CIVIL & ENVIRONMENTAL ENGINEERING
UNIVERSITY of WASHINGTON

Triage Evaluation of Truss Bridge Gusset Plate Connections

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Western Bridge Engineers' Seminar

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Motivation

- Develop an approach that is:
  – Safe
  – Consistent
  – Fast
  – Conservative (but not overly)

Triage Evaluation Procedure for Gusset Plates

- Recognizing that we are looking for a needle in the haystack

Overview

Review FHWA Load Rating Procedure

Present Proposed Triage Evaluation Procedure

Development of Triage Yield Check

Descriptions of Gussets Studied

Descriptions and Validation of Detailed FE Models

Development of Triage Buckling Check

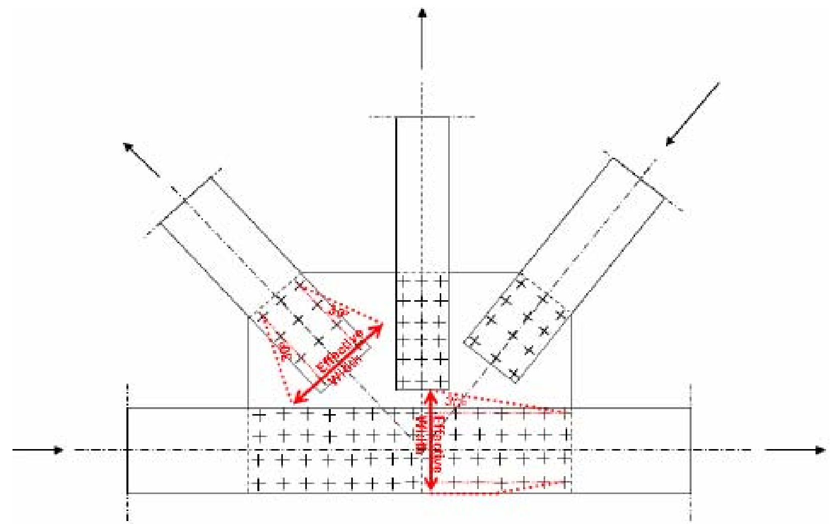
Application of Triage Procedure to WSDOT Bridges and Comparison with FHWA

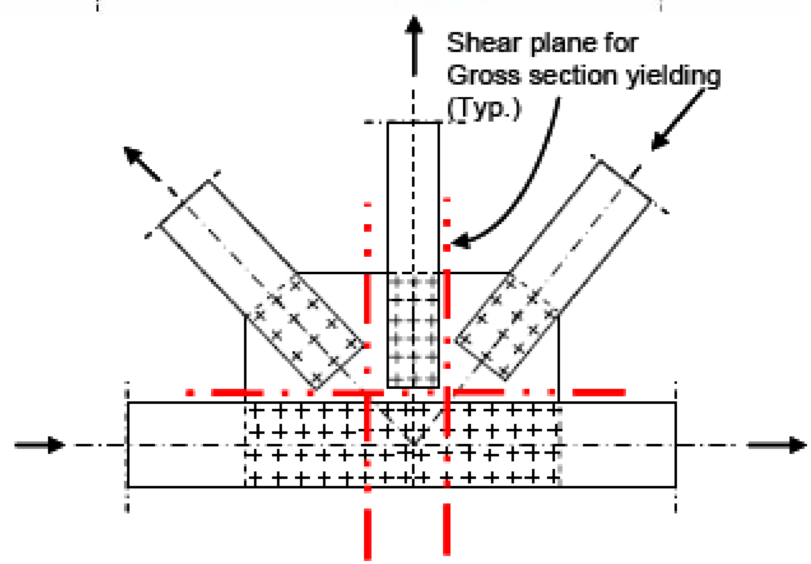
FHWA Load Rating Procedure

- Recommended at “strength” limit state
- Owners may perform checks at other limit states (i.e., serviceability)
- Limit states considered:
  - Rivet shear
  - Gross yielding and net section fracture on the Whitmore section
  - Block shear
  - Compressive buckling
  - Gross shear yielding and net section shear fracture
    - Requires use of loads in equilibrium (Concurrent truss element loads)

$$V_n = 0.58 F_y A_g \Omega \qquad V_n = 0.58 F_u A_n$$

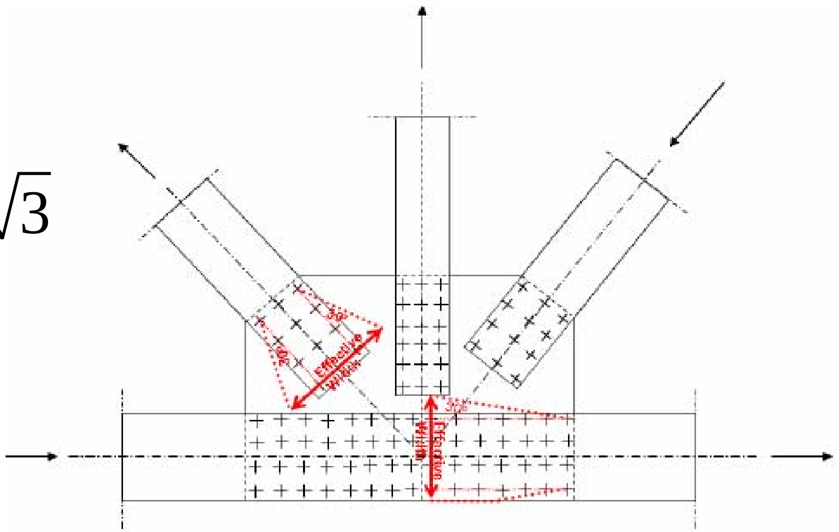
- Ω = 1.0 if the gusset can develop the plastic shear and 0.74 otherwise

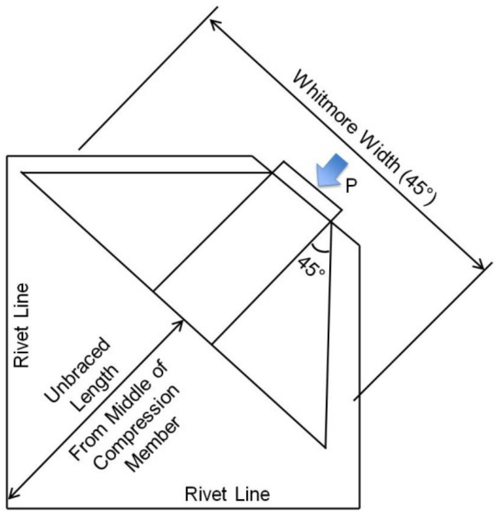




Proposed Triage Evaluation Procedure

- At service loads
- Check for onset of yielding:
  - Maximum Whitmore stress $< F_y / \sqrt{3}$
  - Tension and compression
- Check for buckling:
  - Use 45° Whitmore
  - Use centriodal length with K = 1.0
  - Rarely governs over yielding
- Check rivets

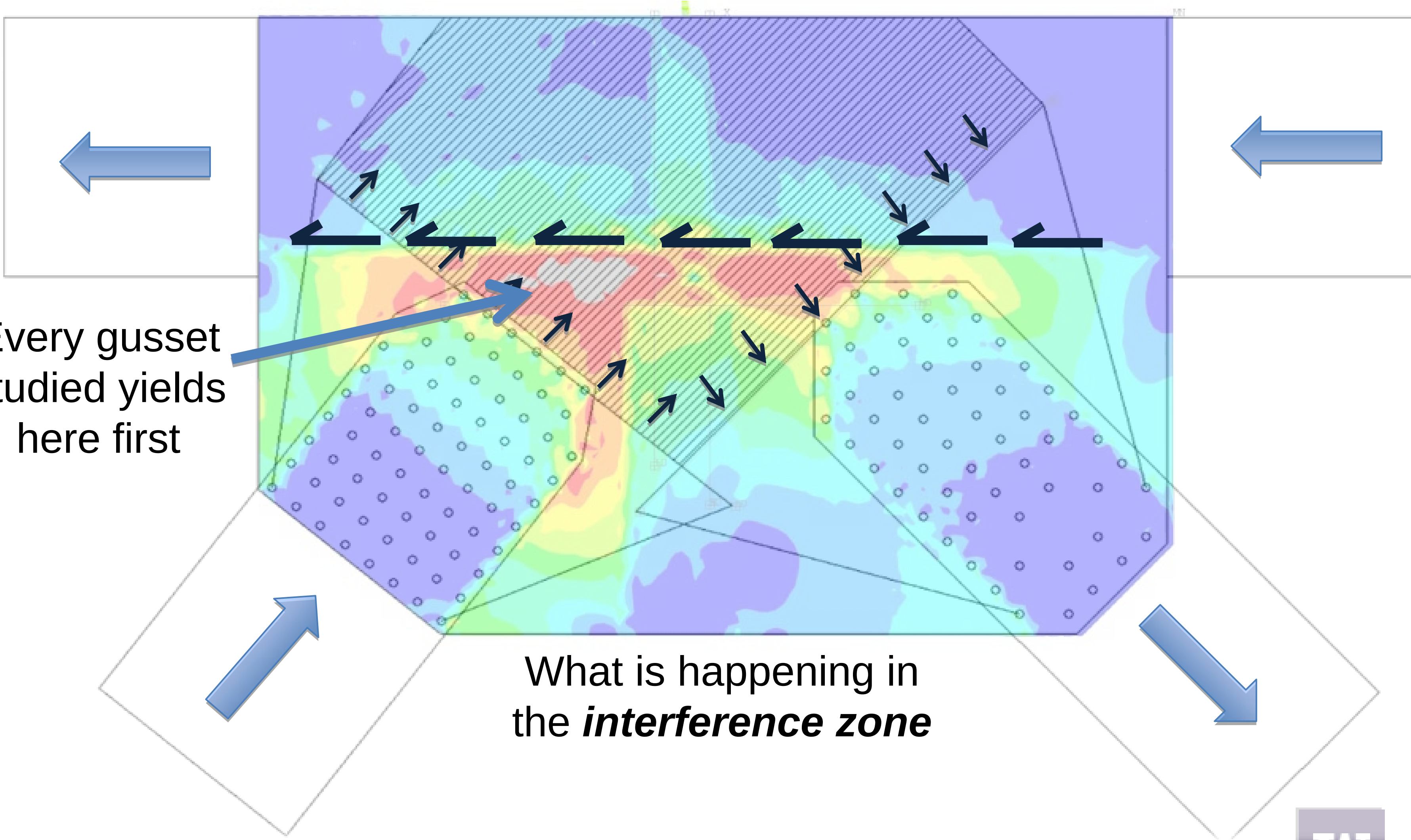




Developing the Triage Procedure

- Yielding:
  - Derive evaluation method to predict yielding considering stress interactions
  - FE models of selected gusset plates
  - Compare results of evaluation method with FE results
  - Demonstrate the proposed check conservatively indicates yielding
- Buckling (Time Constraints – Not Discussed Here):
  - Review established methods for predicting gusset buckling
  - Parametric study of selected gussets with FE models
  - Compare results of established methods with FE results
  - Select an established method
- Ensure the triage check is versatile and not overly conservative
- Compare demand to capacity ratios with those from FHWA procedures

Triage Evaluation Procedure: Yield Check Development

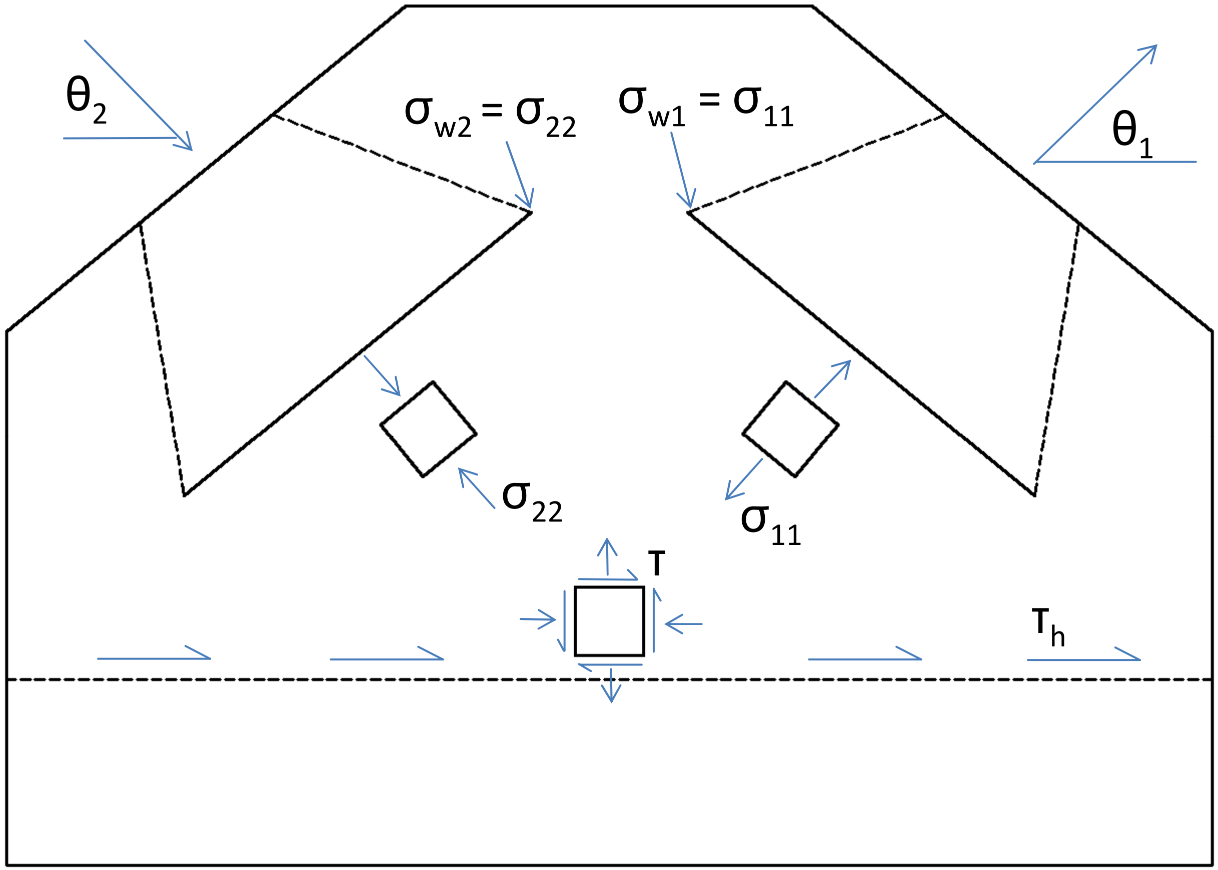


Every gusset studied yields here first

What is happening in the *interference zone*

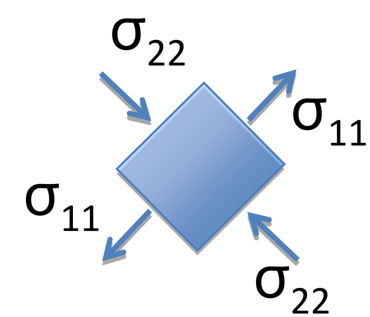
Triage Evaluation Procedure: Yield Check Development

- Consider the interaction between stresses from the diagonals
- Assume that Whitmore stresses are uniaxial at member ends
- Horizontal shear stress is from the difference between chord loads



Stress Condition

Triage Evaluation Procedure: Yield Check Development



- Assumes worst possible stress case:
  - $\theta_1 = \theta_2 = 45°$ (i.e., σ_{11} and σ_{22} are orthogonal, τ at θ_1 is zero, and τ_h = maximum shear)
  - σ_{11} and σ_{22} are equal and opposite and principle
  - Von Mises yield condition: $\sqrt{\sigma_{11}{}^2 + \sigma_{22}{}^2 - \sigma_{11}\sigma_{22} + 3\tau_{12}} = \sigma_y$
  - For above assumptions and 2D: $\sqrt{3}\sigma_{11} = \sigma_y$
- Proposed Triage Procedure Yield Check:
  - Check for element with largest Whitmore stress:

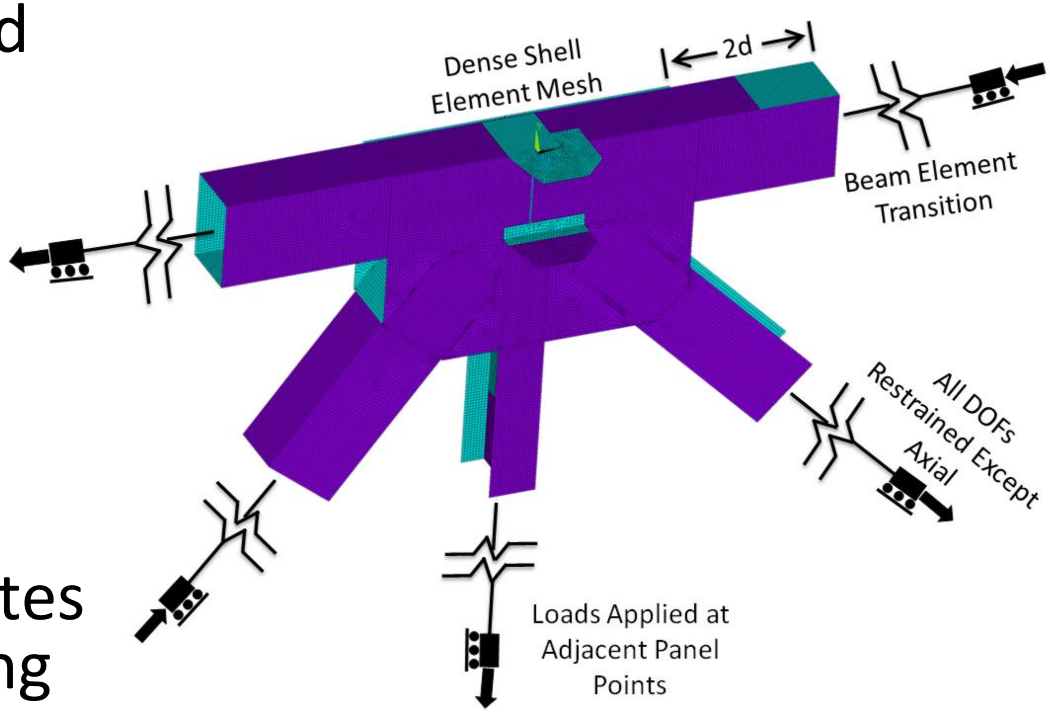
$$\sigma_{wh} < \frac{\sigma_y}{\sqrt{3}}$$

FE Modeling

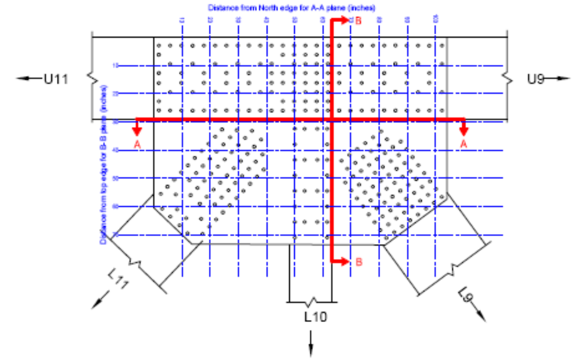
- Modeled 6 joints in detail with ANSYS:
  - Different geometries (6 gussets, 4 described here)
  - Load distributions
    - Point in time load distributions used such that each member to connected a gusset was a maximum value in one load case
- *Validation* of modeling approach:
  - Compare U-10 analysis results with results from Ocel and Wright (2008)
  - Mesh refinement
- Yielding:
  - Onset of significant yielding
  - 4 gussets x 4 or 5 load cases = 19 cases studied
- Buckling:
  - 3 or 4 gusset thicknesses for each connection = 70+ cases studied

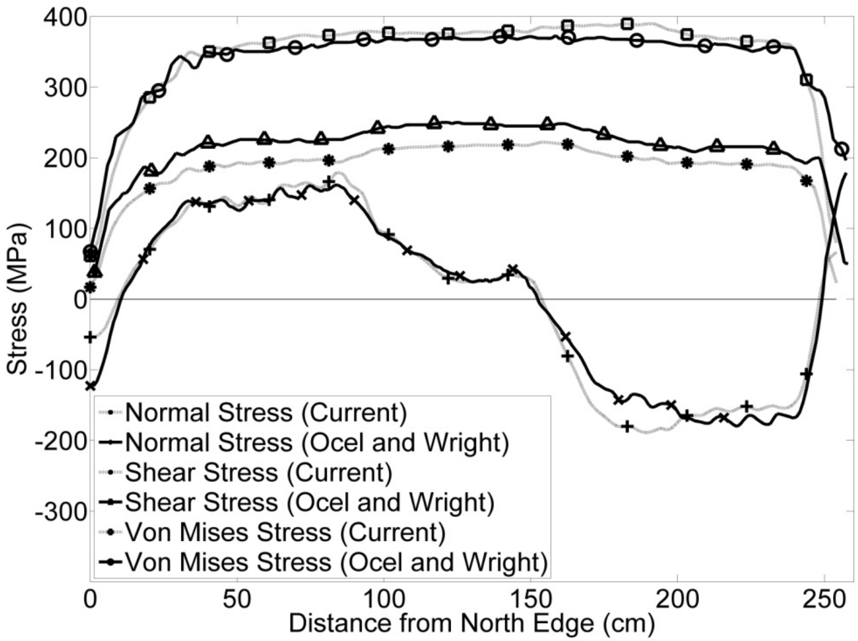
Modeling Approach

- 3D model using shell and beam elements
- Nonlinear analysis
  - Nonlinear materials
  - Nonlinear geometry
- Boundary conditions
- Rivets assumed rigid
- No contact between plates (conservative for buckling later)
- Mesh refinement used to establish mesh density

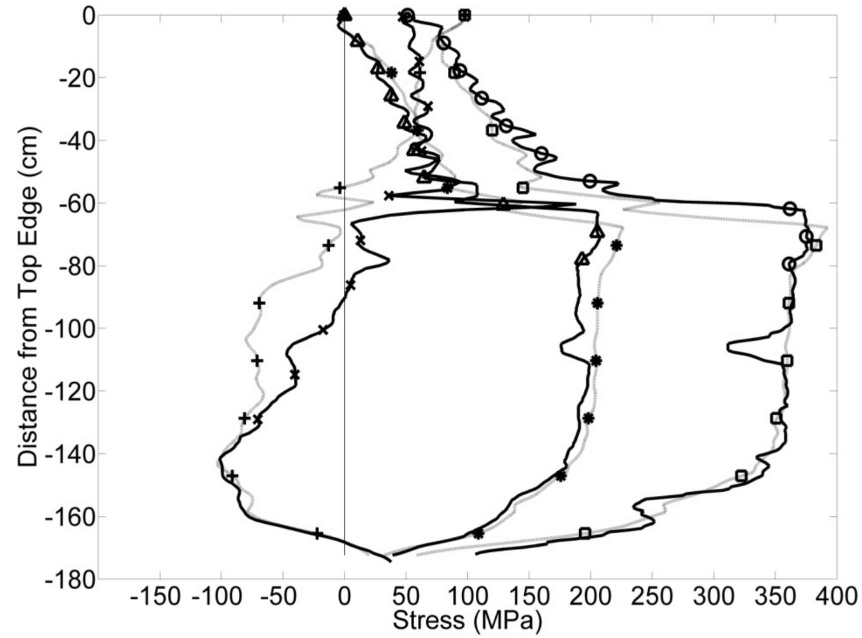


Comparison with FHWA Analyses (I-35 U10)



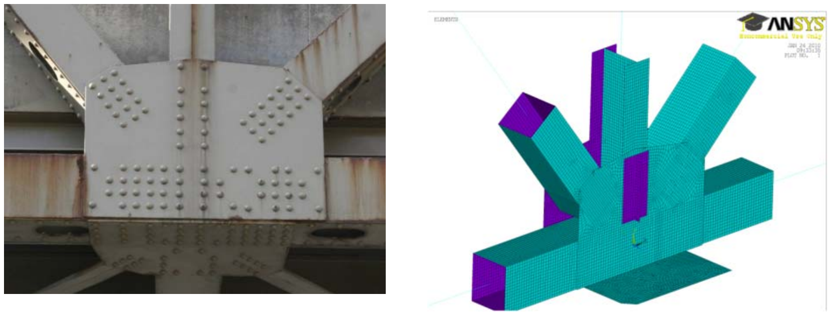


Line A-A

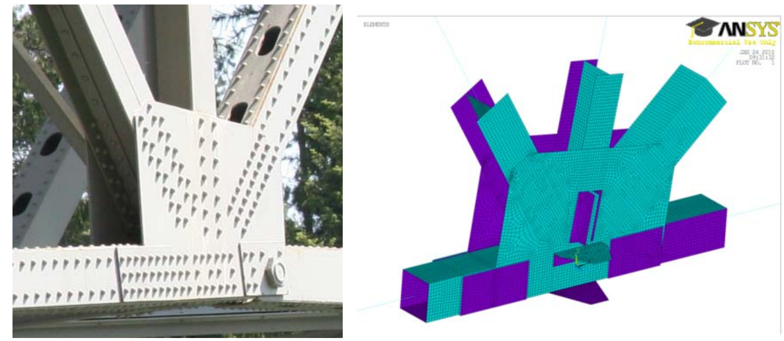


Line B-B

Selected for Joints for Detailed Analysis

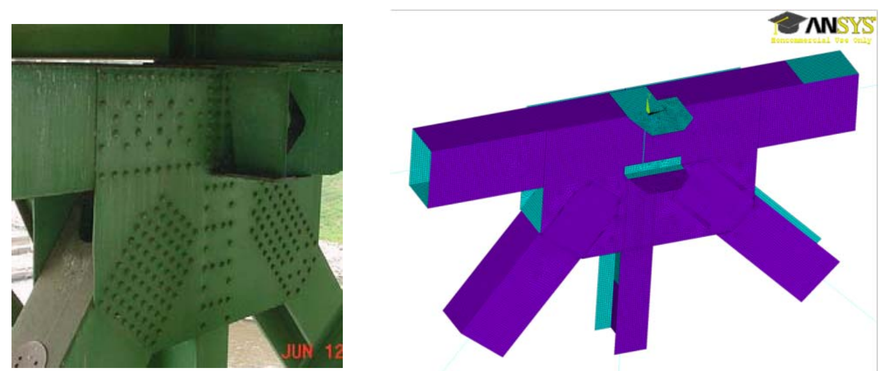


- Joint L2 of WSDOT BR 90-134N
- 1949, t = 0.5”, Silicon Steel F_y = 45 ksi



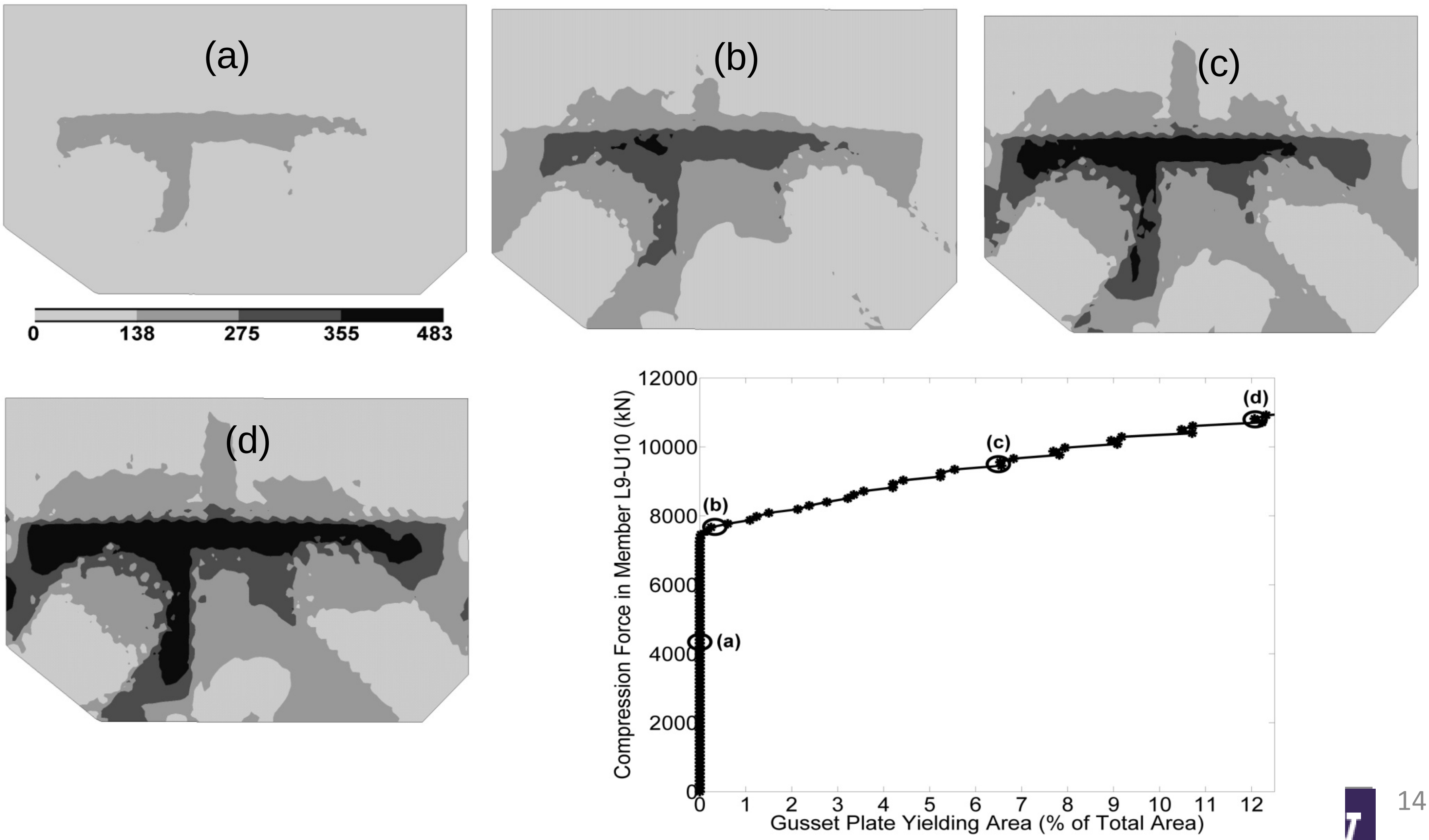
- Joint L9 of WSDOT BR 31-36
- 1950, t = 0.5”, A7 Steel F_y = 33 ksi

- Joint L5 of WSDOT BR 101-217
- 1930, t = 0.375”, “Open Hearth Steel” F_y = 30 ksi



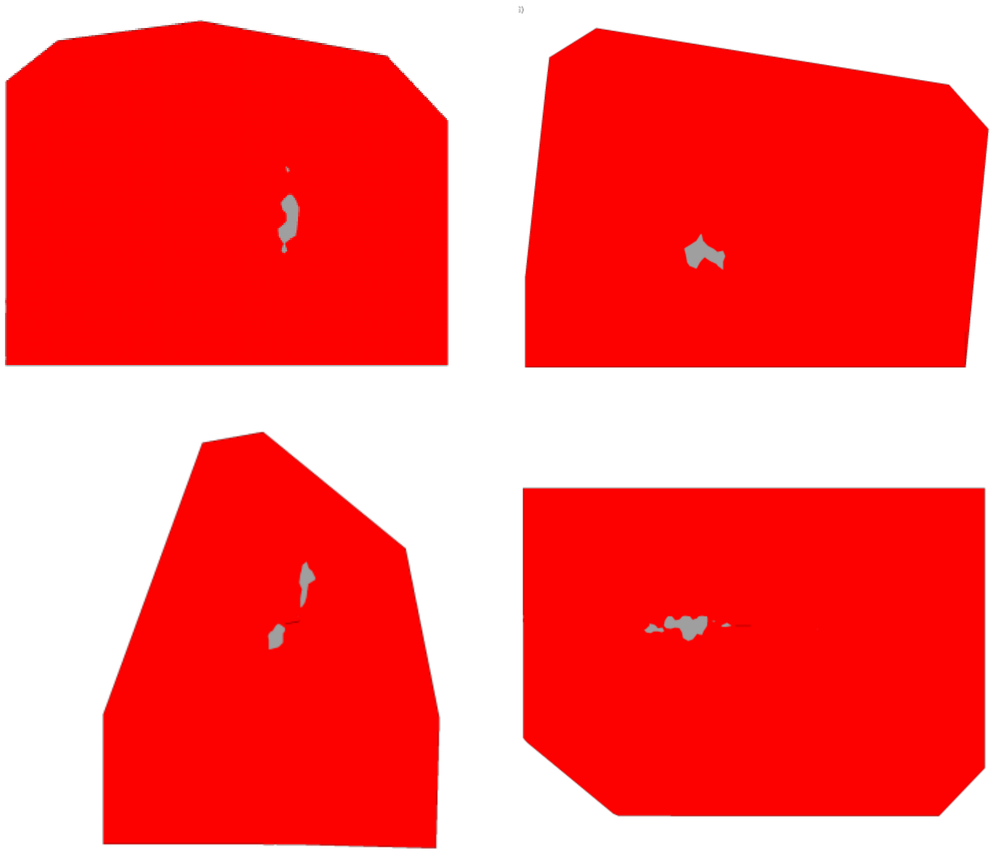
- Joint U10 of I-35 Bridge
- 1965, t = 0.5”, Gr. 50 Steel F_y = 50 ksi

Gusset Plate Yielding



Definition of Onset of Yielding

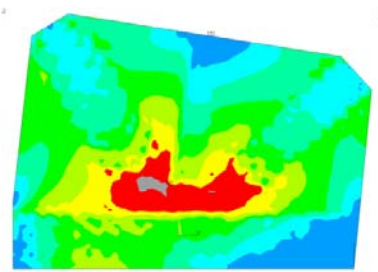
- Onset of yielding is taken to be when 0.5% of the gusset plate has yielded
  - Established in coordination with WSDOT engineers
  - At service loads this represents a problem
- Process:
  - Import ANSYS Von Mises stress contours into MatLab
  - Count pixels to determine how much gusset has yielded
  - Linearly interpolate between analysis steps to determine member loads at 0.5% gusset yield



D/C Ratios for Triage at Sig. Yield

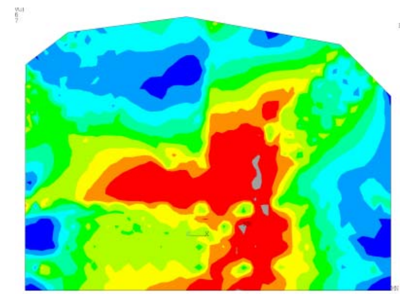
$$D/C_{Triage} = |\sigma_{wh}| / \left(\sigma_y / \sqrt{3}\right) \qquad D/C_{FHWA} = \max\left(All\ \ FHWA\, Checks\right)$$

D/C_{Triage} = 1.00



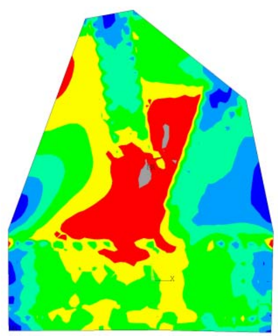
D/C_{FHWA} = 0.87

D/C_{Triage} = 1.46

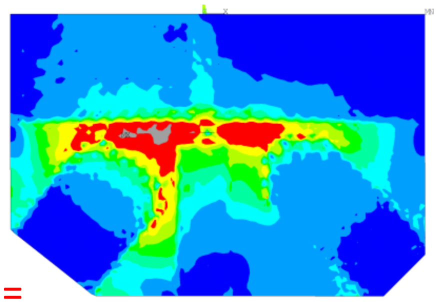


D/C_{FHWA} = 0.76

D/C_{Triage} = 1.48



D/C_{FHWA} = 0.26 (without shear)



D/C_{Triage} = 1.02

D/C_{FHWA} = 1.00

= Yield

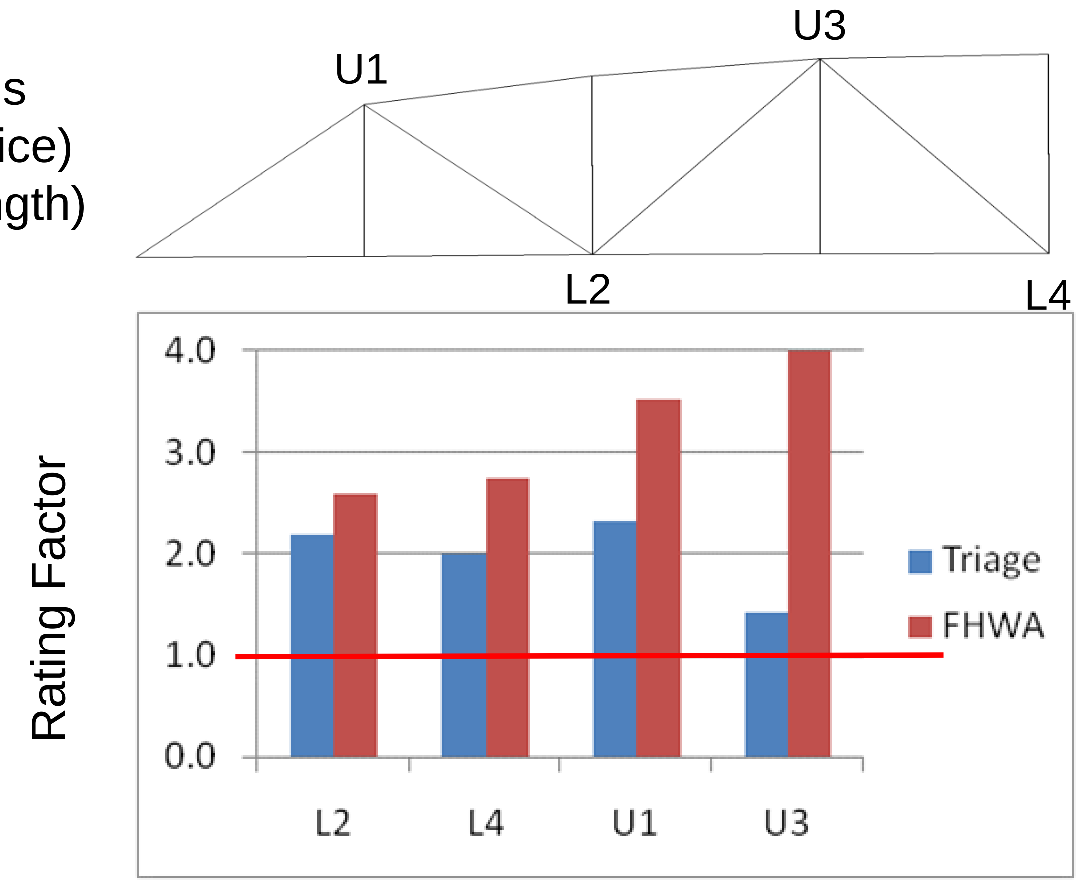
- Observations:
  - Triage evaluation conservatively indicates yielding
  - Load distribution and geometry are closer to assumptions triage check is less conservative
  - FHWA does not indicate onset of yielding, even with Ω = 0.74 (factor on shear strength to account for possible instability)

Application to WSDOT Bridges

- Applied Triage Evaluation to WSDOT bridges and compared with FHWA
  - Manual for Bridge Evaluation (2008) LRFR (ϕ_s = 0.9, ϕ_c = 0.95, I = 1.33):
    - Triage at Service ($\gamma_{DC} = \gamma_{DW}$ = 1.0, γ_{LL} = 1.3)
    - FHWA at Strength (γ_{DC} = 1.25, γ_{DW} = 1.5, γ_{LL} = 1.8)
- Buckling Never Controlled
- Rivets checked separately
- Recall: purpose of the Triage procedure is to be
  - Safe
  - Consistent
  - Fast
  - Conservative (but not overly)

Cle Elum Bridge (BR 90-134N)

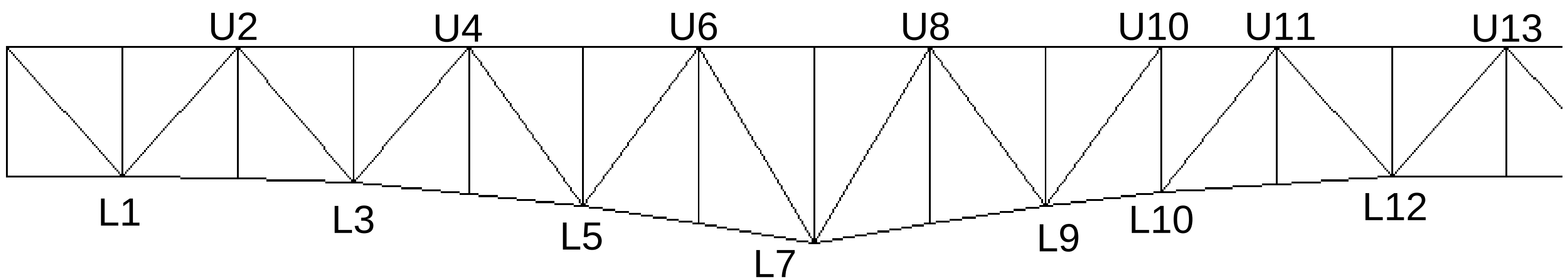
MBE Loads
Triage (Service)
FHWA (Strength)

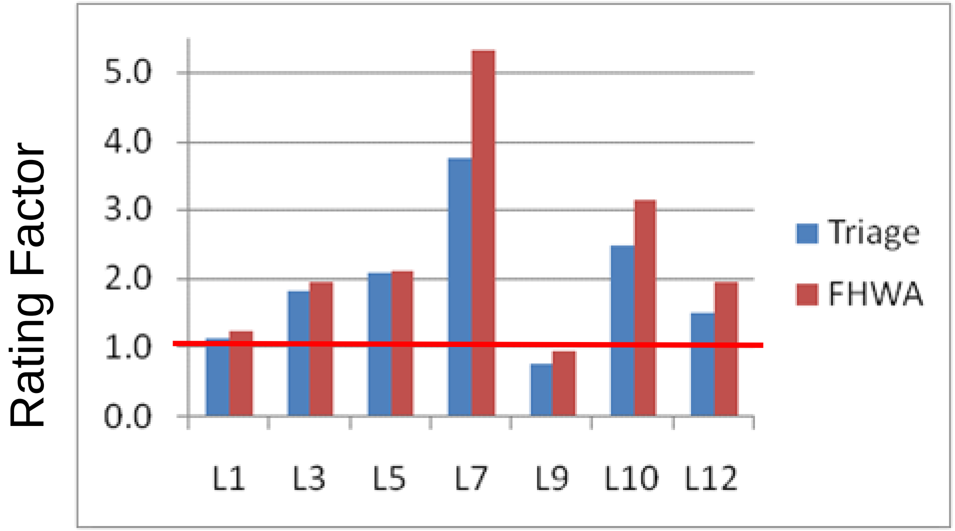


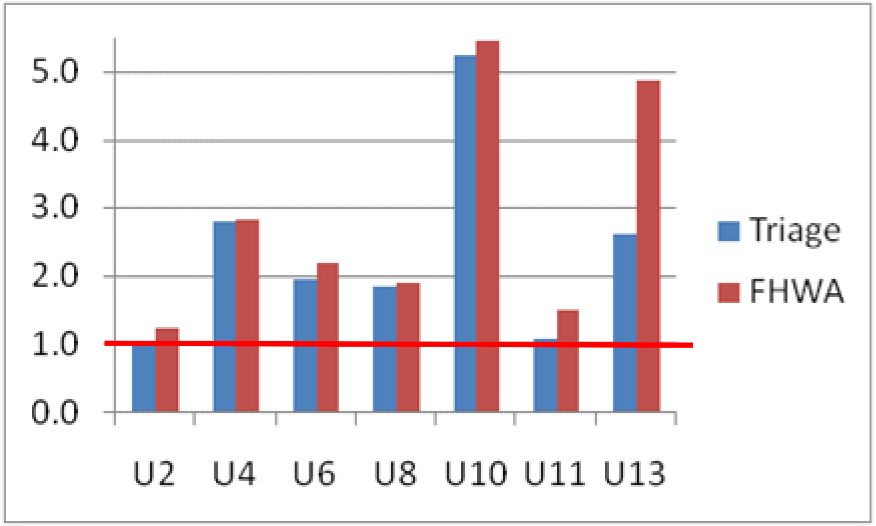
1 Gusset "Flagged" by Triage Procedure

- Triage at Service is conservative relative to FHWA at Strength
- Joint U3 Flagged by Triage

Metaline Falls Bridge (BR 31-36)



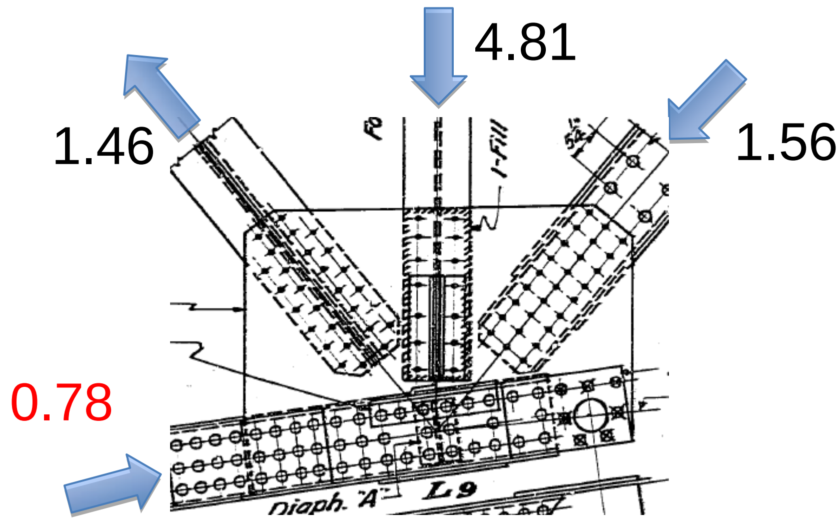




- Triage at Service is conservative relative to FHWA at Strength
- 1 Gusset "Flagged" by Triage Procedure: L9, also has RF<1.0 for FHWA approach

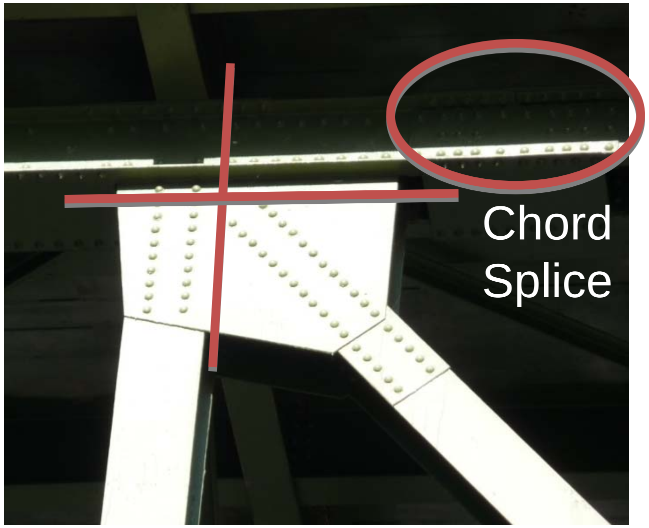
RFs for Flagged Gusset on BR 31-36

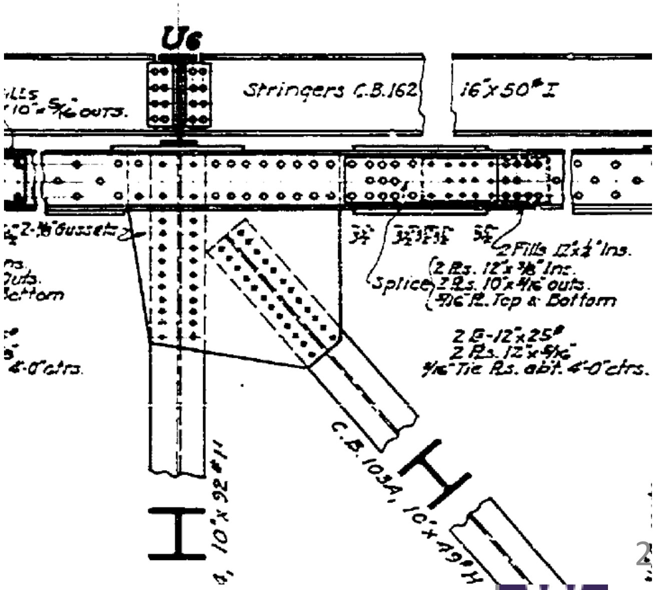
- L9 flagged because of Whitmore stresses at chord attachment
- FHWA RF also less 1.0 (0.95) caused by horizontal shear
- Gusset requires further investigation



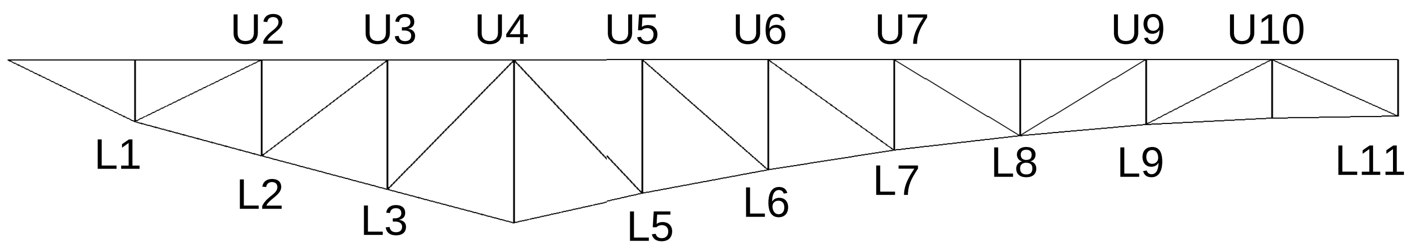
Hoh River Bridge (BR 101-217)

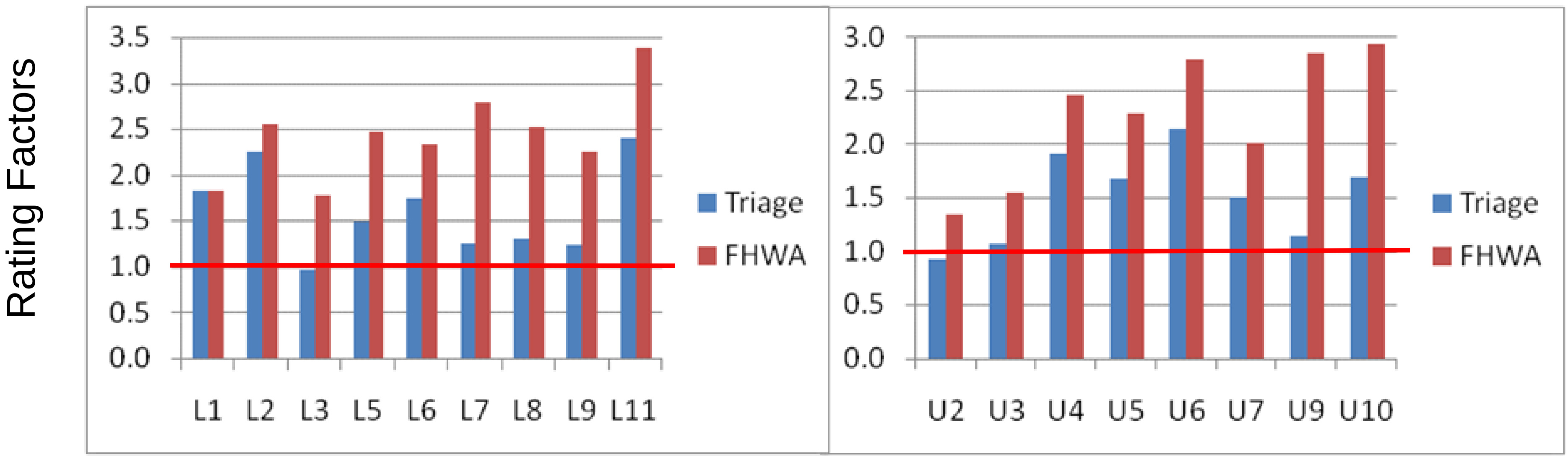
- Issues with applying the FHWA shear check:
  - Chords are often continuous through gusset and spliced outside of gusset
  - Vertical shear:
    - Chords or rivets would have to shear
  - Hangers continue through the gusset to top of chords
  - Horizontal shear:
    - Hangers or rivets would have to shear





Hoh River Bridge (BR 101-217)

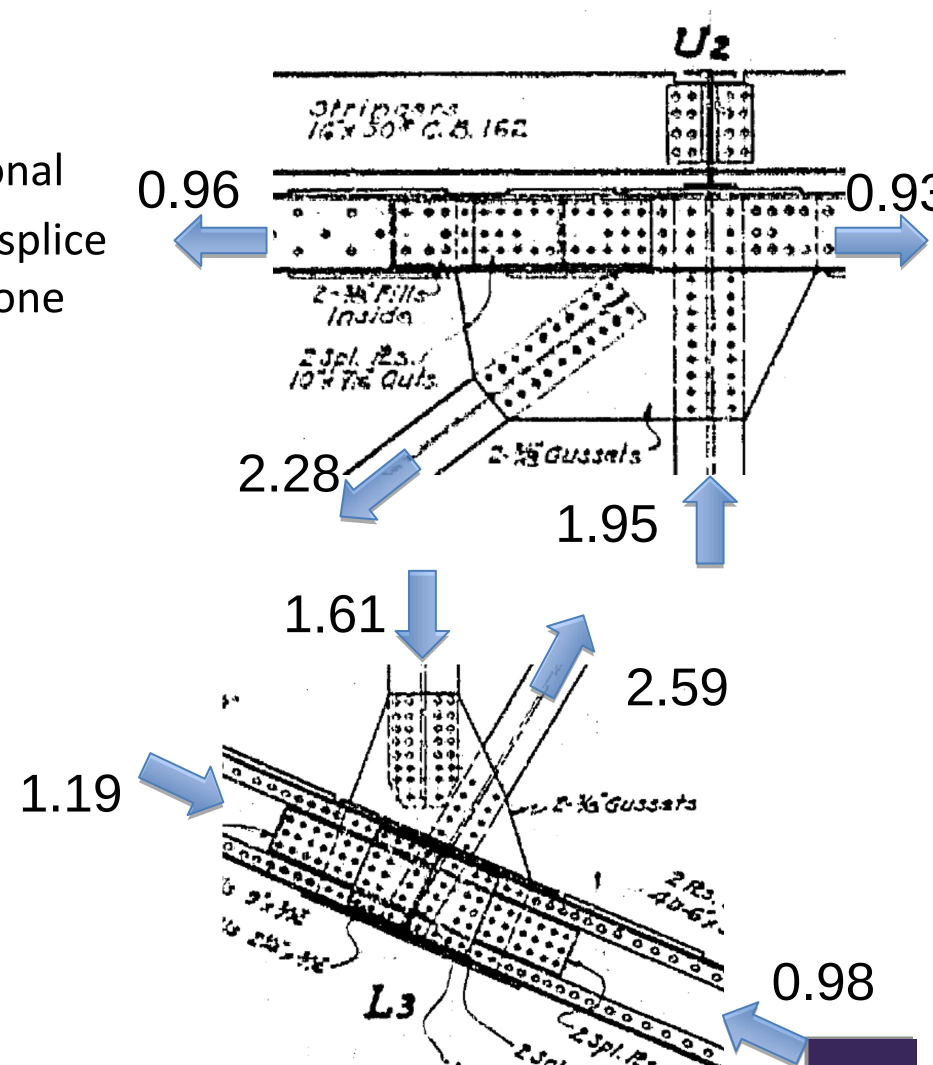




- Triage at Service is conservative relative to FHWA at Strength
- 2 Gussets "Flagged" by Triage Procedure: L3 and U2 have RFs of 0.98 and 0.93

Conservatism in BR 101-217

- U2:
  - Diagonal members are not orthogonal
  - Largest stresses are actually in the splice which is outside the interference zone
  - Gusset is not a concern
- L3:
  - Chords are in compression and are "milled-to-bear"
  - Gusset is not a concern



Rivet Strength: Common Controlling Factor

Current AASHTO Strengths	
Year of Construction	**φF (ksi)**
Prior to 1936	18
After 1936 but Unknown Origin	21
A502 Grade 1	27
A502 Grade 2	32

New Recommendations	
Rivet Specification	**φF (ksi)**
Prior to 1932	
Carbon Steel	34.5
Chrome-Nickel Steel	38.0
Nickel Steel	43.1
1932-Present	
A141	34.0
A502 Grade 1	34.0
A502 Grade 2	48.0

Summary of Collected Test Data

Test Description	Material	Rivet Tensile Properties (ksi)		# of Tests	Mean τu (ksi)	Std Dev. (ksi)
		Fy	Fu			
Watertown Arsenal (1891)	Iron	30.9	50.1	18	38.4	2.6
Flint (1892)	Iron	30.9	49.9	6	46.1	1.2
AREMA (1904)	OH Steel	35.4	60.3	33	48.5	2.8
Talbot & Moore (1911)	Nickel Steel	45.0	68.5	90	56.6	1.8
	Cr-Ni Steel	38.4	59.0	54	52.8	2.5
Woodruff & Davis (1939)	Carbon Steel	39.8	57.6	5	53.2	2.5
	Manganese Steel	54.6	81.0	9	75.1	2.5
Wilson, Bruckner & McCrackin (1940)	Low Alloy A	52.4	74.1	6	62.7	2.0
	Low Alloy B	42.9	65.6	3	64.8	0.6
	Low Alloy C	49.1	76.3	6	73.1	3.8
Munse & Cox (1956)	ASTM A141	28.0	52.0	44	52.7	4.7

Current FHWA Recommendation

Proposed FHWA Recommendation

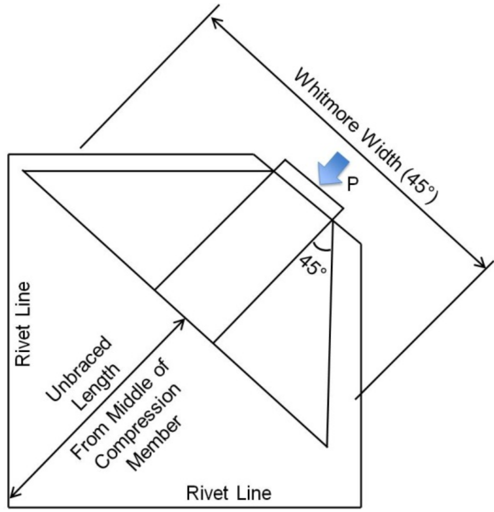
		Rivet Strength (ksi)	
		21	34
Joint ID		Rivet RF	
BR 90-134N: L2	L2-L1	1.19	2.77
	L2-U1	0.67	1.76
	L2-U2	7.14	12.22
	L2-U3	1.15	2.32
	L2-L3	1.26	2.88

		Rivet Strength (ksi)	
		21	34
Joint ID		Rivet RF	
BR 31-36: L5	L5-L4	1.69	2.95
	L5-U4	0.74	1.86
	L5-U5	0.92	1.77
	L5-U6	0.76	1.93
	L5-L6	1.19	2.53

		Rivet Strength (ksi)	
		18	34.5
Joint ID		Rivet RF	
BR 101-217: L9	L9-U9	0.76	2.04
	L9-U10	0.37	1.27
	L9-L10	0.67	1.84

Summary

- Triage Evaluation Procedure @ Service Loads:
  - Yielding: $\sigma_{wh} < F_y / \sqrt{3}$
    - Check for maximum Whitmore stress from all members a joint
  - Buckling:
    - AISC buckling equation with k = 1.0
    - Effective length and compressive stress per Modified Thornton
    - For many gussets yielding will govern: $F_{cr} > F_y / \sqrt{3}$
- Rivets:
  - Current AASHTO shear strengths seem very conservative based on test data
  - Many joints studied have RF’s less than 1.0 when rivet strength is considered
  - New values result in far fewer joints with RF’s less than 1.0
  - UW testing will further inform assumptions regarding rivets:
    - Reductions for connection length and group effects
    - Effects of corrosion



Thank You