study?

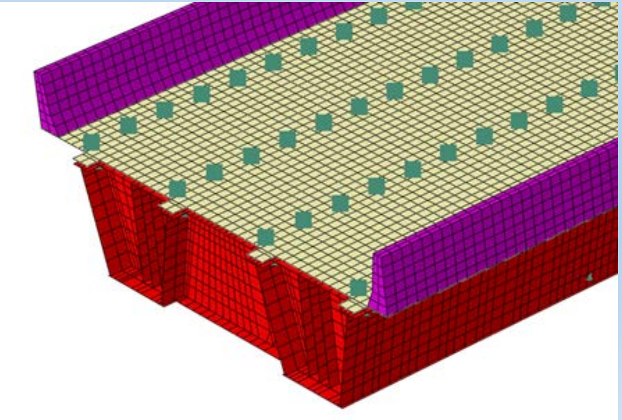
- ALL 21 bridges found to possess significant reserve strength with an entire tub girder fractured
  - “Satisfied” NCHRP 12-87a criteria

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

Moving Forward?

- Once enough structures are analyzed, can likely define a family of bridges that are not FC if "X, Y, and Z" are met
- *"Deemed to Satisfy"*

- Likely about 90% of the way there for continuous twin tubs
- Working to identify these characteristics
- Won't require Non-linear FEA



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

YES SON, BUT THAT WAS A LONG TIME AGO…

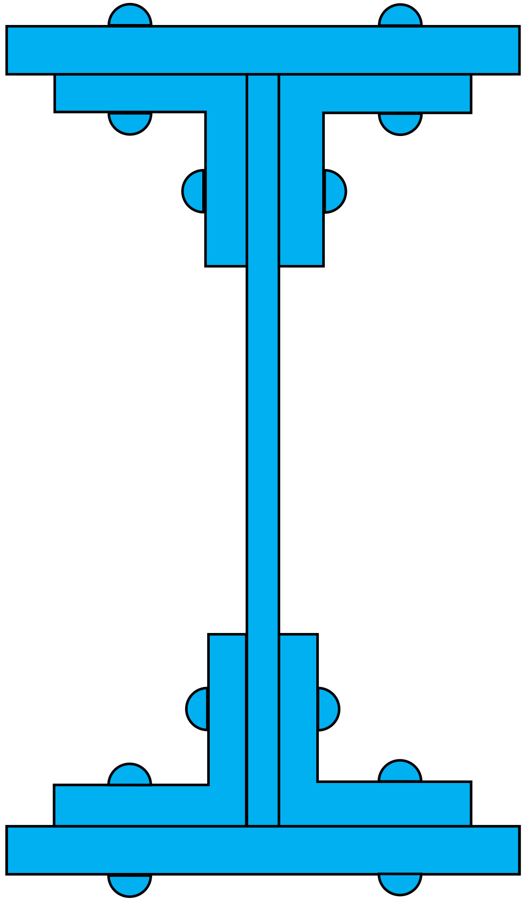
YOU DON’T HAVE TO BE AFRAID OF THEM ANYMORE

Internal Redundancy of Mechanically-Fastened Built-up Steel Flexural Members

Matt Hebdon Ph.D., P.E.

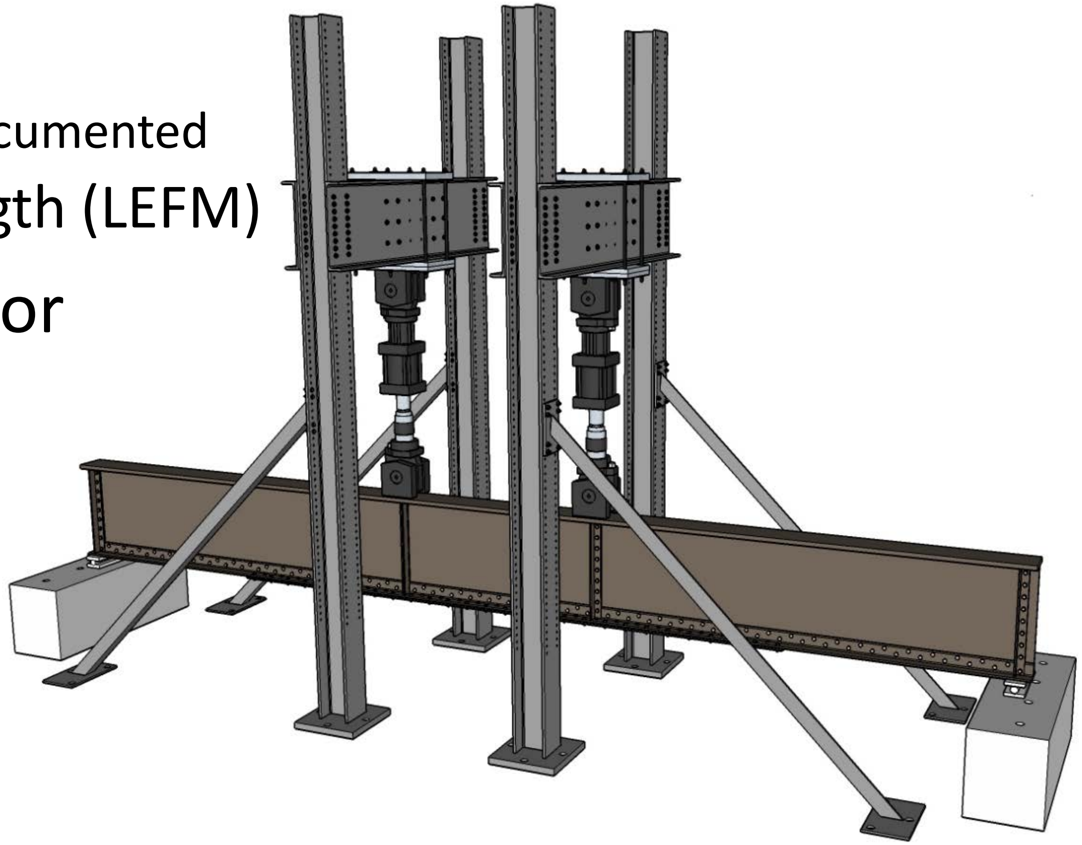
Research Objectives

- Demonstrate fracture resilience
  - Riveted & bolted girders
- Evaluate whether partially failed cross-sections can support design loads
- Determine remaining fatigue life of a partially failed cross-section
- Relate remaining fatigue life to rational inspection intervals



Experimental Test Procedure

- Notched component
    - Controlled location (angle/cover plate)
        - Not investigating initial fatigue life – already documented
    - Crack growth through fatigue to critical length (LEFM)
- Cool beam to achieve lower shelf behavior
    - Max. temp = -60° F (as low as -120° F)
    - Single digit ft-lbs
- Load to induce a fracture
    - 0.55 F_y (Minimum)
    - If no fracture, grow crack and repeat

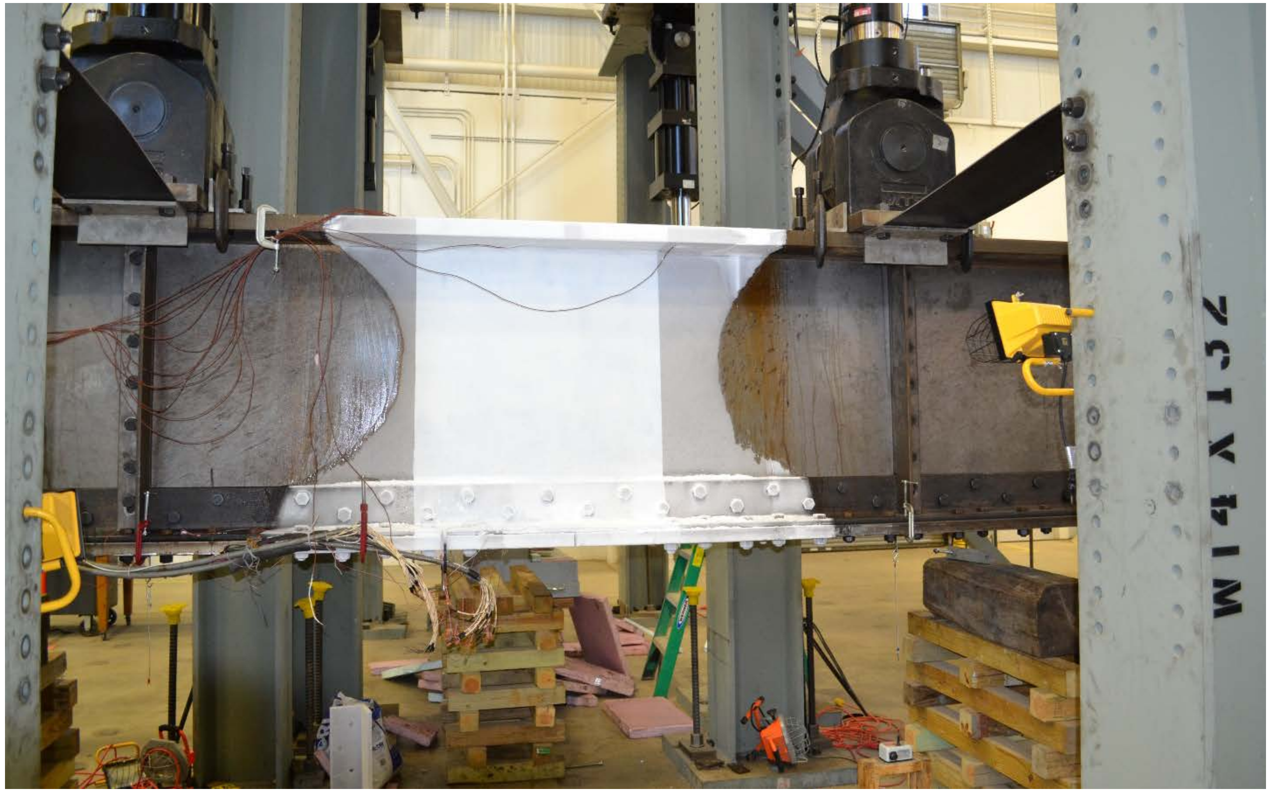


Experimental Test Procedure

- Substantial portion of component cracked
  - Greater than critical crack length (LEFM)
  - Multiple attempts as crack length increased
- To achieve brittle fracture in a cracked component
  - Driven wedges into cover plates
  - Removal of Fasteners near crack
    - Decrease constraint at crack tip
    - Increase strain energy
- Examine stress redistribution
- Determine remaining fatigue life

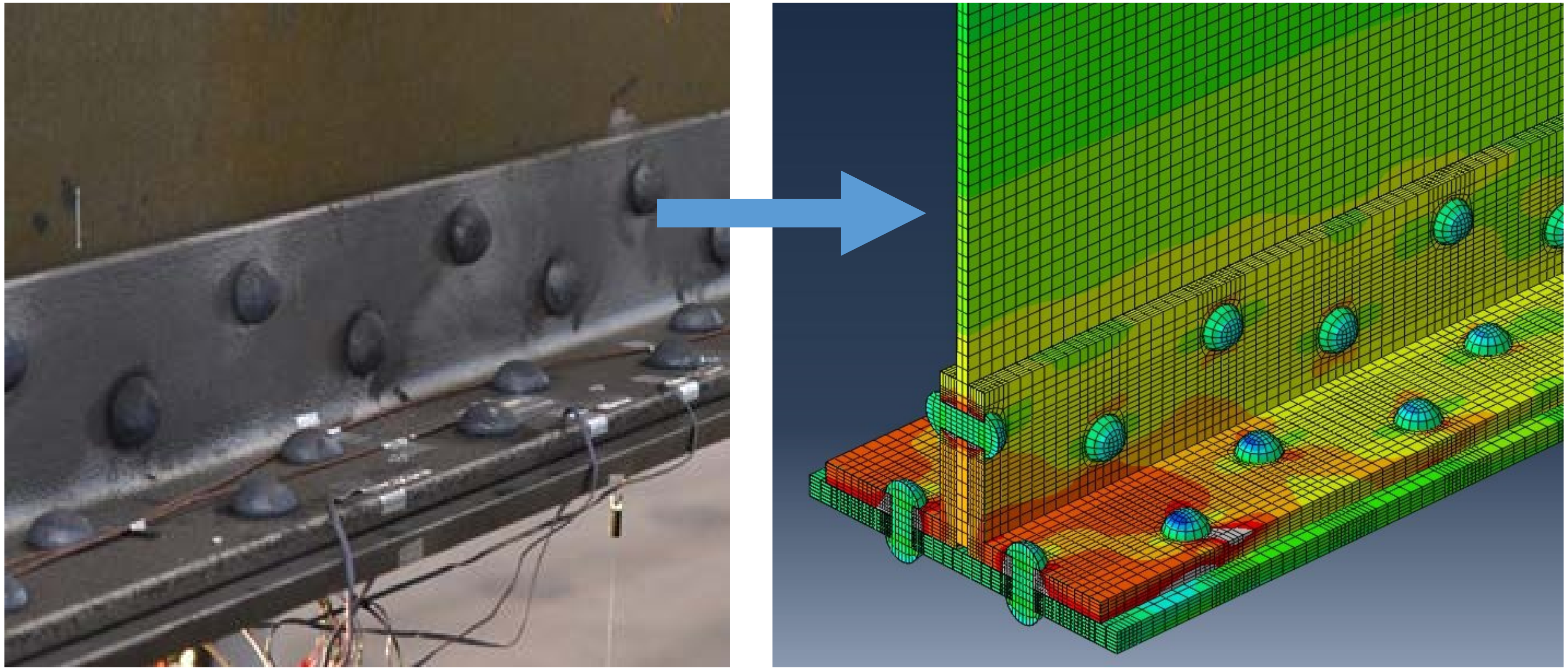
Experimental Test Results: Fracture Resilience

- Built up girders DO NOT permit fracture propagation
  - Appropriately proportioned components
  - Positive fatigue life



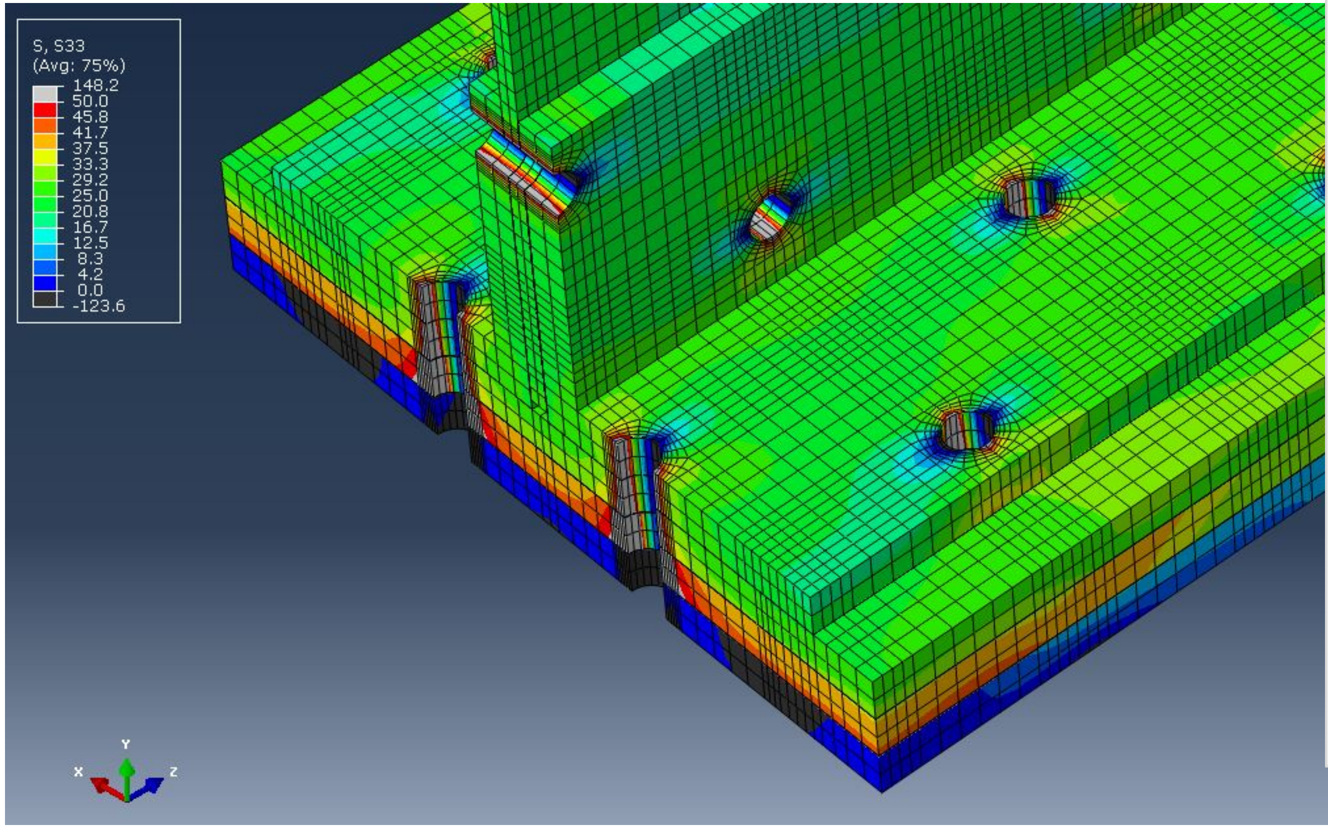
Analytical Evaluation

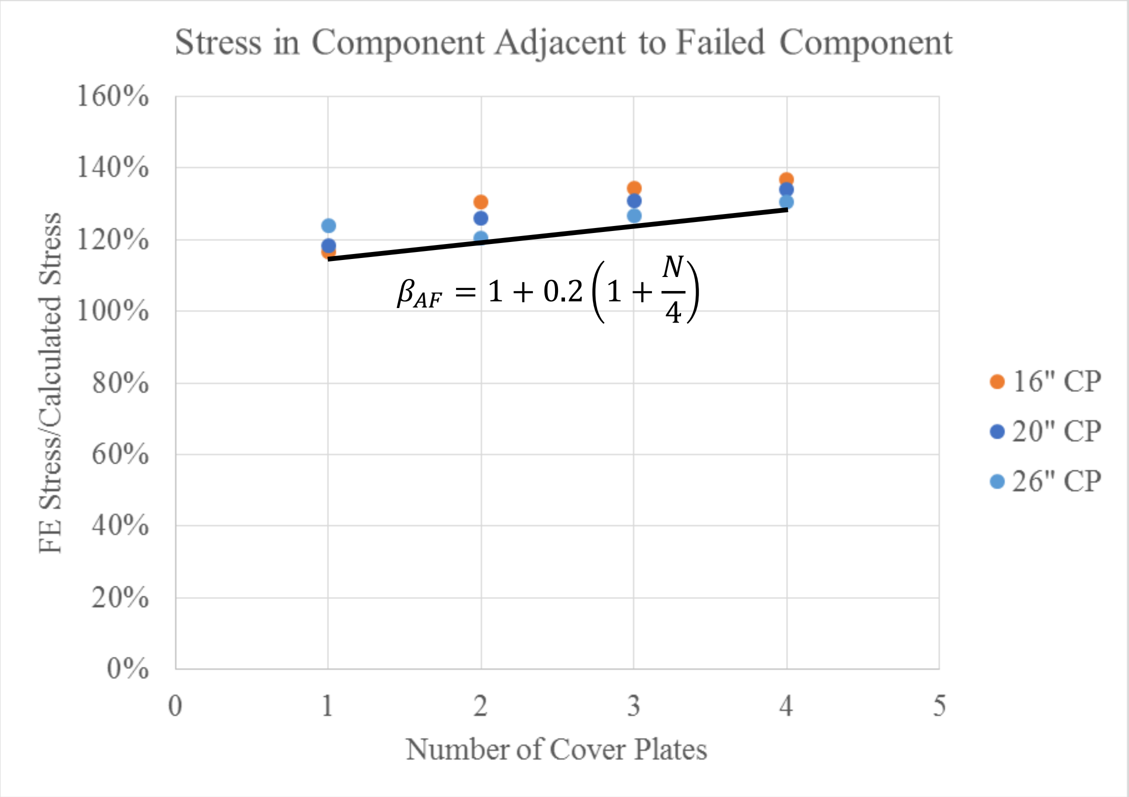
- 3d Finite Element Modeling
  - Local stress distribution
  - Parametric Study



Analytical Evaluation

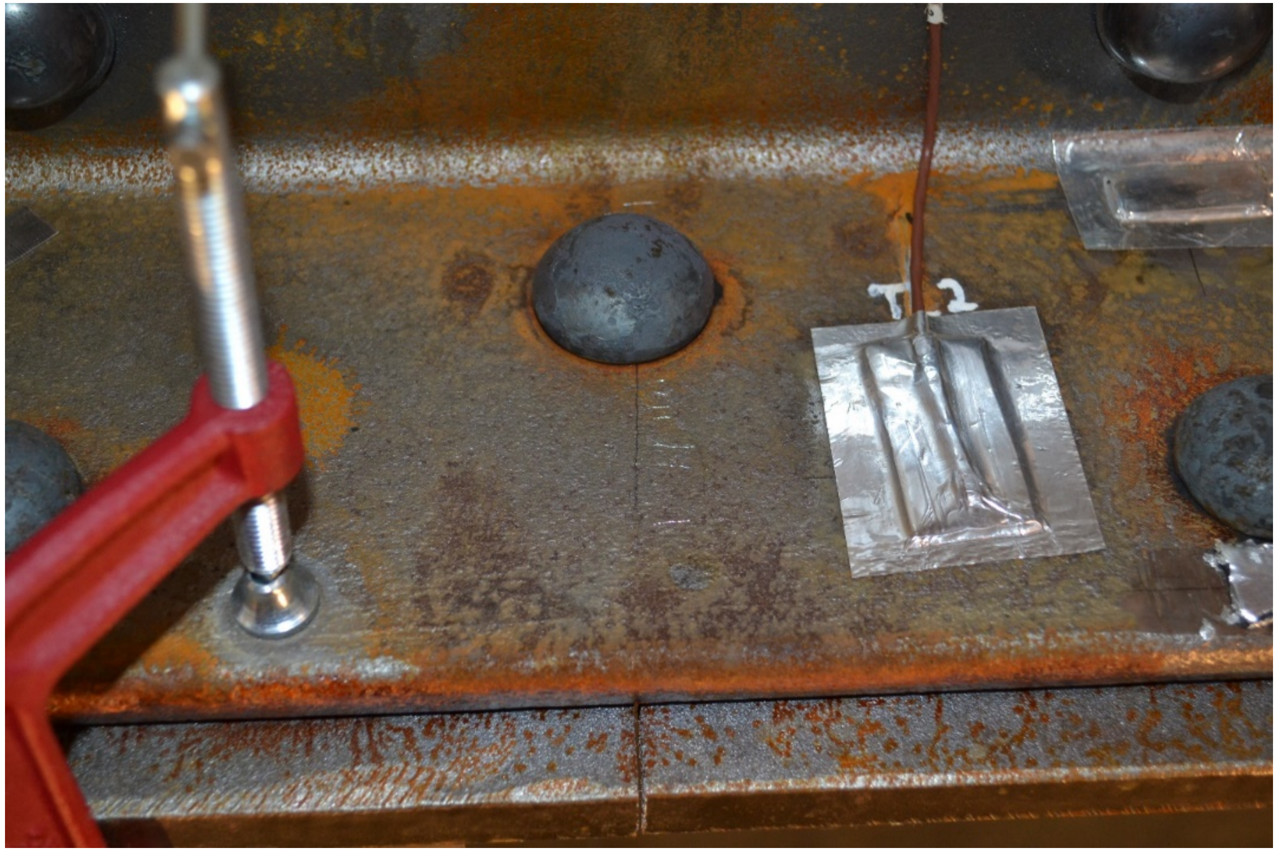
- Parametric study results
  - Capacity is function of number of cover plates

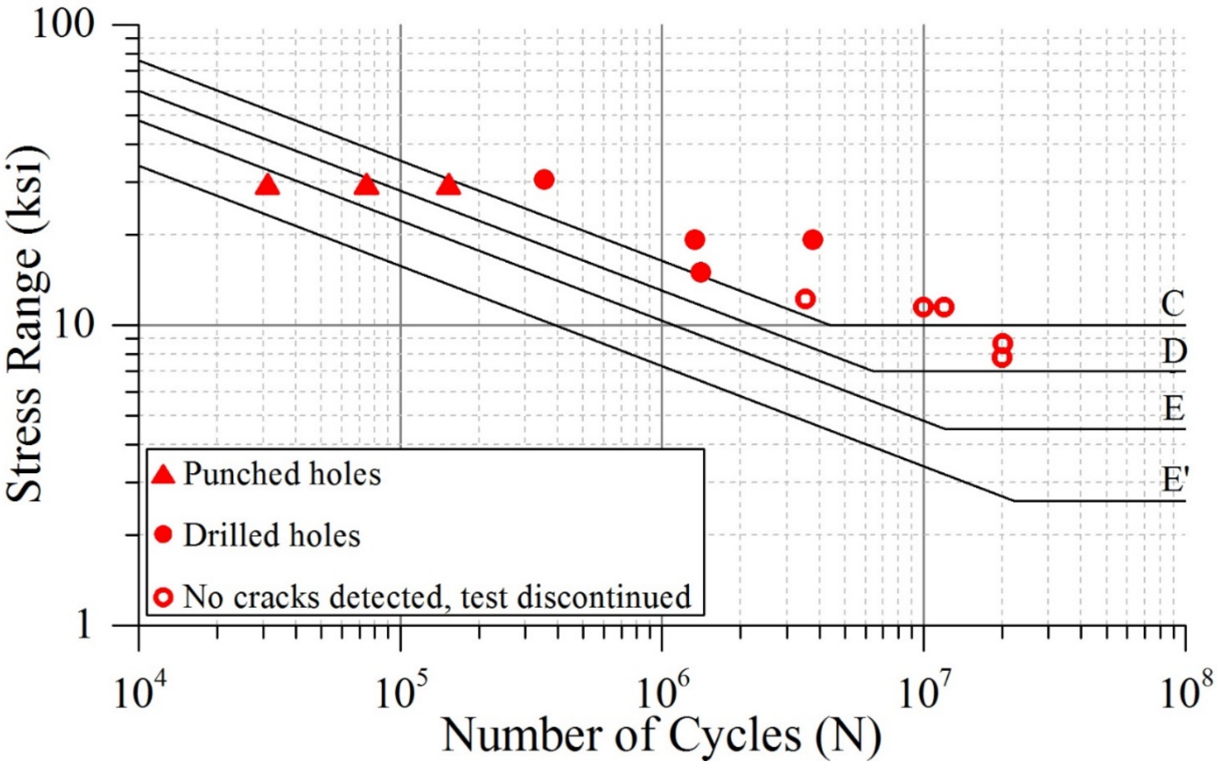




Experimental Test Results: Fatigue Life

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





Research Conclusions

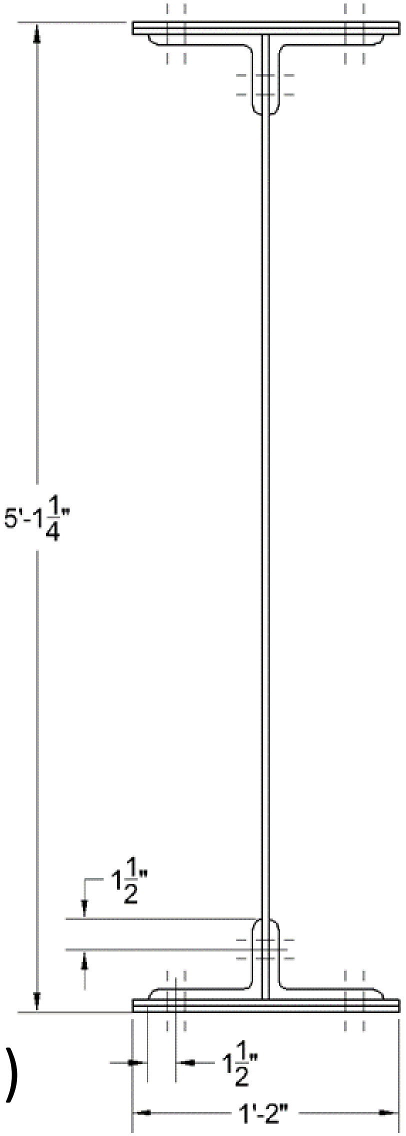
- Fracture Resilience of Built-up Girders
  - Fracture does not propagate into adjacent components

- Localized stress redistribution
  - Concentrated in components adjacent to failed component

- Substantial remaining fatigue life even with a failed component
  - Category C for drilled or subpunched and reamed holes
  - Category E’ for punched holes

Example – Flexural Member

- 2-girder Bridge:
  - 40 ft. span, simply supported
  - 62 years old
  - $(ADTT)_{SL}$ = 600 trucks per day, no growth
  - F_y = 33 ksi
  - F_u = 58 ksi
- Member:
  - Flange composition
    - Double angles
    - Two cover plates
  - Riveted connections with drilled holes
  - All other IRM requirements are met (GS 1.1-1.2)



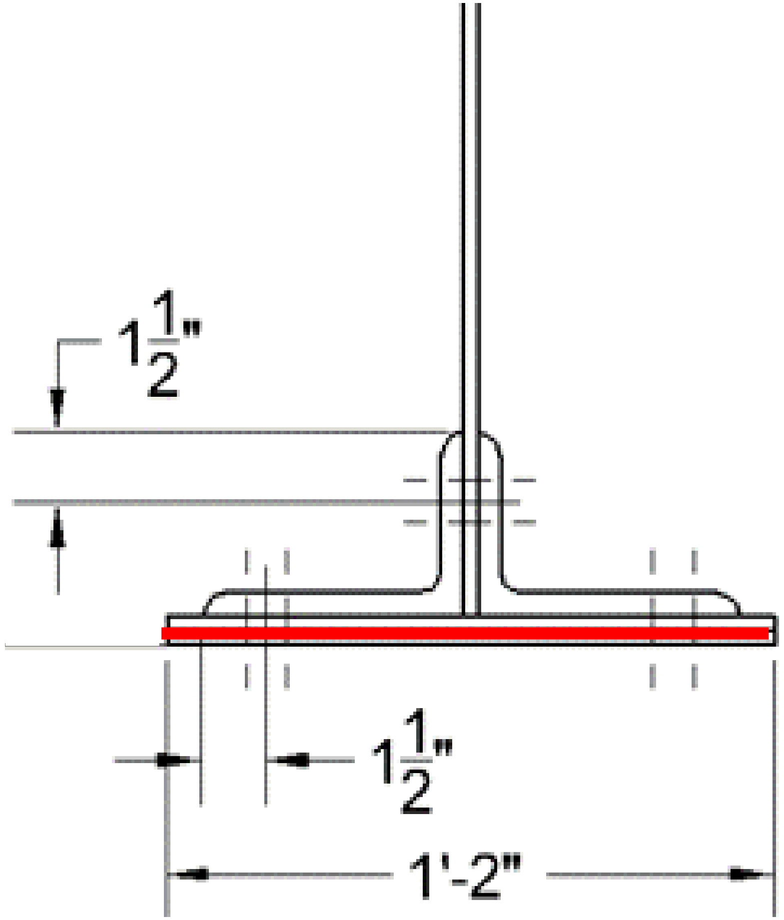
Web:
- PL60x3/8

Flanges (each):
- 2 x L6x4x1/2 (Long Legs Horizontal)
- 2 x PL14x5/16

Fasteners:
- 7/8" dia. Rivets in 15/16" dia. Drilled Holes

Example – Flexural Member

- Midspan Moments (Critical Location)
  - $M_{DC} = 650\ kip * ft$ (unfactored)
  - $M_{DW} = 0$
  - $M_{LL+IM} = 900\ kip * ft$ (unfactored)
  - $M_{Fatigue\ I} = 984\ kip * ft$
  - $M_{Fatigue\ II} = 450\ kip * ft$
- Section Properties
  - Before assumed failure
    - $S_{x-NET} = 1080 in^3$
  - After assumed failure
    - $S_{x-AFN} = 896 in^3$
    - $S_{x-AFG} = 1052 in^3$



Example – Flexural Member

- Strength Limit State Load Combination (GS 1.4)
  - $M_u \; = \gamma_{DC} M_{DC} + \gamma_{DW} M_{DW} + \gamma_{LL} M_{LL+IM}$

Load Combination	γ_{DC}	γ_{DW}	γ_{LL}
Internal Redundancy	1.15	1.25	1.50

  - $M_u = 1.15(650 kip * ft) + 0 + 1.50\,(900 kip * ft) = 2098 kip * ft$

Max Stress in the Faulted State (GS 2.1.2)

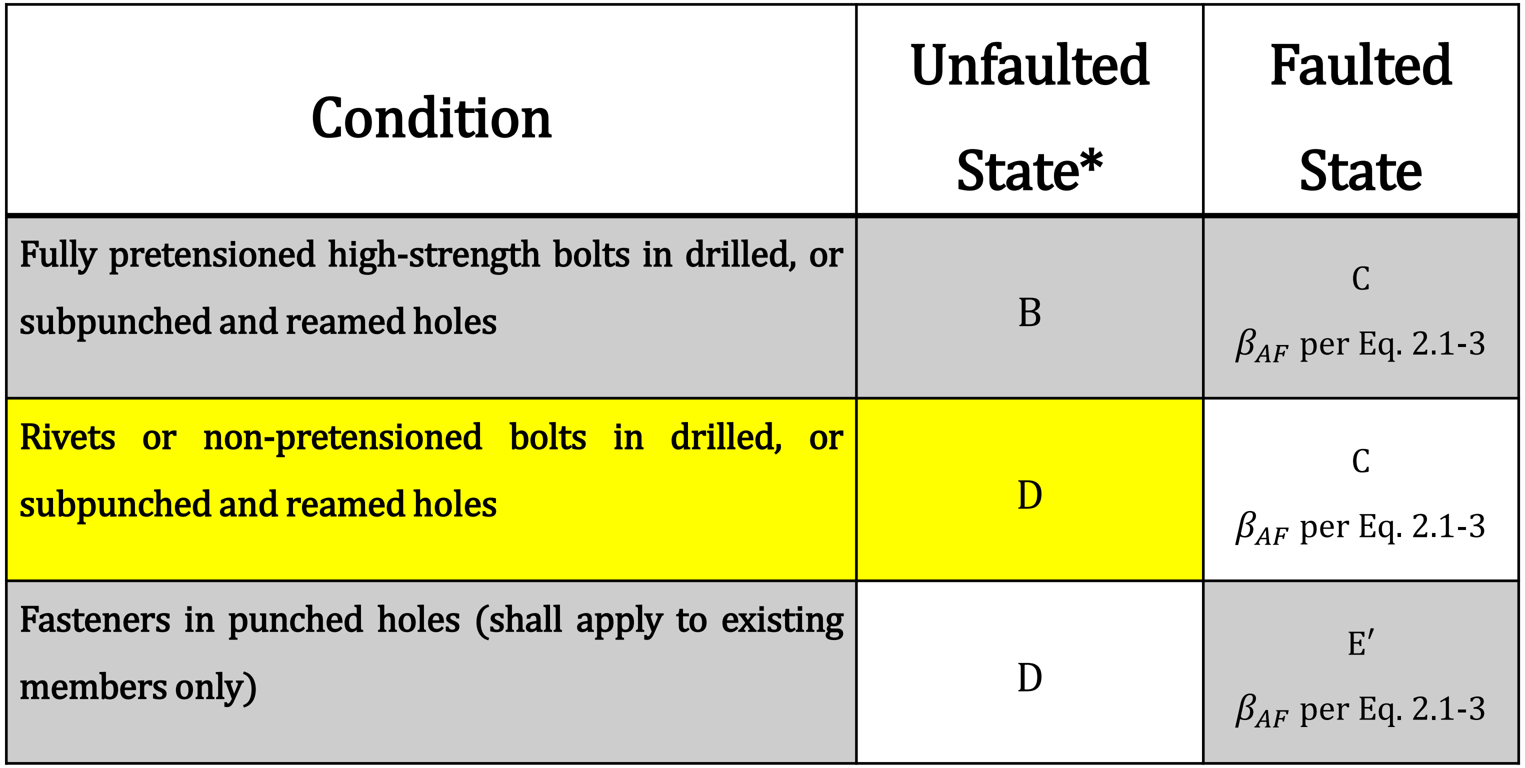
- Calculate the gross and net section stress on the faulted component
  - $\beta_{AF} = 1.0$ for the strength condition
  - $f_{AFG} = \beta_{AF} \frac{M_u}{S_{x-AFG}} = 23.9\, ksi$
  - $f_{AFN} = \beta_{AF} \frac{M_u}{S_{x-AFN}} = 28.1\, ksi$
- Compare to strength criteria (GS 2.3)
  - $f_{AFG} \leq \phi_y F_y = 0.95\, * \, 33\, ksi = 31.4\, ksi \therefore OK$
  - $f_{AFN} \leq \phi_u F_u = 0.8\, * 58\, ksi = 46.4\, ksi \therefore OK$
- The section has adequate strength, the next step is to check fatigue

Fatigue Evaluation (GS 2.5)

- “The minimum expected fatigue life in the unfaulted state shall first be calculated using the provisions of Article 7.2 of the MBE.”
  - Determine the maximum stress range (i.e. Fatigue I)
  - Compare to the CAFL
- Fatigue LL Moments (factored)
  - $M_{Fatigue\ I} = 984\ kip * ft$
  - $M_{Fatigue\ II} = 450\ kip * ft$
- Will the UNFAULTED section have infinite life?
  - i.e. would we expect the possibility of cracking or not PRIOR to a break?
  - Case I: Infinite fatigue life before a failure
  - Case II: Finite fatigue life before a failure

Fatigue Evaluation: Unfaulted Section

- Table 2.5-1



Condition	Unfaulted State*	Faulted State
Fully pretensioned high-strength bolts in drilled, or subpunched and reamed holes	B	C β_{AF} per Eq. 2.1-3
Rivets or non-pretensioned bolts in drilled, or subpunched and reamed holes	D	C β_{AF} per Eq. 2.1-3
Fasteners in punched holes (shall apply to existing members only)	D	E′ β_{AF} per Eq. 2.1-3

*β_{AF} shall not be used in the unfaulted state

Fatigue Evaluation: Unfaulted Section

- Stress range is computed on **UNFAULTED NET SECTION** since section is riveted
  - $\Delta f = \frac{M_{Fatigue\ I}}{S_{x-NET}} = \frac{(984\ kip*ft)(12in/ft)}{1080in^3} = 10.9ksi$
- CAFL = 7 ksi for Cat D
- 10.9ksi > 7ksi

- Infinite life would NOT have been expected in the unfaulted state
- Case II Fatigue applies
  - Implies a portion of life has been consumed and is no longer available AFTER the fracture
  - “The estimated remaining finite fatigue life in the unfaulted state shall be calculated as specified in Section 7.2.5 of the MBE using the appropriate fatigue detail category specified in Table 2.5-1.

Fatigue Evaluation: Unfaulted Section

- Compute the **unfaulted section finite life** using MBE 7.2.5:
- $Y_u = \frac{R_R A}{365n[ADTT_{SL}][\Delta f_{eff}]^3}$
    - Where:
        - $R_R = 1.0$ (MBE Table 7.2.5.2-1);
        - $A = 22.0 \cdot 10^8\ ksi^3$ for a Category D detail
        - $n = 1.0$ (MBE 7.2.5.2);
        - $(ADTT)_{SL} = 600$;
        - $(\Delta f)_{eff} = \frac{M_{Fatigue\ II}}{S_{x-NET}} = \frac{(450\ kip \cdot ft)(12\ in/ft)}{1080\ in^3} = 5.00\ ksi$
- $Y_u = 80.4\ years$
- Bridge age = 62 years old
- Remaining fatigue life = 18 years

Fatigue Evaluation: **Faulted** Section

- Table 2.5-1

Condition	**Unfaulted State***	**Faulted State**
Fully pretensioned high-strength bolts in drilled, or subpunched and reamed holes	B	C β_{AF} per Eq. 2.1-3
Rivets or non-pretensioned bolts in drilled, or subpunched and reamed holes	D	C β_{AF} per Eq. 2.1-3
Fasteners in punched holes (shall apply to existing members only)	D	E′ β_{AF} per Eq. 2.1-3

*β_{AF} shall not be used in the unfaulted state

Fatigue Evaluation: Faulted Section

- Compute the **Faulted section finite life** using MBE 7.2.5:
- $Y_f = \dfrac{R_R A}{365n[ADTT_{SL}][\Delta f_{eff}]^3}$
  - Where:
    - $R_R = 1.0$ (MBE Table 7.2.5.2-1)
    - $A = 44.0 \cdot 10^8\ ksi^3$ for a Category C detail
    - $n = 1.0$ (MBE 7.2.5.2)
    - $(ADTT)_{SL} = 600$
    - For fatigue evaluation $\beta_{AF} = 1 + 0.25\left(1 + \frac{N}{4}\right)$; Where N = the number of cover plates
    - $\beta_{AF} = 1 + 0.25(1 + {}^{2}/_{4}) = 1.375$
    - $(\Delta f)_{eff} = \beta_{AF} \frac{M_{Fatigue\ II}}{S_{x-AFN}} = 1.375 \frac{(450\ kip{\cdot}ft)(12\ in/ft)}{896\ in^3} = 8.3\ ksi$
- $Y_f = 35.3\ years$

Fatigue Evaluation: **Remaining Life**

- The effective stress range in the unfaulted member is 5 ksi
- For a 5 ksi stress range the detail would last about 80 years
- The bridge is only 62 years old

- The effective stress range in the assumed faulted member is 8.3 ksi
- For a 8.3 ksi stress range the detail would last about 35 years
- But there is prior "damage"

- Calculate remaining fatigue life after the assumed fracture:
- $N_f = Y_f\left(1 - {}^{N_u}/_{Y_u}\right)$
  - Where
    - Y_f = total finite life of a faulted member
    - $\left(1 - {}^{N_u}/_{Y_u}\right)$ = fraction of life NOT consumed previously
- $N_f = 35.3(1 - {}^{62}/_{80}) = 8.1\ years$

Determine Special Inspection Interval (GS 3.0)

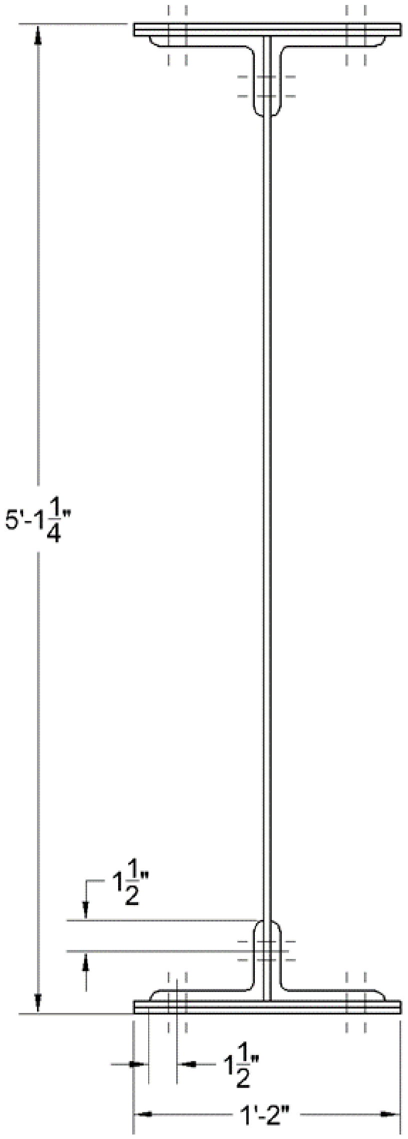
- Table GS Table 3-2:

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

- 0.5 (8.1) = 4.05
  - **Calculated inspection interval may be rounded up to the next even-year interval
- Maximum special inspection interval = 6 years

Flexural IRM Example Summary

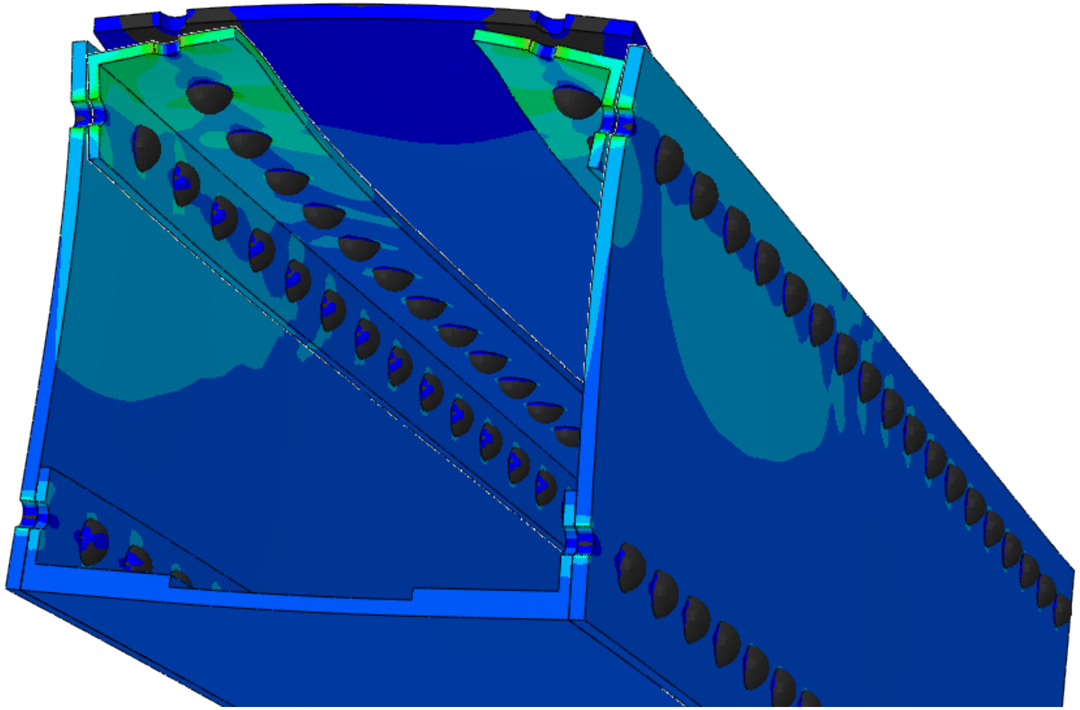
- Beam has adequate strength if a cover plate is completely lost
- Beam does not have infinite life in the unfaulted condition
- The remaining life "after the fault" is 8.1 years
- Maximum special inspection interval is 6 years



Internal Redundancy of Mechanically-Fastened Built-up Steel Axially-Loaded Members

Jason Lloyd, P.E.; Robert Connor, Ph.D.;
Francisco J. Bonachera Martin, Ph.D.; Cem Korkmaz, Ph.D.

Axial Tension Members

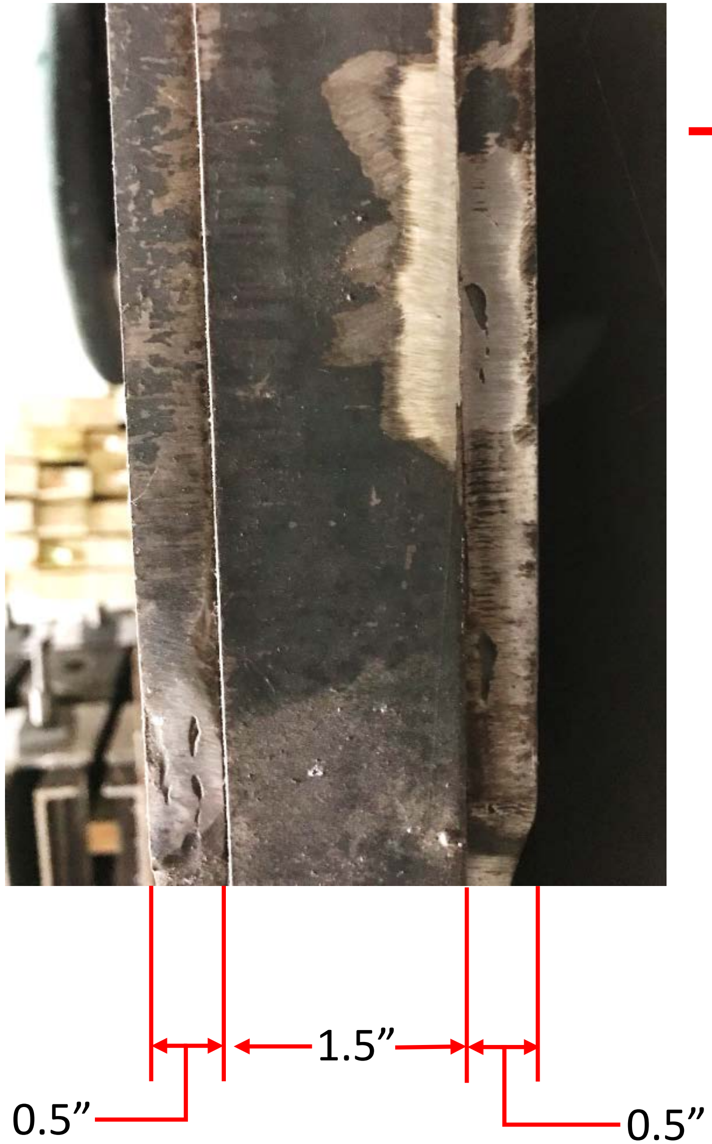


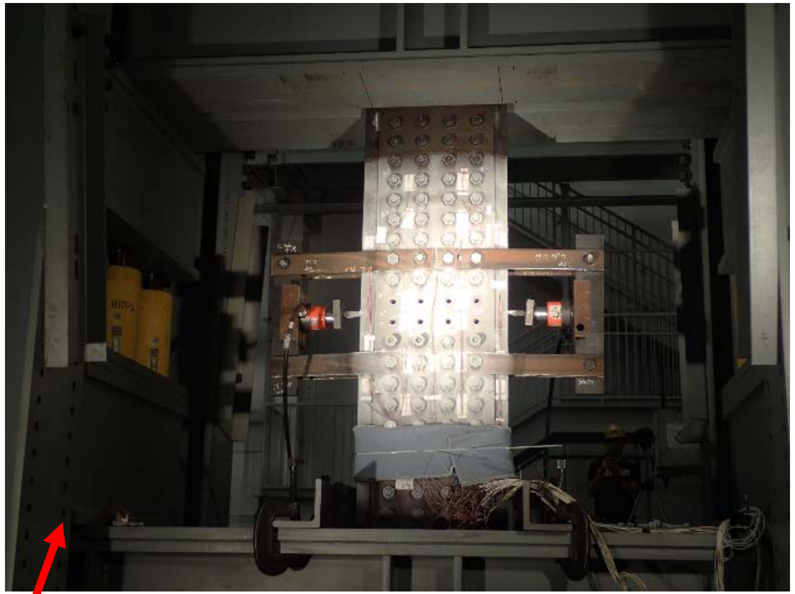
Fracture Tests

- Cross-Boundary Fracture Resistance (CBFR):

  Ability to resist fracture at the boundary between components

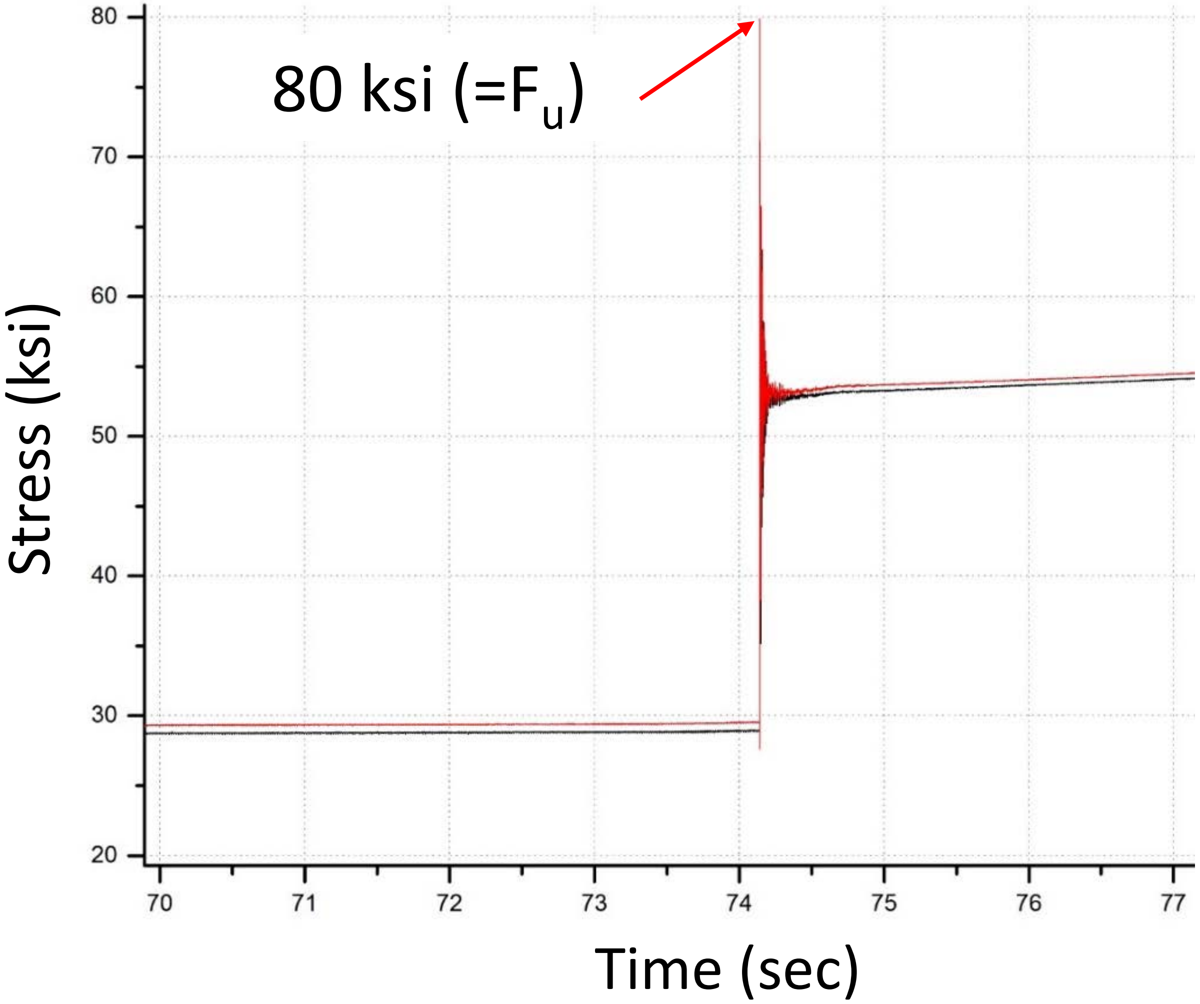
Fracture Tests, cont.





Fracture Tests, cont.

- Load to ≥ $0.55F_y$
- Fracture 66% of X-section
- Lower shelf toughness
- Fasteners in bearing (large demands at hole edges)
- Brittle failure mode (dynamic load redistribution)

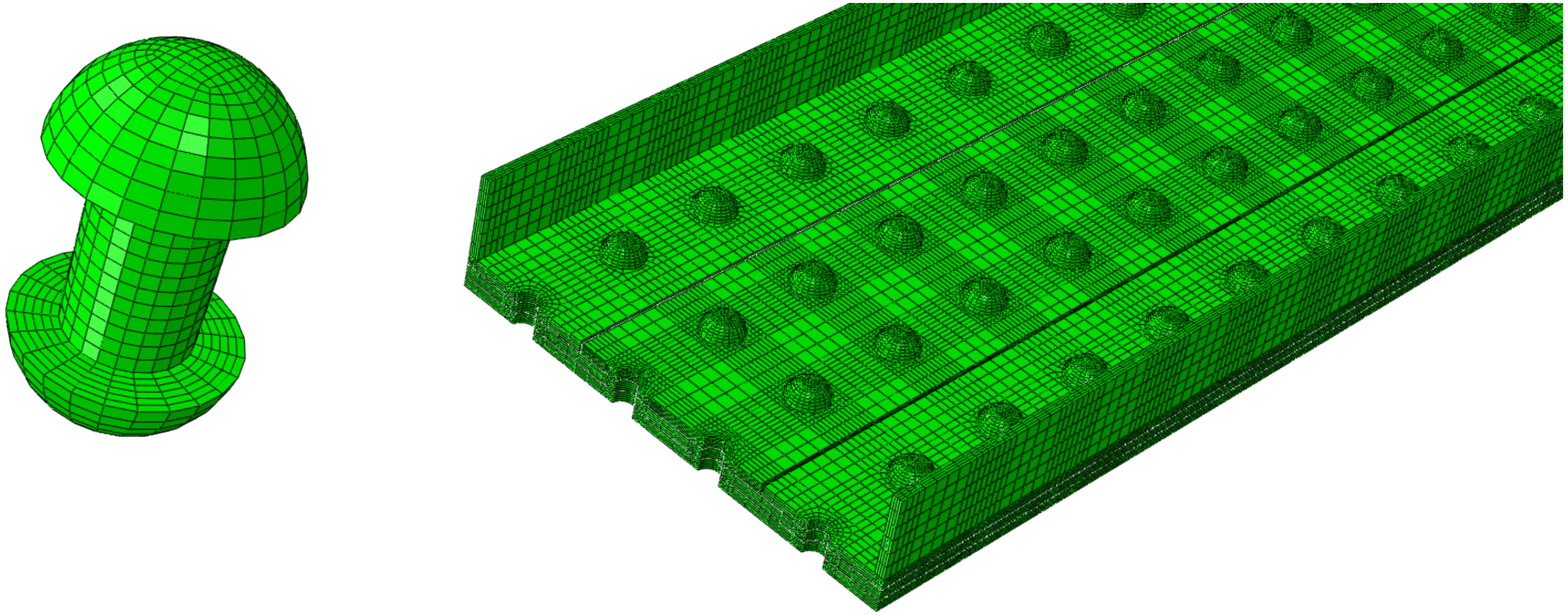


Fracture Test Conclusions

- All 5 specimens possessed CBFR in extreme test
- Toughness is not an essential property for mechanically built-up members
- Tack welds do not affect internal redundancy

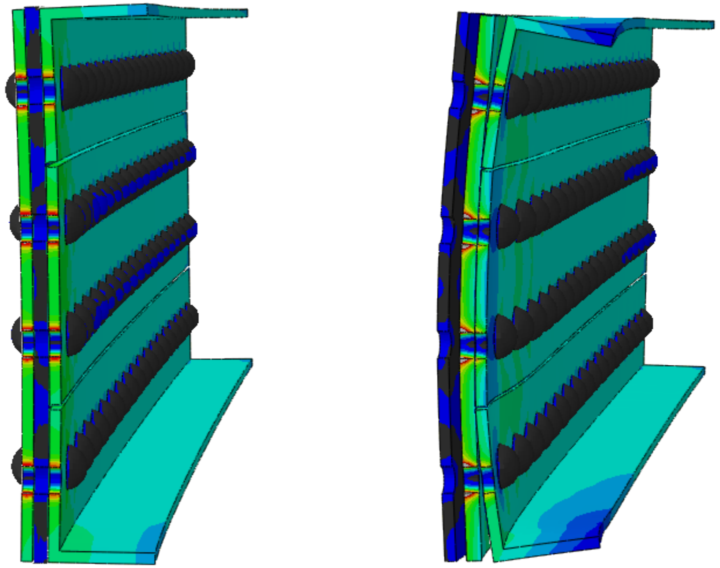
Tack-welded Component Test

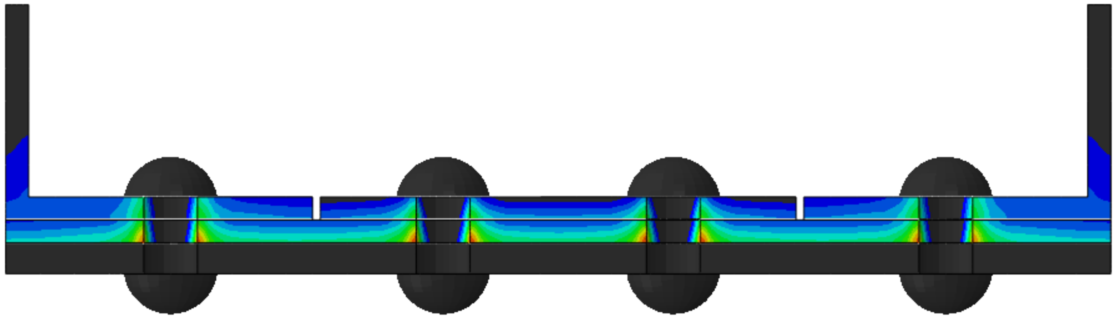
FEM-Based Parametric Study



Multi-Component parameters evaluated:

- Boundary conditions
- Fastener shear stiffness
- Web plate depth
- Web plate thickness
- Angle thickness
- Member length
- Adjacent angle leg length
- Number of web plates
- Position of failed web plate within the member
- Fastener spacing
- Fastener position relative to web plate edge

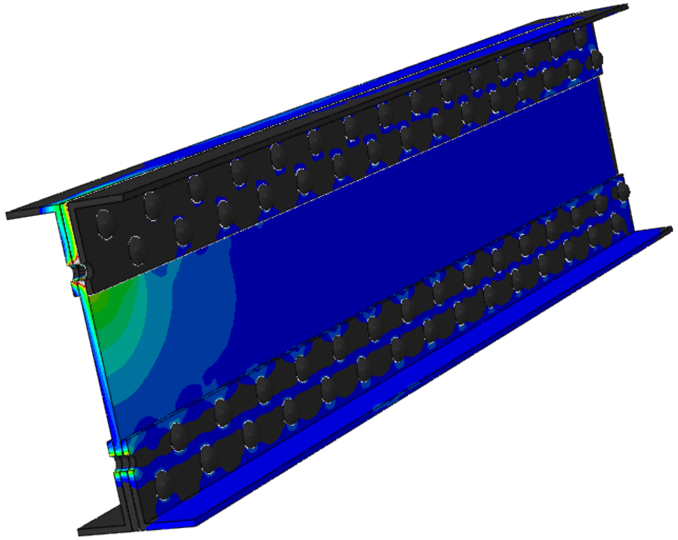




- Shear Lag Factor, Ξ_{VL}
- Bending Factor, Ξ_B

Multi-Component Members

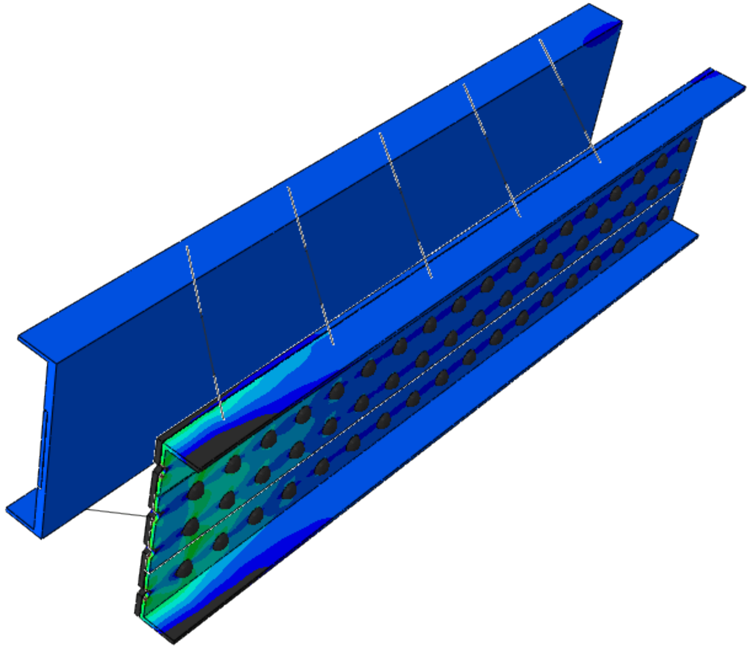
Equation for failed angle:



$$f_{AFN} = \frac{P_u}{A_N} + \frac{0.4P_{u-L}}{l_f t_p}$$

{Check when: Built-up I or A_g of Angle ≥ 1.3 A_g of plate}

Equation for failed plate:



$$f_{AFN} = \Xi_B \Xi_{VL} \sigma_{AFN\_NOM} = \Xi_B \Xi_{VL} \frac{P_u}{2A_{AFN}}$$

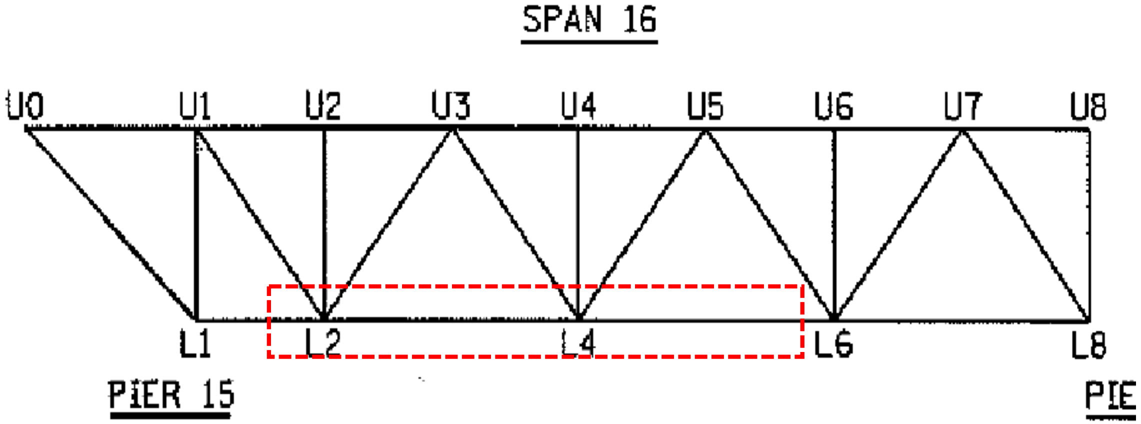
$\Xi_B = 1.04 + 0.3\left(1 - \frac{N}{6}\right)$ and $\Xi_{VL} = 1.2$

Verification of Simplified Approach:

- Proposed approach applied to all models
- Results compared to net section stresses obtained from FEM's
    - 14% of evaluated cases were underestimated (greatest was by 6%, **average was 3.7%**)
    - 86% of evaluated cases were overestimated (greatest was 23%, second was 15%, **average overestimate was 8%**)

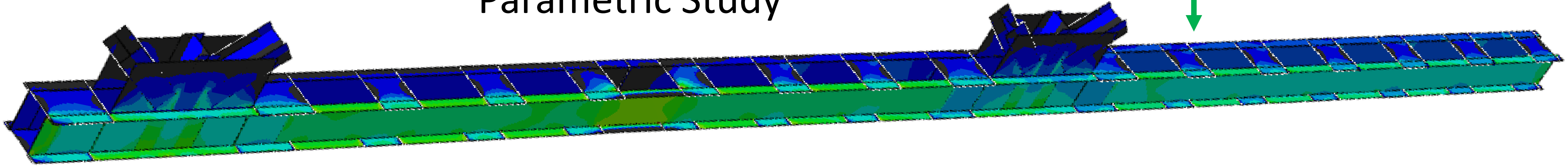
» Proposed simplified approach deemed acceptable

Two-Channel Member study is wrapping up

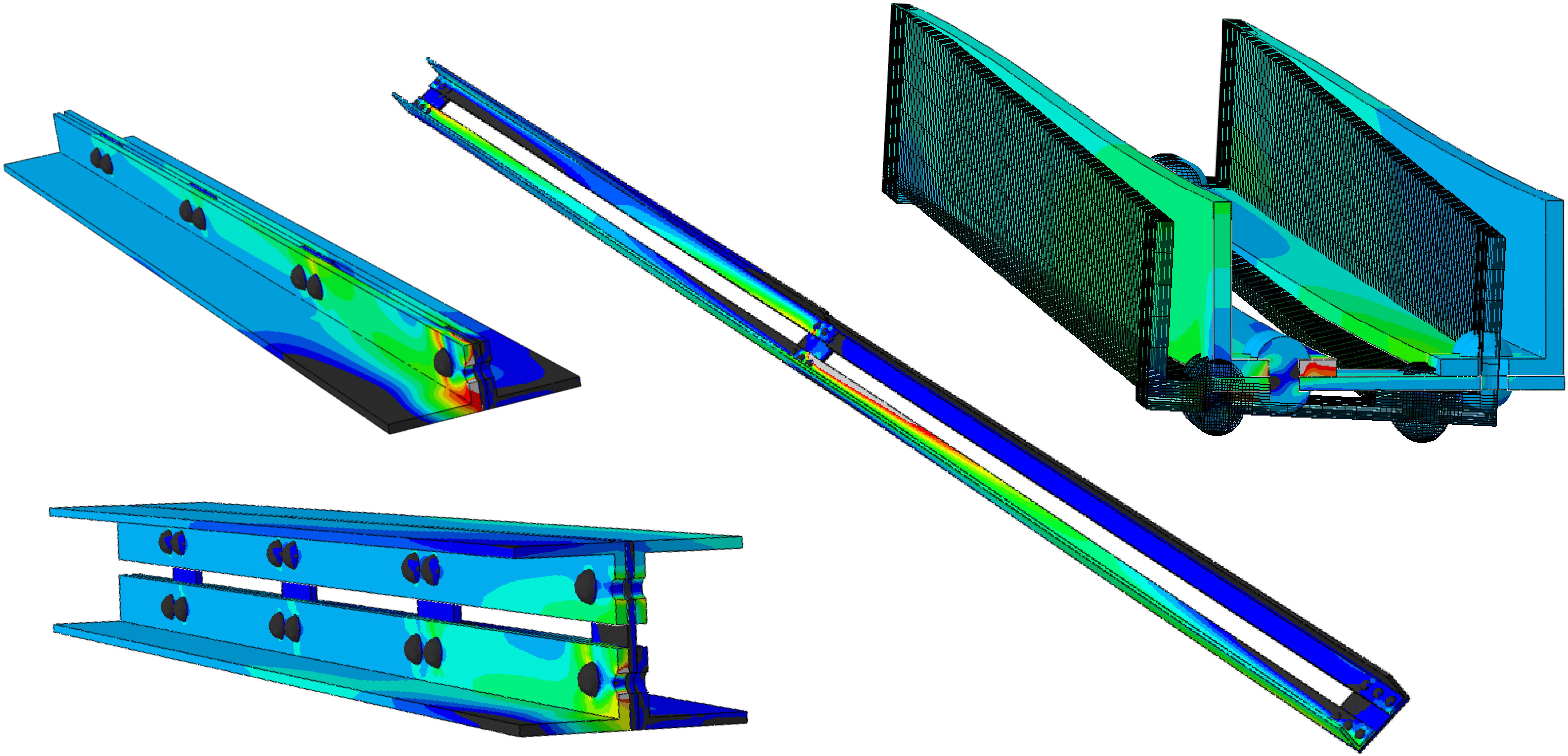


Experimental Testing

Parametric Study



Angle-Only Members study is wrapping up



IRM Example

Axial Member Analysis

Example Goals

- Illustrate analysis of a riveted truss chord with an assumed fractured web plate
- Apply rules laid out in *Guide Specifications for Internal Redundancy* Section 1.3 – Requirements for Axially Loaded Tension Members

Bridge Data

- The bridge is 90 years old (not built to AASHTO/AWS D1.5 FCP)
- $(\mathrm{ADTT})_{SL}$ = 3190, and it will be assumed that no growth occurs
- F_u=58 ksi and F_y=33 ksi
- P_{DC}= 2,050 kips
- P_{DW}= 0
- P_{LL+IM}= 1,384 kips
- $P_{FATIGUE\ II}$= 457 kips

Built-up Cross Section Limits

- Riveted Deck Truss Tension Chord
- Web is 3 full-depth plates, 1 partial depth plate, & corner angles
- 7/8” diameter rivets in holes punched full size

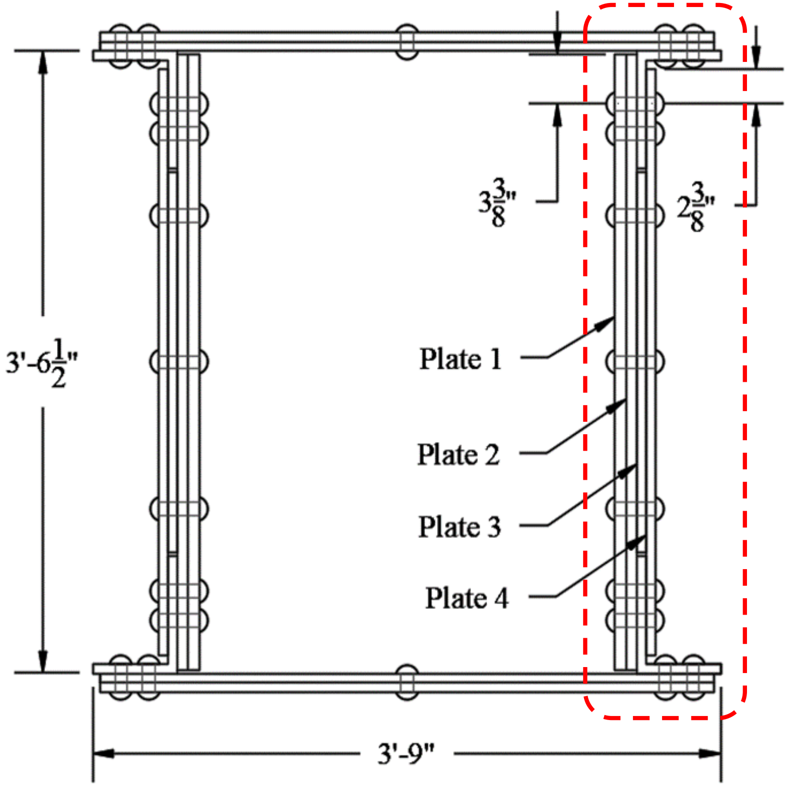
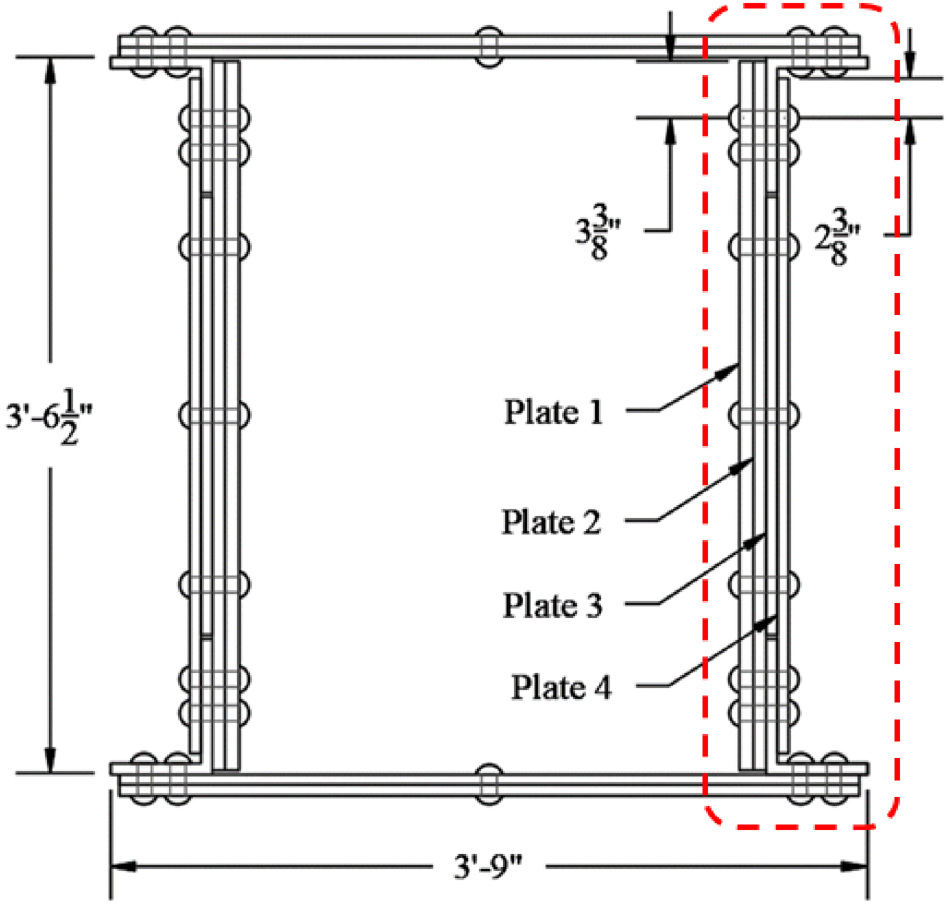


Plate 1 & 2: 42x13/16”
Plate 3: 26x5/8”
Plate 4: 40x11/16”
Angles: 8x6x5/8”

Total Member Gross Area = 257.5 in^2
Gross Area in dashed line = 128.75 in^2
Net Area in dashed line = 109 in^2

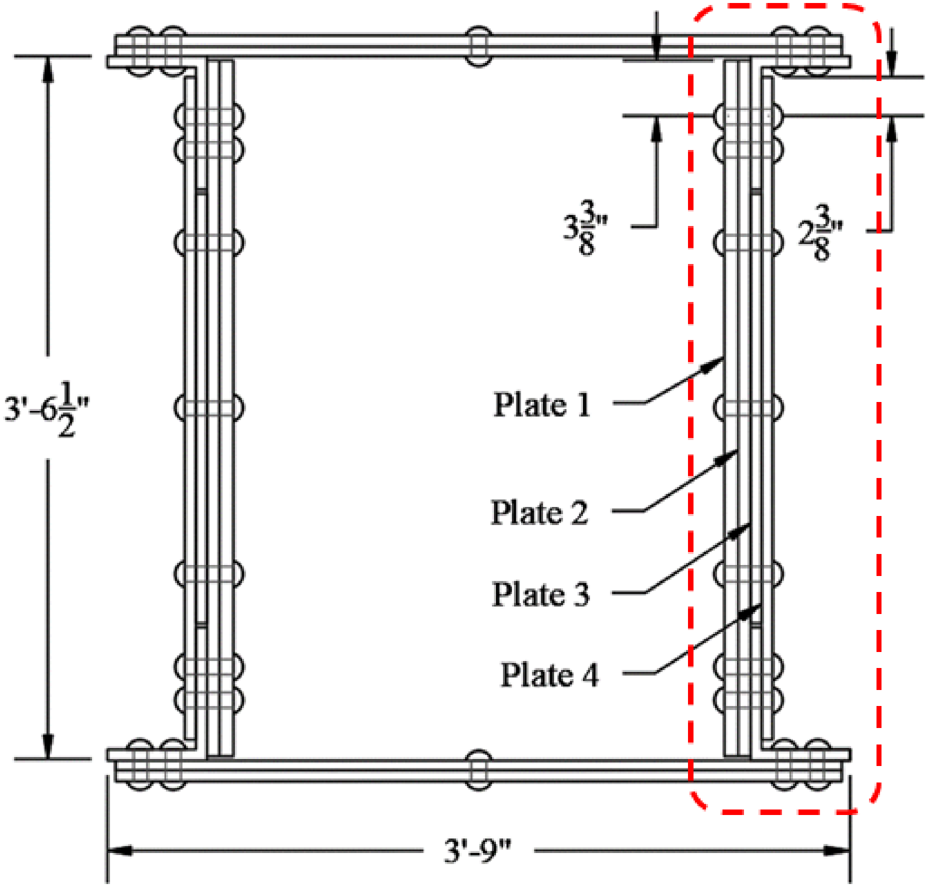
Compute Strength Amplification Factors



For all cases:

- $\Xi_B = 1.0$
- $\Xi_{VL} = 1.0$

Compute Fatigue Amplification Factors



- When $2 \leq N_{AX} \leq 6$, and the full-depth plates are not of equal thickness, then,
- For case of a failed *exterior* plate,

$$\Xi_B = 1.04 + 0.3\left(1 - \frac{N_{AX}}{6}\right) = 1.14$$

$$\Xi_{VL} = 1.2$$

- For case of a failed *interior* plate,

$$\Xi_B = 1.0$$

$$\Xi_{VL} = 1.2$$

Strength Limit State Load Combination
(GS 1.4.2)

- $\mathrm{P}_u = \gamma_{DC}\mathrm{P}_{DC} + \gamma_{DW}\mathrm{P}_{DW} + \gamma_{LL}\mathrm{P}_{LL+IM}$

Load Combination	γ_{DC}	γ_{DW}	γ_{LL}
Internal Redundancy	1.15	1.25	1.50

- $\mathrm{P}_u = 1.15(2{,}050\ \mathrm{kips}) + 0 + 1.50\ (1{,}384\ kips)$

  » $\mathrm{P}_u = 4{,}434\ kips$

Check Strength in the Faulted Condition

(GS 2.2.1 and 2.3)

- Assume Plate 1, the largest plate, fails for a conservative strength check

$$f_{AFG} = \Xi_B \Xi_{VL} \frac{P_u}{2A_{AFG}} = (1.0)(1.0)\frac{4434}{2(94.65)} = 23.4ksi$$

$$f_{AFN} = \Xi_B \Xi_{VL} \frac{P_u}{2A_{AFN}} = (1.0)(1.0)\frac{4434}{2(79.6)} = 27.8\ ksi$$

$$(f_{AFG} = 23.4\ ksi) \leq (\phi_y F_y = 0.95(33\ ksi) = \ 31.4\ ksi)$$ ✓

$$(f_{AFN} = 27.8\ ksi) \leq (\phi_u F_u = 0.80(58\ ksi) = \ 46.4\ ksi)$$ ✓

Check Fatigue (GS 2.5)

- First check for infinite life in the unfaulted state

$$\Delta f = \frac{P_{FATIGUE\ I}}{A_N} = \frac{(1000\ kips)}{218\ in^2} = 4.6\ ksi$$

- Category D resistance for riveted connections with punched holes, i.e., CAFL = 7ksi.
  - » **Therefore the detail has infinite life in the unfaulted state.**
    This is called "Case I"

- $Y_u = \infty$ (i.e. the life is infinite in the unfaulted condition)

Determine Fatigue Life in the Unfaulted State

(GS Table 2.5-2)

Condition	Unfaulted State*	Faulted State
Fully pretensioned high-strength bolts in drilled, or subpunched and reamed holes	B	C Ξ_B, Ξ_{VL} for fatigue per Table 2.2.1-1
Rivets or non-pretensioned bolts in drilled, or subpunched and reamed holes	D	C Ξ_B, Ξ_{VL} for fatigue per Table 2.2.1-1
Fasteners in punched holes (shall apply to existing members only)	**D**	E′ Ξ_B, Ξ_{VL} for fatigue per Table 2.2.1-1

Evaluate Fatigue After Hypothetical Fracture

- Consider the hypothetical fracture of Plates 1, 2, or 4

$(\Delta f)_{eff} = R_s \Delta f_{AFN}$ where R_s = 1.0

- For fracture of Plate 1, A_{AFN} = 79.6 in^2 (i.e., 109 in^2 – 29.4 in^2)

$$\Delta f_{AFN} = \Xi_B \Xi_{VL} \frac{P_{FATIGUE\ II}}{2A_{AFN}} = (1.14)(1.2)\frac{(457\ kips)}{(2)79.6\ in^2} = 3.9\ ksi$$

- For fracture of Plate 2, A_{AFN} = 79.6 in^2

$$\Delta f_{AFN} = \Xi_B \Xi_{VL} \frac{P_{FATIGUE\ II}}{2A_{AFN}} = (1.0)(1.2)\frac{(457\ kips)}{(2)79.6\ in^2} = 3.4\ ksi$$

- For a fracture of Plate 4 (not shown) = 3.6 ksi

Check for Infinite / Finite Life After Fracture

- From the prior slide, the max effective stress range is Δf_{eff} = 3.9 ksi

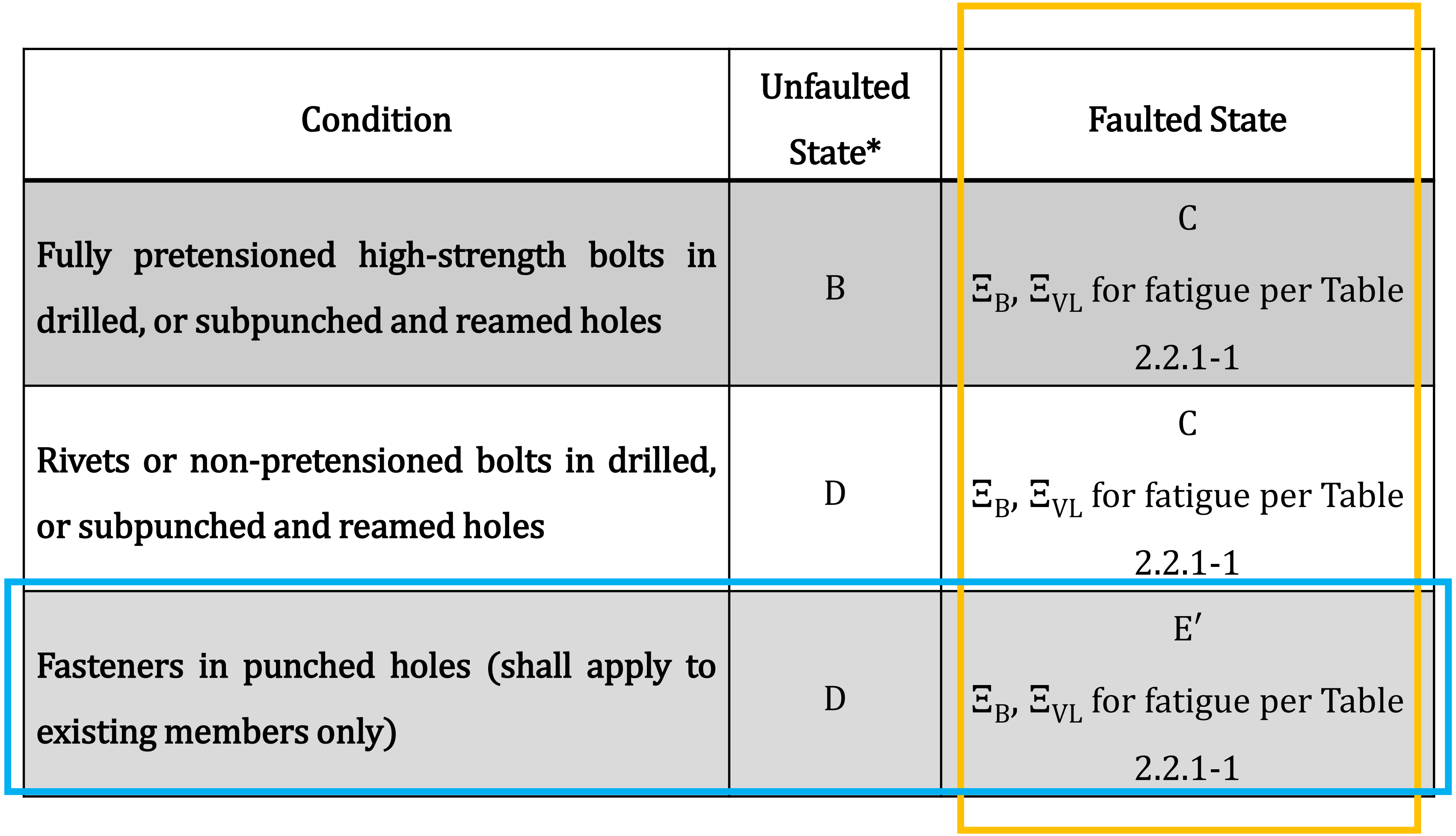
» Therefore the maximum stress range is found approximately as:

$$(\Delta f\, AFN)_{max} = 2.2(\Delta f_{AFN})_{eff} = 2.2(3.9\; ksi) = 8.58\; ksi$$

- The threshold for riveted connections in punched holes in the faulted state is Cat E’, i.e. CAFL = 2.6 ksi

» The member does not have infinite life in the faulted condition

Determine Fatigue Life in the Faulted State
(GS Ta 2.5-2)



Condition	Unfaulted State*	Faulted State
Fully pretensioned high-strength bolts in drilled, or subpunched and reamed holes	B	C Ξ_B, Ξ_{VL} for fatigue per Table 2.2.1-1
Rivets or non-pretensioned bolts in drilled, or subpunched and reamed holes	D	C Ξ_B, Ξ_{VL} for fatigue per Table 2.2.1-1
Fasteners in punched holes (shall apply to existing members only)	D	E′ Ξ_B, Ξ_{VL} for fatigue per Table 2.2.1-1

Find the Finite Fatigue Life (from MBE)

- Compute the **finite life in the faulted condition** using the following:

$$Y_f = \frac{R_R A}{365n[ADTT_{SL}]\left[\Delta f_{eff}\right]^3}$$

- Where:
  - $R_R = 1.0$ (Minimum Life, MBE Table 7.2.5.2-1);
  - $A = 3.9 \cdot 10^8\ ksi^3$ for a Category E’ detail
  - $n = 1.0$ (MBE 7.2.5.2, LRFD Design Table 6.6.1.2.5-2);
  - $(ADTT)_{SL} = 3190$;
  - $(\Delta f)_{eff} = 3.9\ ksi$

Find the Finite Fatigue Life

- Compute the finite life in the faulted condition (from previous slide):

$$Y_f = \frac{R_R A}{365n[ADTT_{SL}]\left[\Delta f_{eff}\right]^3} = \frac{1.0\ x\ 3.9 \cdot 10^8}{365(1)[3190][3.9ksi]^3} = 5.65\ years$$

Compute the Inspection Interval

- $N_f = Y_f \left(1.0 - \frac{N_u}{Y_u}\right)$

Where,

- Y_f = 5.65 years
- N_u = 90 years
- $Y_u = \infty$

» $N_f = 5.65\left(1.0 - \frac{90}{\infty}\right) = 5.65\ years$

Compute the Inspection Interval

- $N_f = 5.65\ years \ \rightarrow\ N_f < 20\ years\ \rightarrow Max.Interval = 0.5N_f = 2.83\ years$
- This is permitted to be rounded up to the next even year interval, i.e. 4 years
- **Conclusion – *special* inspection interval not to exceed 4 years**

Implementing New Approaches to Fracture Critical Members

Steps Needed to Implement

- Adoption by AASHTO of the approaches presented
  - AASHTO Committee on Bridges and Structures
  - Annual meeting June 24th – 28th, 2018
- Revision to current FHWA memo clarifying FHWA policy
  - Current version dated June 20th, 2012
  - Prohibits Internal Redundancy as a means of avoiding FCM designation

Adoption by AASHTO

- Currently being considered by:
  - Technical Committee 14 – Steel Bridges
  - Technical Committee 18 – Bridge Management, Evaluation, and Rehabilitation
- Proposed as Guide Specifications:
  - “AASHTO Guide Specifications for Analysis and Identification of Fracture Critical Members and System Redundant Members”
  - “AASHTO Guide Specifications for Internal Redundancy of Mechanically-fastened Built-up Steel Members”

Guide Specifications

- Are not compulsory, unless adopted by a State
- Often times serve as a stepping stone to inclusion in the LRFD Bridge Design Specifications
- Examples of current Guide Specifications:
  - Guide Specifications for LRFD Seismic Bridge Design
  - LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings
  - Guide Specifications for Bridges Vulnerable to Coastal Storms
  - LRFD Guide Specifications for the Design of Pedestrian Bridges

Guide Specification Status

- Both are on the agenda for the June Committee on Bridges and Structures meeting
- Technical Committees will need to move them to ballot
- General Session votes to adopt
- Published versions would be available in early 2019

FHWA Memo on FCM Policy

- Revisions needed to allow for Internally Redundant Members to qualify as Non-FCM
- Currently under consideration by FHWA

Today's Participants

- Frank Bonachera Martin, *Purdue University,* fbonache@purdue.edu
- Rob Connor, *Purdue University,* rconnor@purdue.edu
- Matt Hebdon, *Virginia Tech,* mhebdon@vt.edu
- Jason Lloyd, *Purdue University*, lloyd1@purdue.edu
- Tom Murphy, *Modjeski and Masters,* TPMurphy@modjeski.com

Get Involved with TRB

- Getting involved is free!
- Join a Standing Committee (http://bit.ly/2jYRrF6)
- Become a Friend of a Committee (http://bit.ly/TRBcommittees)
  - Networking opportunities
  - May provide a path to become a Standing Committee member
  - ***Sponsoring Committee: AFF20***
- For more information: www.mytrb.org
  - Create your account
  - Update your profile

Receiving PDH credits

- Must register as an individual to receive credits (no group credits)
- Credits will be reported two to three business days after the webinar
- You will be able to retrieve your certificate from RCEP within one week of the webinar