2023 Western Bridge Engineers' Seminar

LRFR Calibration of Two-Strut Buckling Model for Evaluation of Compression Diagonal Gusset Plates of Steel Bridges

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Outline

Importance of Compression Gusset Plates

Current Evaluation Procedures and Challenges

Two-Strut Buckling (TSB) Model

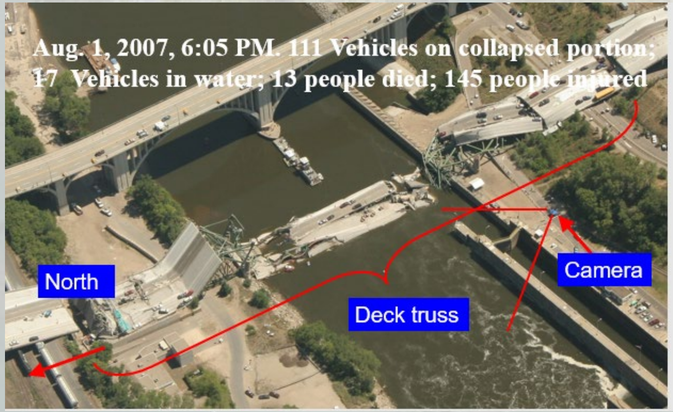
Load Resistance Factor Rating (LRFR) Calibration

Conclusions

Importance of Compression Gusset Plates

I-35W Bridge Collapse in Minneapolis, MN
August 1, 2007

- ❖ Compression Gusset Plate Design Error
- ❖ Increased Dead Load & Truck Weight
- ➢ Deck Modification – 20% increase
- ➢ Concentrated Construction Load

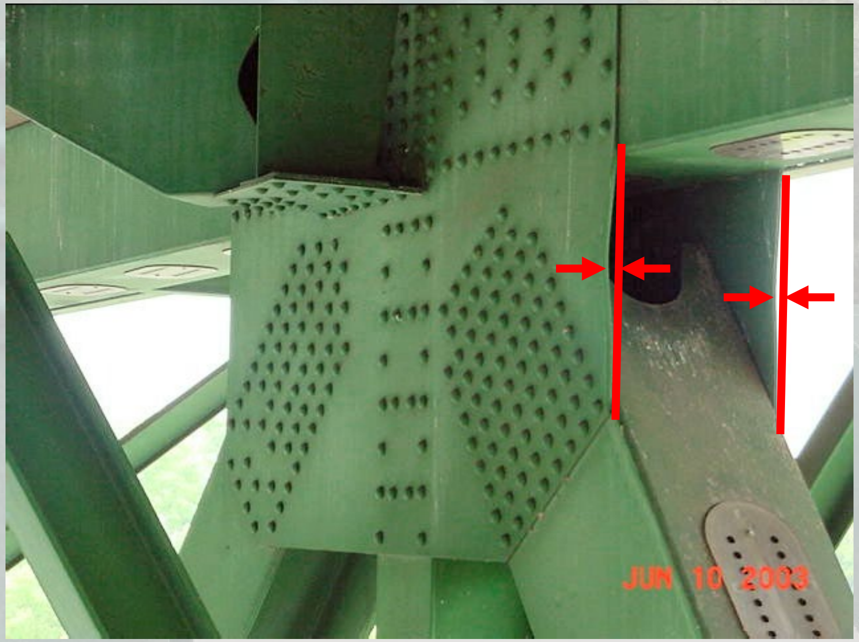


Importance of Compression Gusset Plates

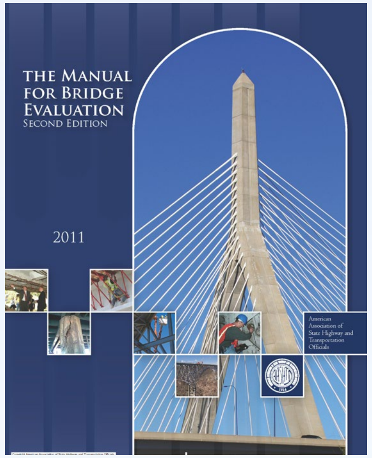
I-35W Bridge Collapse in Minneapolis, MN (August 1, 2007)

- Inadequate Attention to Compression Gusset Plates during Inspection and Load Rating Analysis
- Collapse initiated from U10E Compression Diagonal Gusset Plate

U10E West Gusset Plate



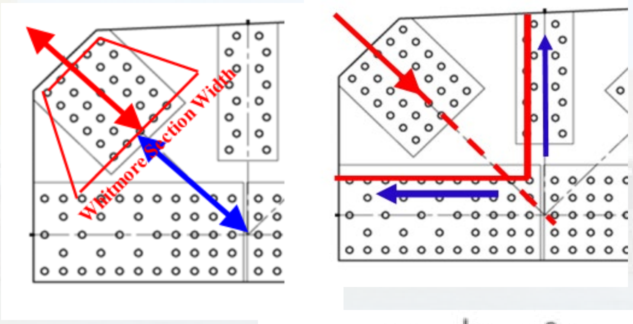
Current Evaluation Procedures and Challenges

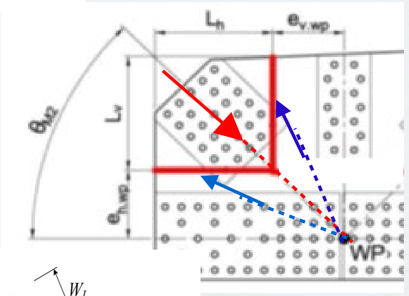


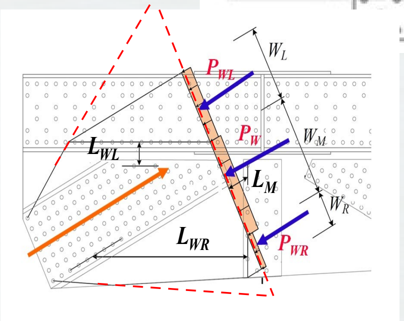
- The Manual for Bridge Evaluation (MBE) Compression Gusset Plate Evaluation Procedure

➢ First to Check - Whitmore Section Buckling and Partial Shear Plane Yielding

➢ If RF < 1.0, then Perform Refined Analysis
  - ❖ Basic Corner Check (BCC), or
  - ❖ Truncated Whitmore Section (TWS), or
  - ❖ Nonlinear Finite Element Analysis

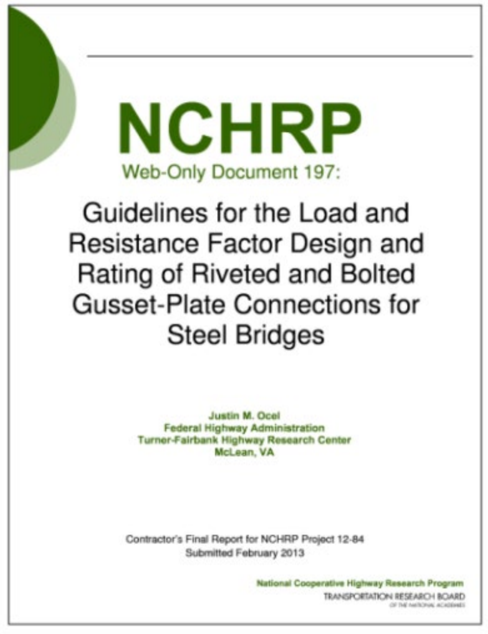


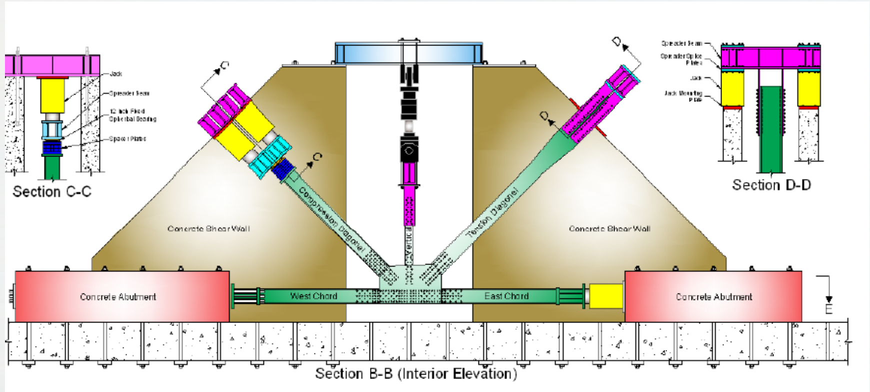


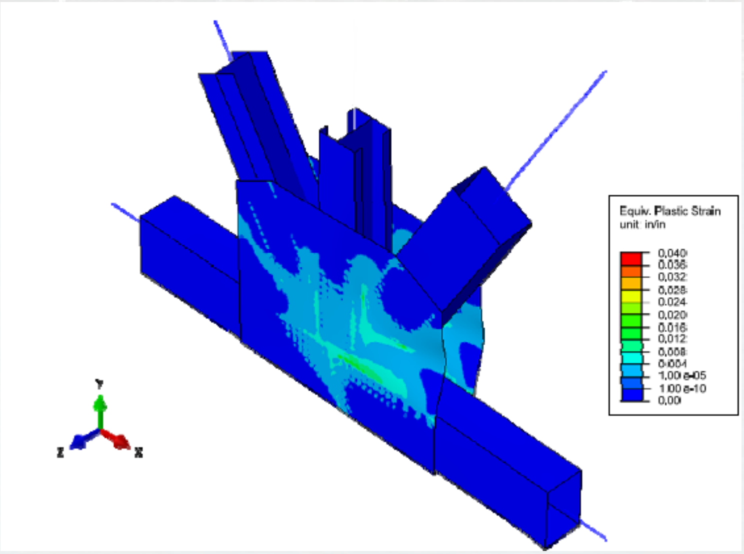


Current Evaluation Procedures and Challenges

- NCHRP Web-Only Document 197
  - ➢ Basis for gusset plate design in AASHTO LRFD BDS and evaluation in AASHTO MBE

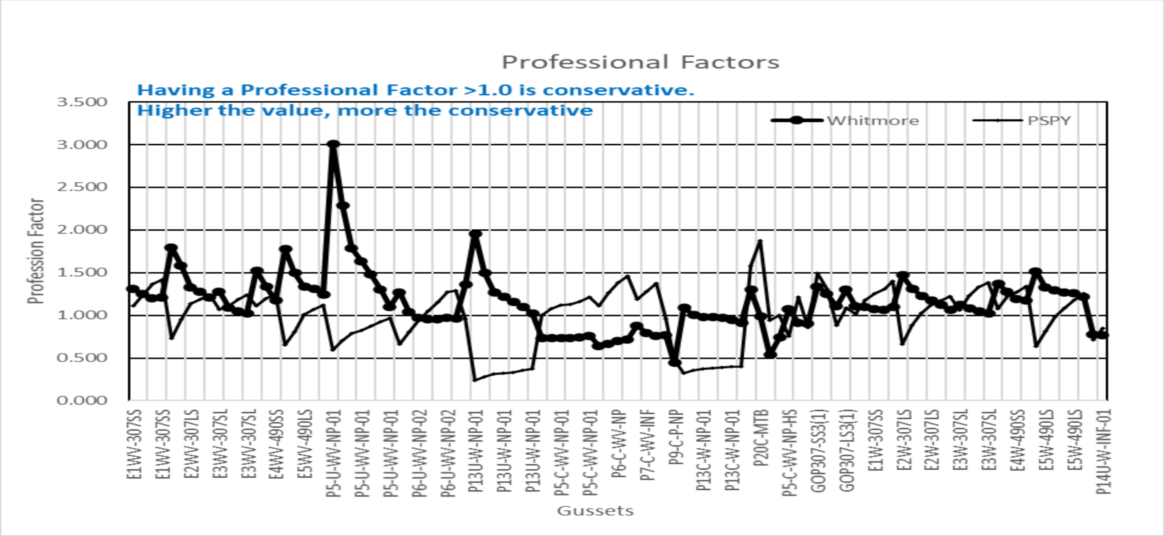

NCHRP
Web-Only Document 197:
Guidelines for the Load and Resistance Factor Design and Rating of Riveted and Bolted Gusset-Plate Connections for Steel Bridges
Justin M. Ocel
Federal Highway Administration
Turner-Fairbank Highway Research Center
McLean, VA
Contractor's Final Report for NCHRP Project 12-84
Submitted February 2013
National Cooperative Highway Research Program
TRANSPORTATION RESEARCH BOARD





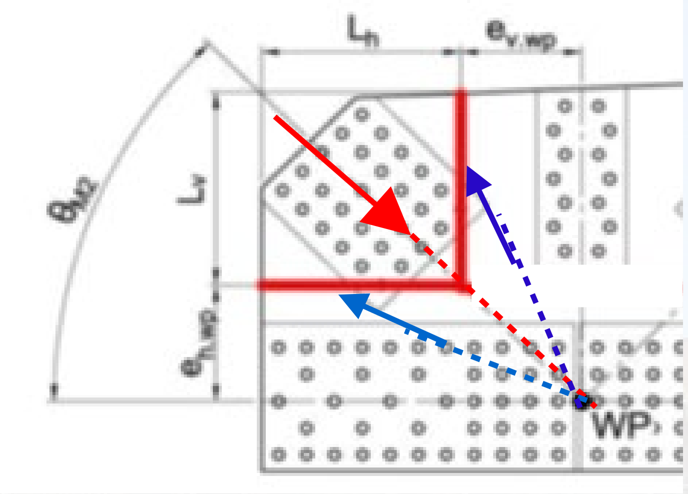
Shortcomings of Current Standard Methods

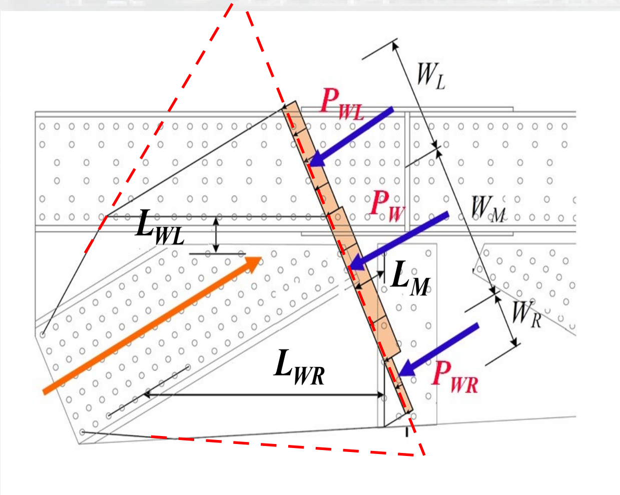
- Two-Fold Method - Generally Conservative
- While Traditional Whitmore Is <u>Conservative</u>, a Partial Shear Check Is <u>Un-Conservative</u> and Vice Versa.
- For Older Existing Bridges, this Inconsistency Results in Unnecessary Strengthening for Bridge Owners.



Shortcomings of Current Refined Methods

- Basic Corner Check (BCC)
  - Failure Surfaces Carry NO Moment
  - Force Acted Through WP
  - One of Lower Bound Solution
  - **Generally Conservative**
- Truncated Whitmore Section (TWS)
  - Smaller Coefficient of Variation
  - Significant Minimum PF
  - **Does Not Satisfy Equilibrium**
- Finite Element Analysis
  - **Modeling Dependent**
  - **Too Complex** for Ordinary Load Rating Engineers



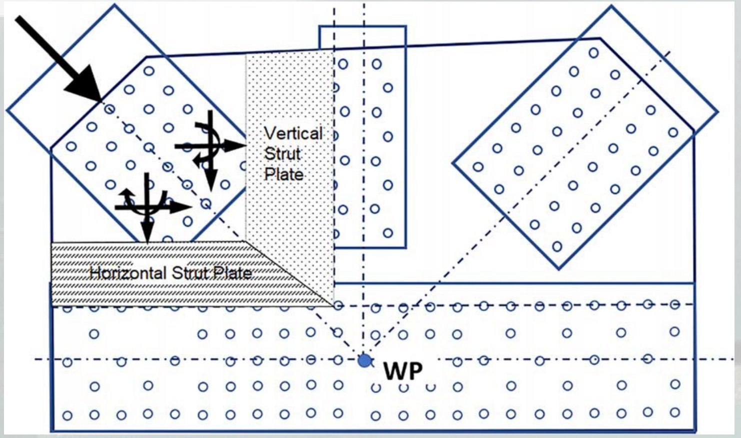


An Example Evaluated Using Current MBE Methods

Method (Calc performed) Ø	Whitmore $Ø_{compression}$	Partial Shear $Ø_{shear\ yielding}$	Basic Corner Check $Ø_{compression}$	Truncated Whitmore Check $Ø_{compression}$
HL93 Operating RF	**1.120**	-0.640	0.057 or 0.057	**1.019**

- Results Significantly Vary Between These Methods.
- While One Method Shows a <u>Negative</u> Rating, (indicate it fails under dead load). Other Method Shows Ample Capacity (rating factor of 1.019 for HL-93 loading).

Two-Strut Buckling (TSB) Model for Compression Diagonal Gusset



Main Assumptions:

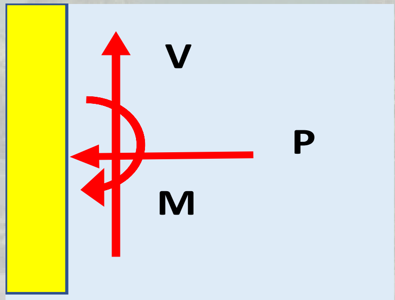
- Two Struts (Vertical and Horizontal) Resist Diagonal Compression Force.
- Strut Plates Carry Different Forces and Satisfy Equilibrium.
- Strut Plates Buckle under a Specific M-P-V Interaction Equation.
- Lower Bound Theorem of Limit Analysis

(Duan, L. and Vinayagamoorthy, M. (2023) "Limit Analysis for Evaluation of Compression Diagonal Gusset Plates in Steel Truss Bridges," *ASCE Journal of Bridge Engineering*, 28(9): 04023056-01-11)

TSB Model for Compression Diagonal Gusset

M-P-V Interaction Equation:

- Overview: mathematical equations to model how the moment(M), axial force (P), and shear force (V) interact in the two-strut plates.
- Details: equations based on previous work and consider different characteristics like modulus of elasticity, gusset plate thickness, and nominal resistances.



$$\frac{M}{M_n} + \left(\frac{P}{P_n}\right)^2 + \frac{\left(\frac{V}{V_n}\right)^4}{\left(1 - \left(\frac{P}{P_n}\right)^2\right)} = 1.0$$

TSB Model for Compression Diagonal Gusset

Comparison with BCC and TWS model (Professional Factor and COV) :

- ➢ Based on 116 Gusset Specimens

Method	All gusset configurations	
	Mean ($P_{test}/P_{predicated}$)	COV
BCC	1.228	0.292
TWS	1.081	0.090
TSB	0.996	0.103

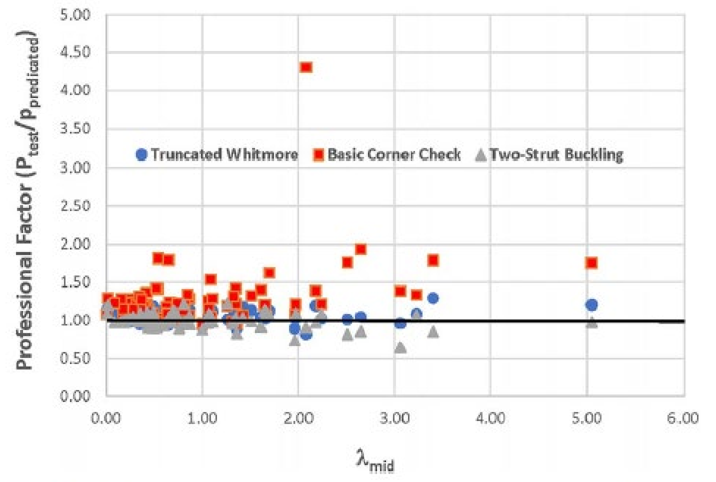


Fig. 5. PF for NCHRP 12-84 analytical tests (gusset plates with vertical member).

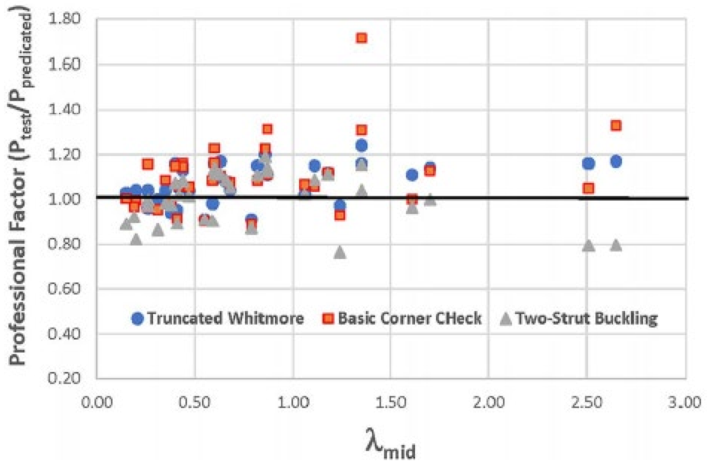


Fig. 6. PF NCHRP 12-84 analytical tests (gusset plates without vertical member).

LRFR Resistance Factor Calibration Principles

Calibration Principles used in Load Resistance and Factor Design (LRFD) Specifications:

- LRFD design specifications are Level 1 Codes. These Codes Use Deterministic Design Formulas.
- The Safety Margin is Introduced Through Partial Safety Factors (Load and Resistance Factors).
- Design Equation "$\phi R_n \geq \sum \gamma_i Q_{ni}$"
- The Partial Safety Factors ϕ and γ Calibrated Based on the Target Reliability Index, β_T

LRFR Resistance Factor Calibration Principles

For Gusset Plate ONLY:
According to NCHRP Web-Only Document 197, Strength I Limit State, the Inventory Level, the Target Reliability Index, β_T is set to 4.5 for Design, while for the Operating Level, the Corresponding β_T is 3.5 for Evaluation/Rating.

LRFR Resistance Factor Calibration

Design Formula in AASHTO LRFD:

- Load & Resistance Factors Represent Partial Safety Margins

$$\gamma_D \, DL + \gamma_L \, (LL + IL) \leq \phi \, R$$

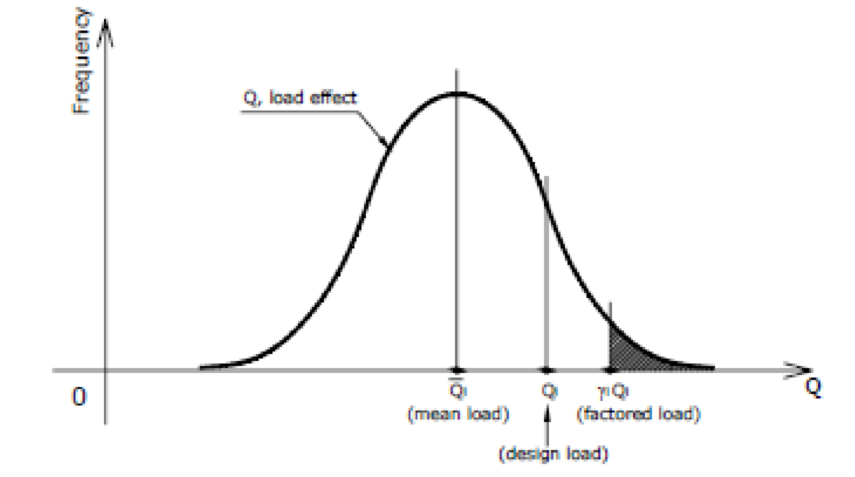


Figure 1 - Mean Load, Design (Nominal) Load and Factored Load

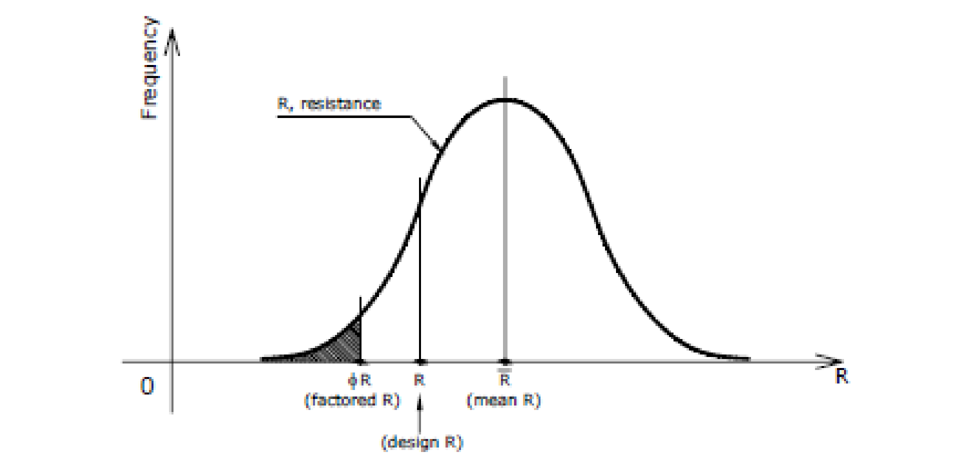


Figure 2 - Mean Resistance, Design (Nominal) Resistance and Factored Resistance

LRFR Resistance Factor Calibration

Methods to Determine Reliability Index:

- According to NCHRP Web-Only Document 197,
  - Perform Monte Carlo Simulation to Conduct a Total of 3,000,000 limit state Checks and Verify to Have 10 Failures with a Probability of Failure (β_T = 4.5)
  - The Manual for Bridge Evaluation (MBE) Gusset Plate Ratings use Monte Carlo Simulation Calibration

LRFR Resistance Factor Calibration

Calibration Process and Method:

- Model Resistance in the Form of $R = (M)(F)(P)(R_n)$ **Resistance Factor** Needs to be Established to a Target Reliability Index, β_T according to LRFD Design Specifications.
- ➢ M = variation factor in material properties.
- ➢ F = uncertainties factor in the fabrication in terms of dimensions.
- ➢ P = professional factor = test capacity / predicted capacity
- ➢ R_n = nominal resistance

LRFR Resistance Factor Calibration

Statistical Parameters for Loads, Materials, Fabrication :

Table 32 Assumed Calibration Statistics

	Bias Factor (λ)	COV
Dead Load	1.05	0.10
Live + Impact	1.15	0.12
Yield or Tensile Strength (F_y or F_u)	1.10	0.11
Fabrication Factor (F)	1.00	0.05

M-factor (Yield or Tensile Strength)

F-factor (Fabrication Factor)

$\mu_{DL} = (\lambda_{DL})(DL_n)$; $\sigma_{DL} = (\mu_{DL})(V_{DL})$

$\mu_{LL} = (\lambda_{LL})(LL_n)$; $\sigma_{LL} = (\mu_{LL})(V_{LL})$

from NCHRP Web-Only Document 197

$R = (R_n)(M)(P)(F)$

$\lambda_R = (\lambda_M)(\lambda_P)(\lambda_F)$

$(V_R)^2 = (V_M)^2 + (V_P)^2 + (V_F)^2$

$\mu_R = (\lambda_R)(R_n)$

$\sigma_R = (\mu_R)(V_R)$

Results of Resistance Factors Study of TSB Model

Summary of Exact Resistance Factors:

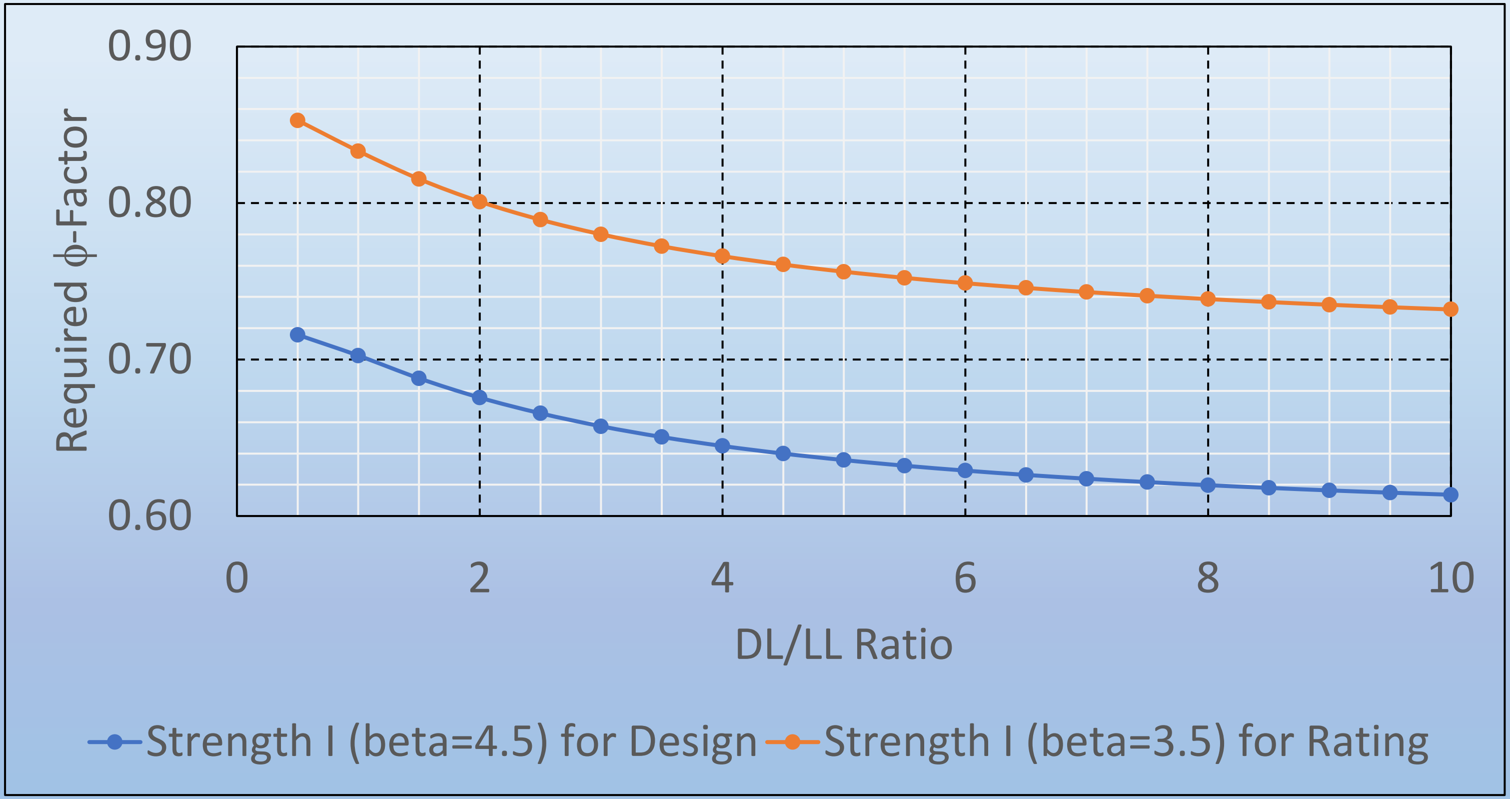
γ_{LL} = 1.75 (Strength I - HL-93 loading)

Reliability Index	β_T = 4.5				β_T = 3.5				β_T = 2.5			
DL/LL ratio	0.5	1.0	2.0	6.0	0.5	1.0	2.0	6.0	0.5	1.0	2.0	6.0
t ≥ 3/8"	0.72	0.70	0.68	0.63	0.85	0.83	0.80	0.75	1.02	0.99	0.95	0.89
t < 3/8"	0.64	0.63	0.61	0.57	0.78	0.76	0.73	0.68	0.94	0.92	0.88	0.83

Results of Resistance Factors Study of TSB Model

Required ϕ-factor for Plate ≥ 3/8"

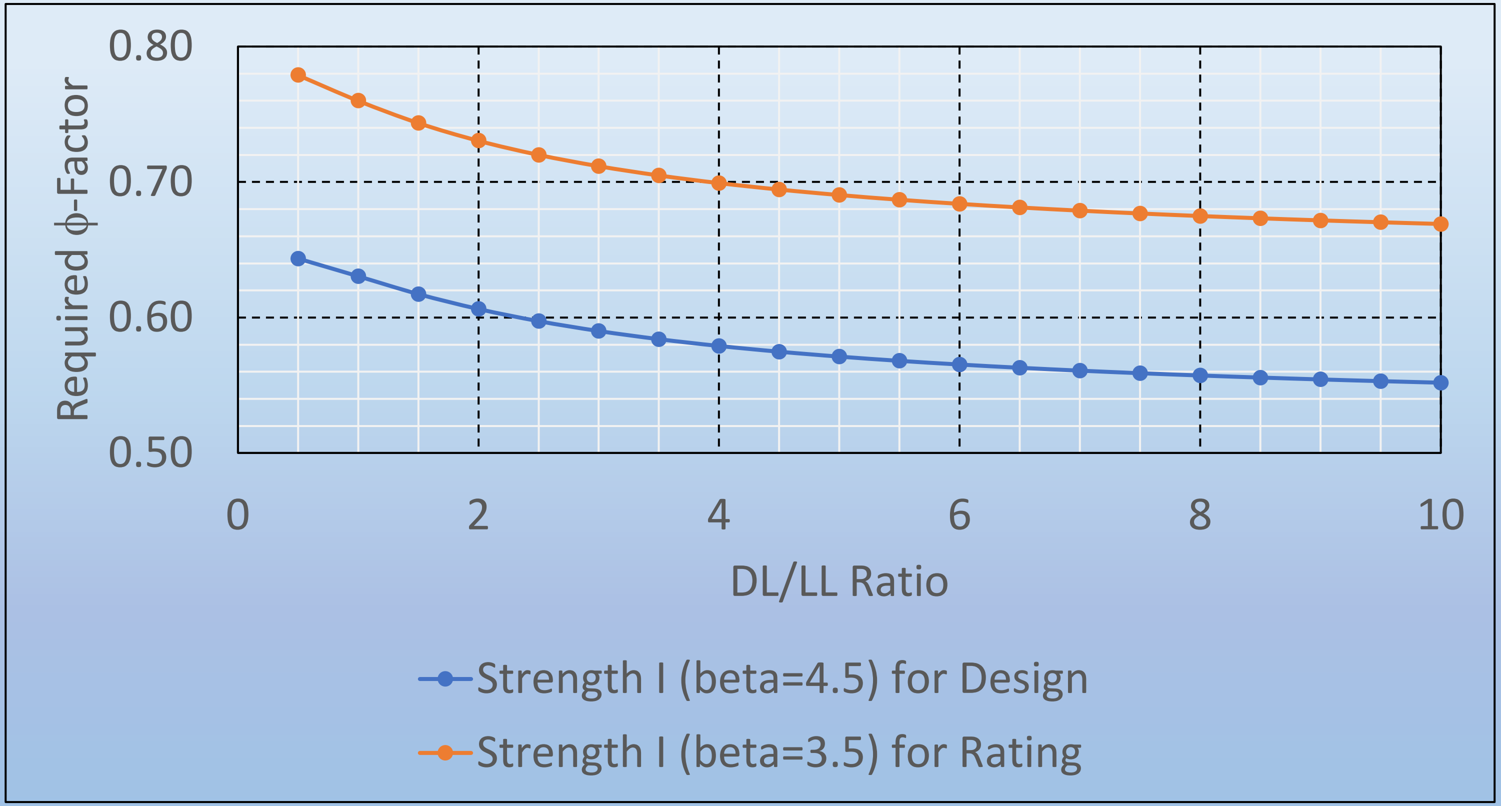
γ_{LL} = 1.75 (Strength I - HL-93 loading)



Results of Resistance Factors Study of TSB Model

Required ϕ-factor for Plate < 3/8"

γ_{LL} = 1.75 (Strength I - HL-93 loading)



Results of Resistance Factors Study of TSB Model

Reliability Index (β_T) for selected ϕ-factor for Strength I (Design & Evaluation)

γ_{LL} = 1.75 (Strength I - HL-93 loading)

	Reliability Index, β_T							
DL/LL ratio	0.5	1	2	3	4	6	8	Notes
ϕ = 0.70 (for Design)	4.63	4.52	4.29	4.13	4.02	3.89	3.81	t ≥ 3/8"
ϕ = 0.80 (for Rating)	3.86	3.74	3.51	3.35	3.25	3.12	3.05	t ≥ 3/8"
ϕ = 0.75 (for Rating)	3.70	3.57	3.36	3.22	3.13	3.02	2.95	t < 3/8"

Conclusions

- The Manual for Bridge Evaluation Two-Fold Whitmore Section Buckling (Whitmore) and the Partial Plane Shear Yielding (PPSY) are overly conservative and may result in unnecessary strengthening and retrofitting.

- Of three Refined Methods (Basic Corner Check - BCC, Truncated Whitmore Section – TWS, and Two-Strut Buckling - TSB), TSB has the best professional factor and the relatively low coefficient of variation (COV).

Conclusions

- Based on LRFR Resistance Factor Calibration Principles, Resistance Factors for TSB Model Can Be Codified for Application

  - For Design, $\phi = 0.70$
  - For Evaluation, $\phi = 0.75$ for $t < 3/8''$;

    $\phi = 0.80$ for $t \geq 3/8''$

Acknowledgments

- Professional Engineers in California Government (PECG) Sponsored this Presentation
- ASCE Journal Peer Reviewers Recommended LRFR Calibration of Two-Strut Buckling (TSB) Model for Codified Application
- Dr. Justin Ocel of FHWA Provided NCHRP 12-84 Gusset Plate Calibration Development Background

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Thank you!
Questions?

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