

Understanding Resilience & Reserve Capacity of Riveted Girders

Matthew H. Hebdon, PhD, PE – Virginia Tech

Robert J. Connor, PhD – Purdue University

Iron & Steel Preservation Conference

May 18, 2016



Contributors

◎ TPF 5(253) funded by:

Indiana DOT	Iowa DOT	Minnesota DOT
New York DOT	Oregon DOT	Wisconsin DOT
Wyoming DOT	US Army Corps of Engineers	FHWA

◎ Industry Partners

Steel Dynamics	Hirschfeld Industries Bridge	Nucor Fastener	TVA
----------------	------------------------------	----------------	-----

Redundancy of Built-up Members

- ◎ Internal redundancy widely recognized in built-up members
 - Based on historical performance
 - AASHTO Manual for Bridge Evaluation
- ◎ Current regulations classify 2-member built-up systems as 'Fracture Critical'



Redundancy of Built-up Members

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



Lovejoy, 2001

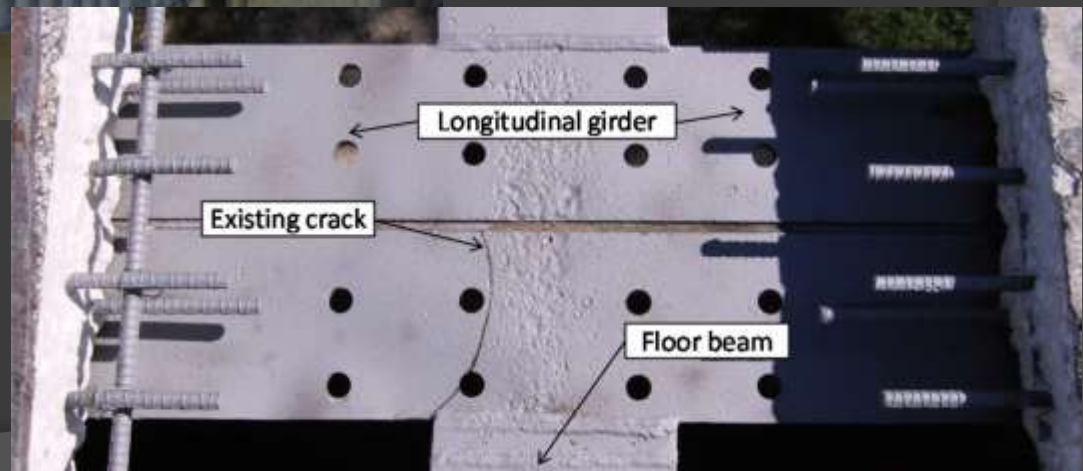


Redundancy of Built-up Members

- ◎ Texas – 2 Girder Bridge
 - Fatigue through cracks in flange angle of built-up member (negative moment region)

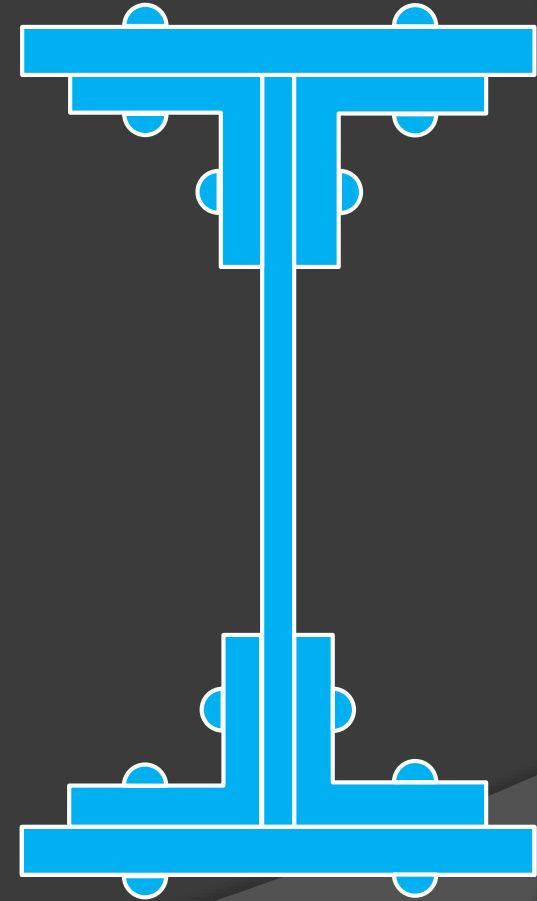


Fasl, 2013



Research Objectives

- Show that built-up sections are fracture-resilient
- Can partially failed built-up members support design loads?
- Evaluate effect on remaining fatigue life in partially failed state
 - How long until next component fails



Research Process



Historical specimens



Newly fabricated specimens

Research Process

● Riveting of Specimens



Research Process



Research Process

⦿ Experimental Tests

- 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 → lower shelf behavior
- Load to induce a fracture
 - $0.55 F_y$ (Minimum)
- Examine stress redistribution
- Determine fatigue life

Research Process

(15 specimens)

Specimen Height	Failed 1 st 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	

Experimental Testing

Conditions required for Fracture:

- ◎ All material on lower shelf
 - Single digit ft-lbs
 - Test temperature -60F (warmest temp)
 - As low as -120F
- ◎ Applied stress = $0.55 F_y$ (MINIMUM)
- ◎ Substantial portion of component cracked
 - Greater than critical crack length per LEFM
- ◎ VERY challenging to obtain brittle fracture from cracked component
- ◎ Multiple attempts as crack length increased

Experimental Testing

Conditions required for Fracture:

- Load shedding
- Had to get creative
 - Initial notches at holes
 - Moved notches to edges
 - Driven wedges
 - Removal of Fasteners near crack
 - Decrease constraint at crack tip
 - Increase strain energy



Experimental Testing

● Driven wedges



Experimental Testing

● Fracture resilience

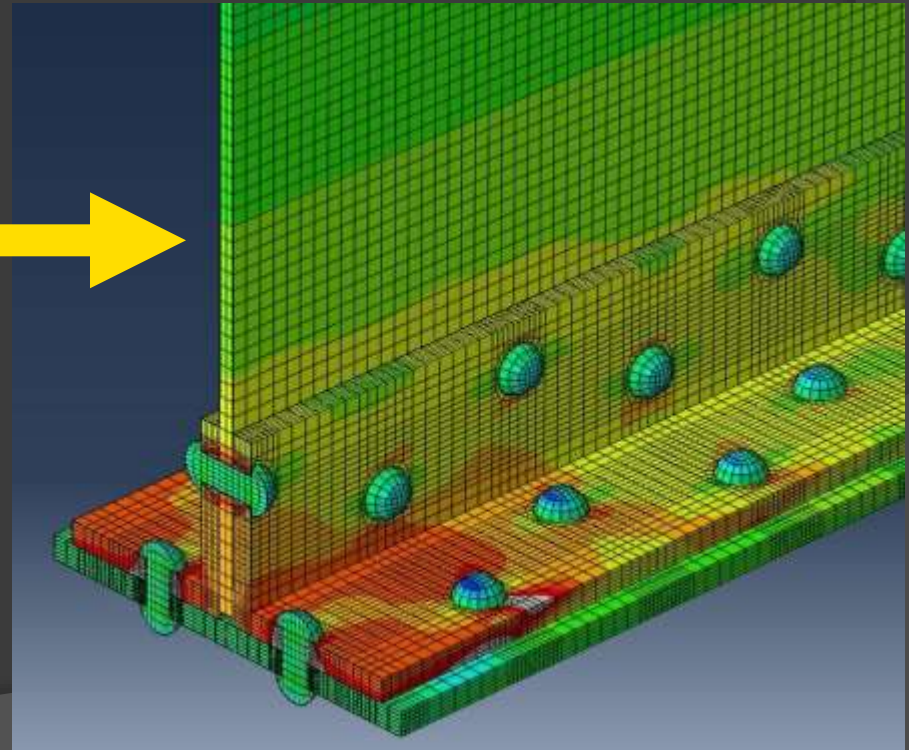
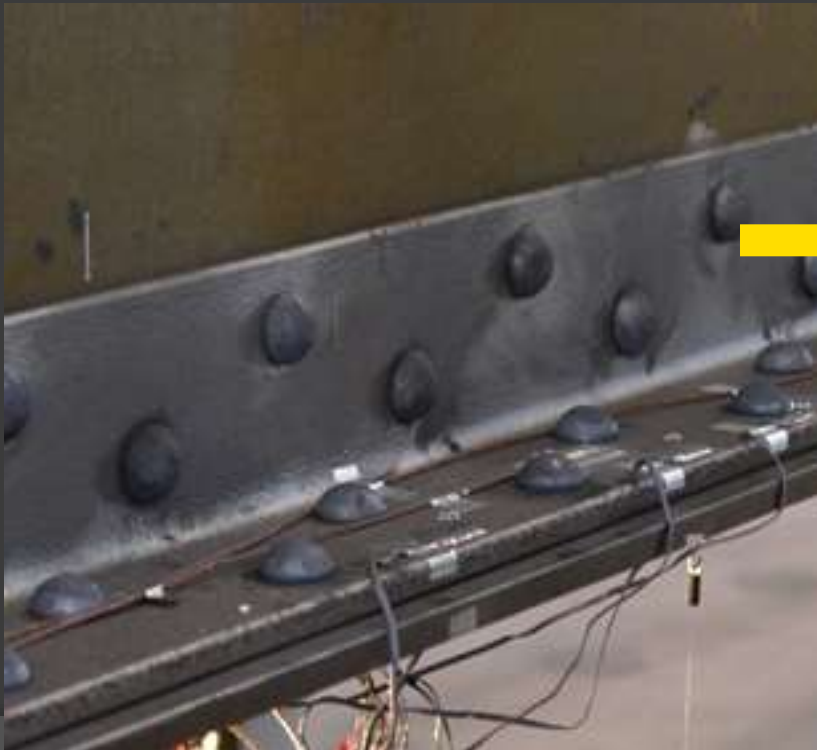


Experimental Testing

- ⦿ Fracture Resilience
- ⦿ What are the limits?
 - Proportions of bottom flange components
 - Fatigue cracks introduced to ALL components
- ⦿ Catastrophic failure ONLY a concern if:
 - Abnormal proportions AND extensive fatigue history

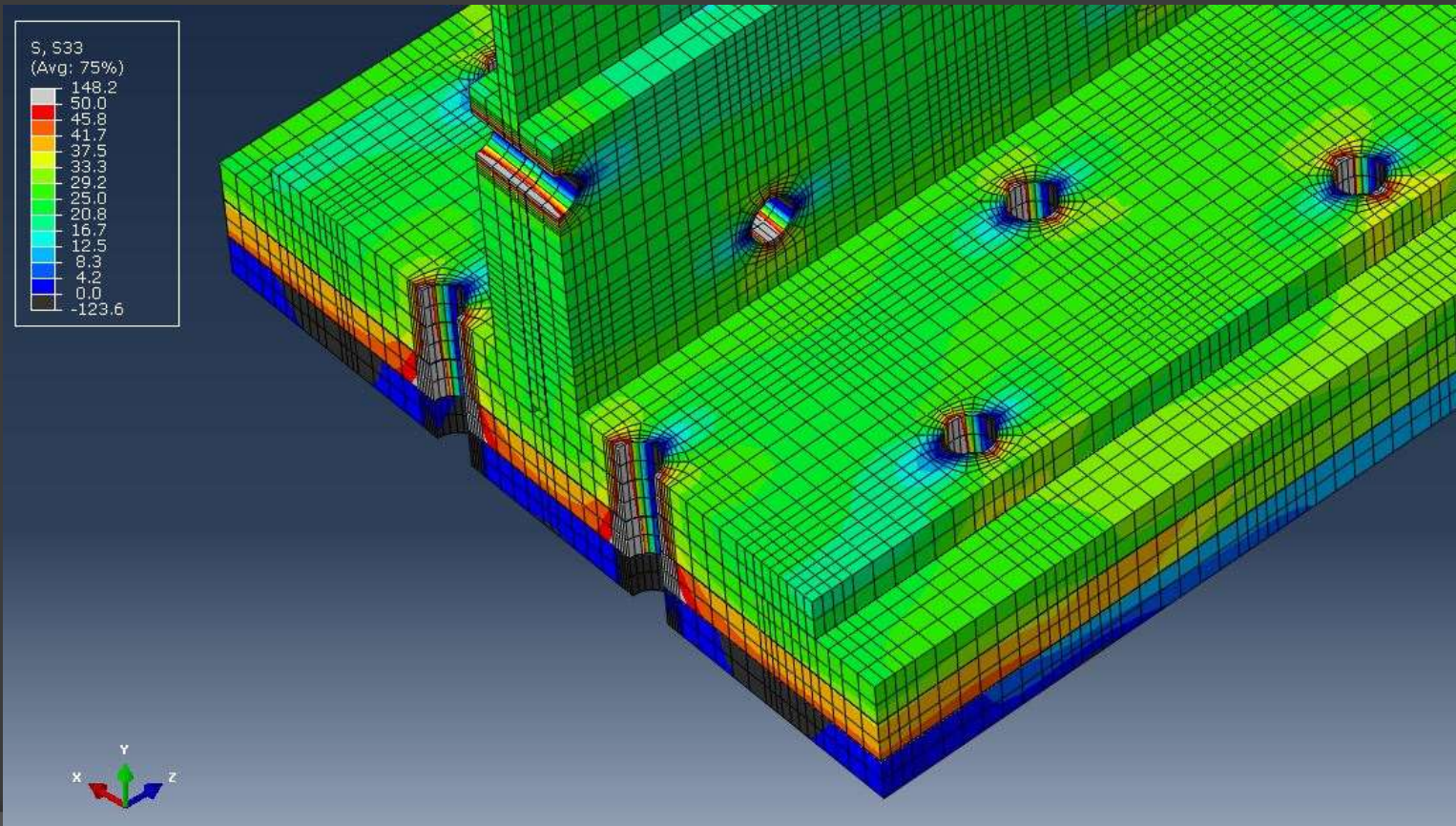
Analytical Evaluation

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



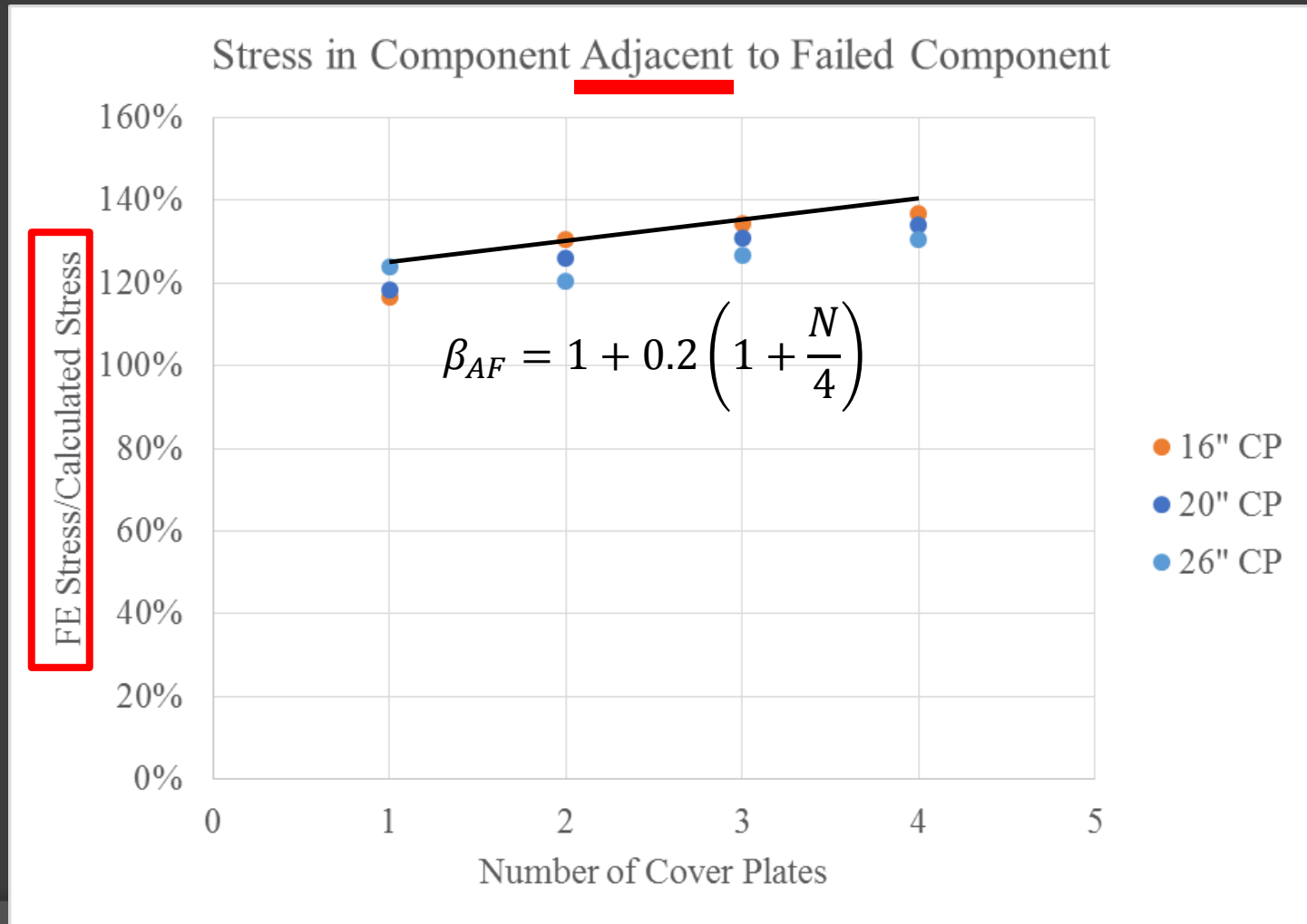
Analytical Evaluation

● Parametric Study: Number of cover plates



Analytical Evaluation

Effect of # of CPs on Stress Amplification



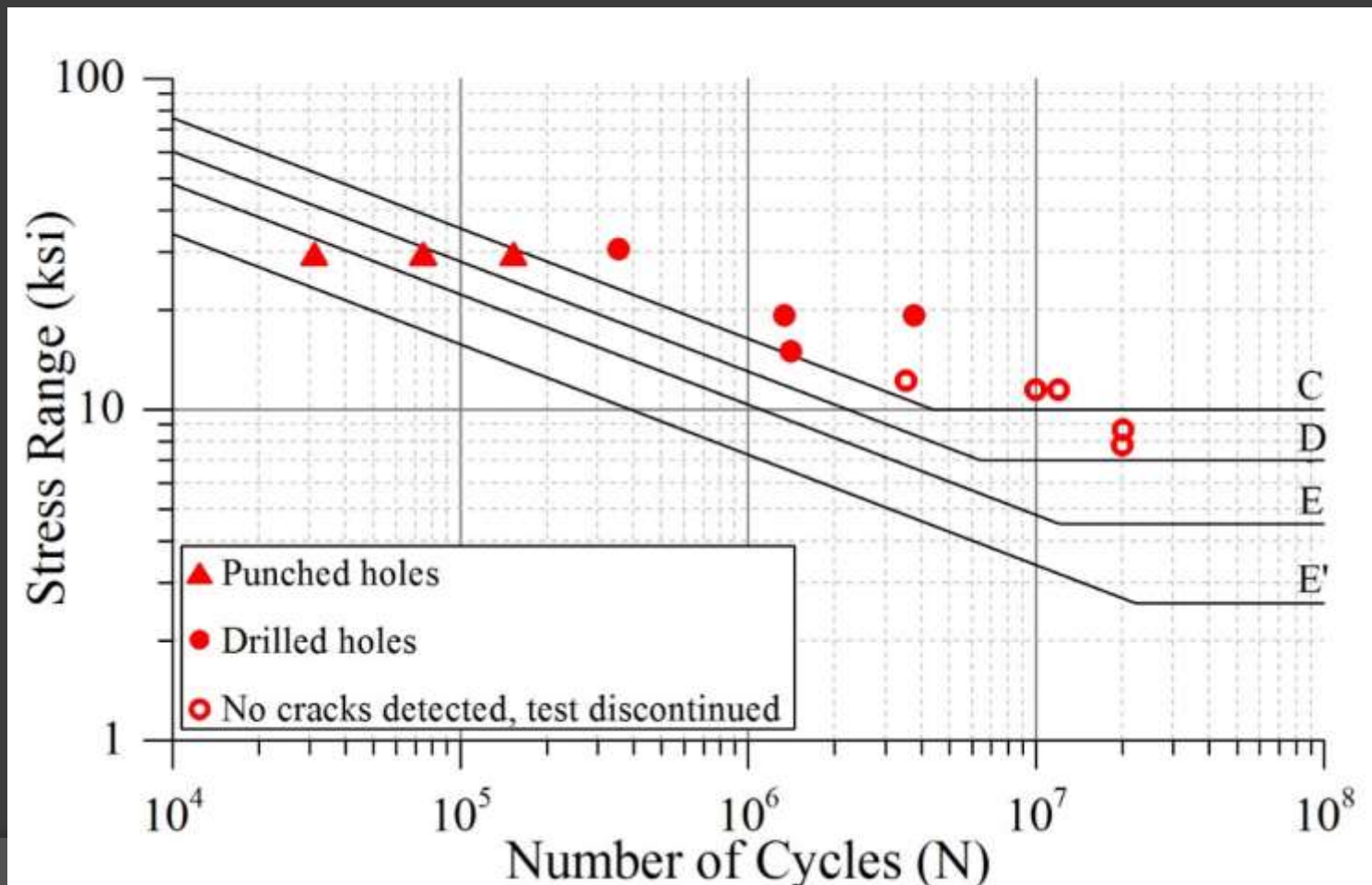
Experimental Testing: Phase 2

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



Experimental Testing: Phase 2

● Fatigue life of partially failed cross-sections



Implementation

- Guidelines for Evaluation
- Determine capacity of partially failed built-up section
- Determine remaining fatigue life
 - Influenced by prior fatigue history and fatigue life of partially failed cross-section
- Recommend procedure for setting a rational hands-on inspection interval based on results

2—Performance in the Faulted State		
2.1—Calculated Stress in the Faulted State		C2.1
The calculated flange stress acting on the net and gross section of the faulted member shall be calculated as follows:		The section modulus in the faulted state is calculated by subtracting the area of the component assumed to be fractured. When a single angle is assumed to have failed, full-scale testing and FEA has demonstrated there is no need to consider secondary lateral bending due to the presence of an unsymmetrical cross-section (Hebdon 2015).
$f_{AFN} = \beta_{AF} \frac{M_u}{S_{N-AFN}}$	(2.1-1)	Research shows that the number of cover plates affects the distribution of stress in the remaining components, and that the components closest to the failed component have the largest increase in stress (Hebdon, 2015). The cover plate adjustment factor, β_{AF} , accounts for this effect. While the cover plate adjustment factor was developed based on an assumed failure of the outer cover plate, it is conservative to apply this factor when an interior cover plate is assumed to have failed.
$f_{AFG} = \beta_{AF} \frac{M_u}{S_{G-AFG}}$	(2.1-2)	
in which:		
β_{AF} = cover plate adjustment factor = $1 + 0.2 \left(1 + \frac{N}{4}\right)$		(2.1-3)
where:		
f_{AFN} = net-section stress in the faulted state (ksi)		
f_{AFG} = gross-section stress in the faulted state (ksi)		
S_{N-AFN} = elastic section modulus of the net section of the member in the faulted state including the effect of fastener holes (in ³).		
S_{G-AFG} = elastic section modulus of the gross section of the member in the faulted state (in ³)		
M_u = factored moment determined from Eq. 1.1-1 (kip-ft)		
N = number of cover plates on the tension flange		
2.2—Strength Criteria		C2.2
Gross section yielding and net section fracture shall be checked according to Eq. 2.2-1 and 2.2-2 to ensure that the member has sufficient strength in the faulted state.		The assumption is made herein that the section cannot develop the full plastic moment capacity of the unfaulted section in the faulted state.
The stresses in the faulted condition, calculated in accordance with Article 2.1, shall satisfy the following:		
$f_{AFG} \leq \phi_y F_y$	(2.2-1)	
and:		
$f_{AFN} \leq \phi_u F_u$	(2.2-2)	

Conclusions

- ⦿ Member-level redundancy of built-up steel girders
- ⦿ Fracture-resilience
- ⦿ Significant fatigue life in partially-failed condition
- ⦿ Evaluation guidelines:
 - Determine remaining capacity
 - Set an appropriate hands-on inspection interval

Questions

