Steel I-Girder Bridge Cross-Frame Strength and Stiffness Requirements

Western Bridge Engineers' Seminar, September 6, 2017

Outline

- Stability Bracing
- Practical Implementation
- Design Example
- Summary

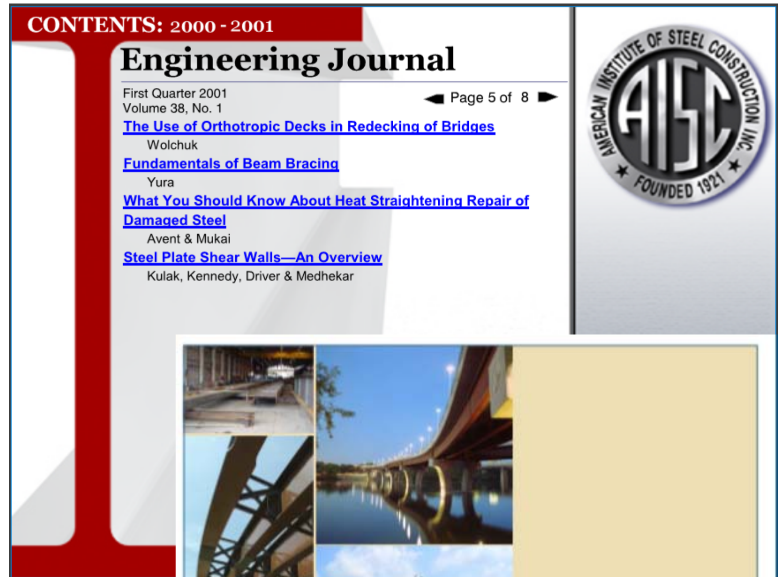
Outline

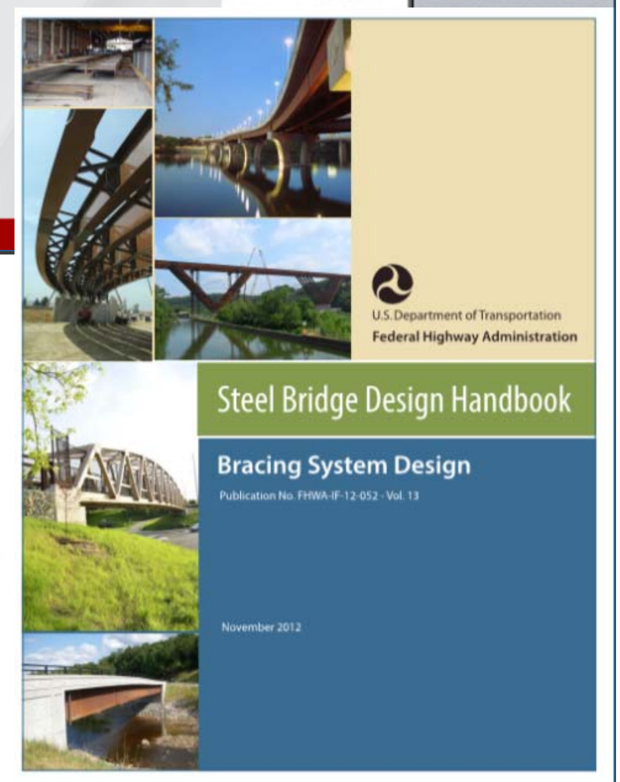
- Stability Bracing
- Practical Implementation
- Design Example
- Summary

- Typical Steel I-Girder Bridge Components
  - Deck
  - Girders
  - Cross-frames or diaphragms
- Stability Bracing
  - Restrains lateral torsional deflection of I-girders
  - Resists lateral-torsional buckling of I-girders
  - Continuous bracing by composite deck
  - Discrete bracing ("brace points")
    - Cross-frames – truss framework
    - Diaphragms – solid web
- Mostly familiar concepts…

- Traditional Design Approach – 2 Categories
  - Curved or severely skewed bridges
    - V-Load, 2D, or 3D analysis
    - Analysis results include cross-frame forces
    - Significant DL and LL forces
    - Cross-frame strength and stiffness OK by inspection
  - Straight bridges with little or no skew
    - Line girder analysis
    - Analysis doesn't provide cross-frame forces
    - DL and LL forces in cross-frames neglected
    - Cross frames designed for wind loading and maximum member slenderness limits

- Recent Advances
  - Stability bracing strength and stiffness requirements
  - Yura, JA, "Fundamentals of Beam Bracing," *AISC Engineering Journal*, 1st Quarter 2001
  - AISC *Specifications for Structural Steel Buildings*, Appendix 6.3
  - Yura, JA, Helwig, TA, Volume 13: Bracing System Design, *FHWA Steel Bridge Design Handbook*, November, 2012





- Two primary design requirements
  - Stiffness requirement

$$(\beta_T)_{req} = \frac{\beta_T}{\left(1-\frac{\beta_T}{\beta_{sec}}\right)}$$

Where: $$\beta_T = \frac{2.4\, L\, M_f^2}{\phi n\, E\, I_{eff}\, C_b^2}$$

  - Strength Requirement

$$(M_{br})_{req} = \frac{(0.005) L_b\, L\, M_f^2}{n\, E\, I_{eff}\, C_b^2\, h_o}$$

  - Simple equations… but how do you implement in bridge design?

Outline

- Stability Bracing
- Practical Implementation
- Design Example
- Summary

Outline

- Stability Bracing
- Practical Implementation
- Design Example
- Summary

- FHWA SBDH: Defines equations and variables, with figures and discussions, then says:

  "Using these equations the stability bracing forces are additive to the bracing forces resulting from a first-order type of analysis (dead load, live load, etc.)."

- But how?
  - No DL or LL cross-frame forces from LGA?
  - What limit states to investigate?
  - What load combinations and factors to use?
  - What about negative moment regions?

- Loads
  - Straight bridges with little or no skew
  - Line girder analysis – no cross-frame results
  - DL and LL forces in cross-frames negligible
  - Wind forces by simplified hand calculations
  - Stability bracing forces from Yura's equations

- Limit States, Load Combinations, Load Factors
  - AASHTO LRFD and engineering judgment

Notes:

1. Including dynamic effects if applicable.

2. DC is weight of structural steel only

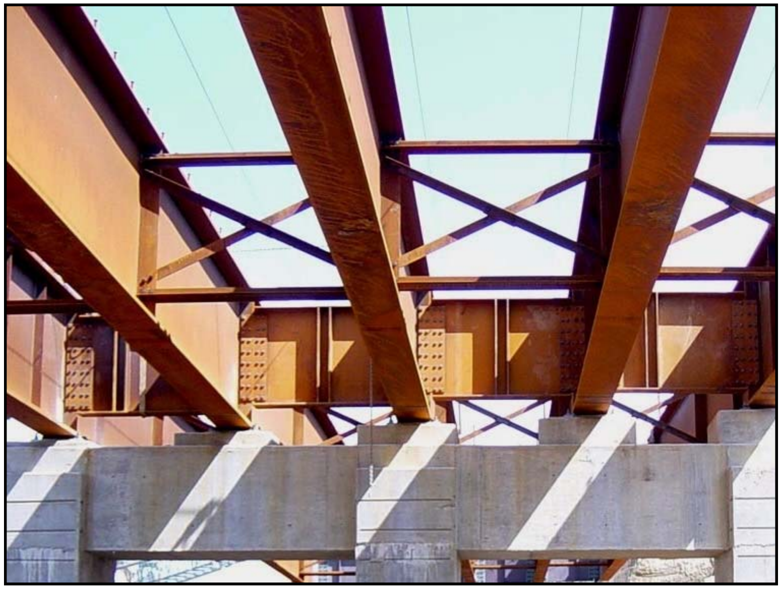
Limit State	Condition	Composite or Noncomposite?	Pos or Neg Moment?	Load Combination
Strength I	Final	Composite	Negative	1.25 DC + 1.5 DW + 1.75 LL
Strength I	Constr.	Noncomposite	Positive or Negative	1.25 DC + 1.5 DW + 1.5 Constr. *(Note 1)*
Strength III	Final	Composite	Negative	1.25 DC + 1.5 DW + 0 LL + 1.4 WS
Strength III	Constr.	Noncomposite	Positive or Negative	1.25 DC + 1.25 DW + 1.25 WS + 1.25 Constr. *(Note 2)*
Strength V	Final	Composite	Negative	1.25 DC + 1.5 DW + 1.35 LL + 0.4 WS + 1.0 WL
Special	Constr.	Noncomposite	Positive or Negative	1.4 DC + 1.5 Constr. *(Note 1)*

- Limit States, Load Combinations, Load Factors
  - Stability bracing forces calculated using factored major-axis bending moment (M_f)
  - Multiply by a load factor of 1.0 for combination with other force effects
  - Str I, Constr.: No wind, but full constr loads for deck placement, with constr. live loads and dynamic effects as applicable.
  - Str III, Constr.: Include wind, with reduced construction loads (e.g., constr. equipment, stored materials, but no constr. live load). Not checked for deck placement conditions.
  - Constr. Conditions: DW includes applicable utility loads but not future wearing surface loading.
  - Local owner-agency construction load case guidance governs

- Continuous Span Bridges
- Positive Moment Regions
  - Addressed by Yura
- Negative Moment Regions
  - Not investigated by Yura
  - Does deck stabilize girders?

    Assume it does not until further research is completed
  - Use maximum negative moment at pier?

    Assume bearings/anchor bolts provide bracing at pier; use moment at first cross-frame away from pier
- Positive vs. Negative Moment Regions
  - Moment, cross-frame spacing, properties by region



- Simplifications for Cross-Frame System Stiffness Parameter, β_b
  - Use FHWA SBDH Figure 9 equations – conservatively only considers two girders
  - Otherwise can use FHWA SBDH Figure 23 equations with number of girders per cross-frame taken as:

$$n_{gc} = \frac{number\ of\ girders\ in\ cross\ section}{number\ of\ cross\text{–}frames}$$

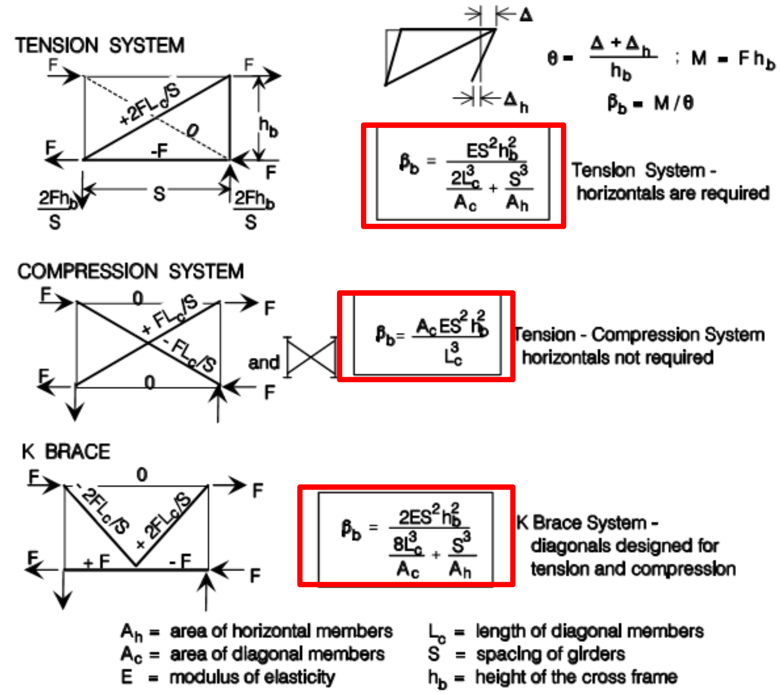


Figure 9 Stiffness Formulas for Twin Girder Cross Frames [20]

- Simplifications for Web Distortional Stiffness Parameter, β_{sec}
  - Can use FHWA SBDH Figure 10 eq.
  - For most cases with "full-depth cross-frames" web distortional effects can be neglected and β_{sec} taken as infinity
  - However, AASHTO allows shallower cross-frames or diaphragms – consider calculating β_{sec} explicitly when appropriate
  - Evaluate β_{sec} for each region of girder height using FHWA SDBH Figure 11 equation

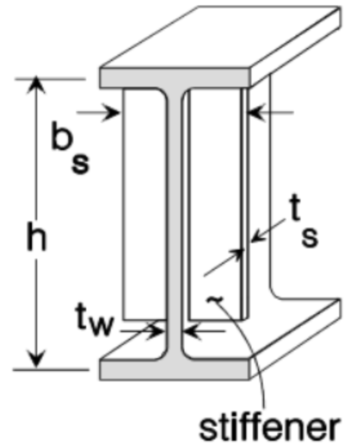


Figure 10 Web Stiffener Geometry

$$\beta_{sec} = 3.3\frac{E}{h_o}\left(\frac{(1.5h_o)t_w^3}{12} + \frac{t_s b_s^3}{12}\right)$$

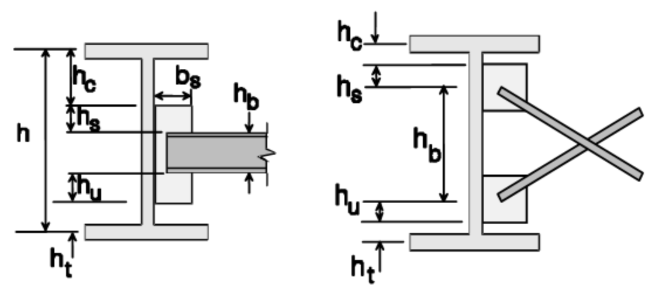


Figure 11 Cross frame and Diaphragm Geometry

$$\beta_c, \beta_s, \beta_t, \beta_u = \frac{3.3E}{h_i}\left(\frac{h_o}{h_i}\right)^2\left(\frac{(1.5h_i)t_w^3}{12} + \frac{t_s b_s^3}{12}\right)$$

- Simplifications for In-Plane Girder Stiffness Parameter, β_g
  - Equation for β_g assumes only one brace at midspan
  - Conservative worst-case simplification when more than one brace per span is provided – can derive equations for multiple braces
  - For most bridges with 4, 5, or more girders, the effect of β_g is less significant
  - For narrow bridges, if β_g dominates the calculation of the overall brace stiffness, then global system buckling might be a concern

$$\beta_g = \frac{24(n_g - 1)^2}{n_g} \frac{S^2 EI_x}{L^3}$$

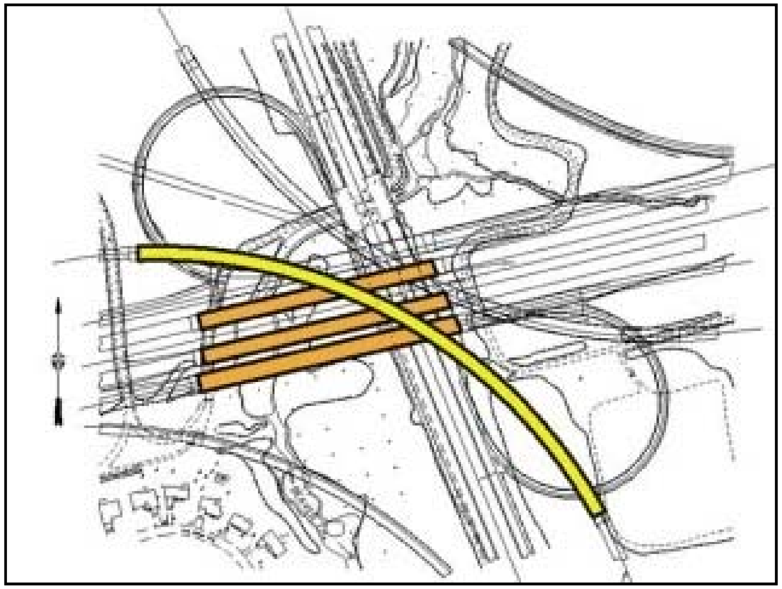
Outline

- Stability Bracing
- Practical Implementation
- Design Example
- Summary

Outline

- Stability Bracing
- Practical Implementation
- Design Example
- Summary

- Practical design project
- Three straight steel I-girder bridges
- Little or no skew
- Basic design parameters:
  - Six units, mix of 2- and 3-span units
  - Spans: 113' to 164'
  - Girder spacing: 9'-4" to 10'-9"
  - Girder web depths: 62" to 74"
  - Cross-frame spacing: 21' to 25'



- Representative Calculations
  - Required cross-frame stiffness:

$$(\beta_T)_{req} = \frac{\beta_T}{\left(1 - \frac{\beta_T}{\beta_{sec}}\right)} \qquad (2)$$

  - Required cross-frame strength:

$$(M_{br})_{req} = \frac{(0.005) L_b \, L \, M_f^2}{n \, E \, I_{eff} \, C_b^2 \, h_o} \qquad (3)$$

Representative Calculations

- Values of key design parameters:

β_T	=	overall required brace system stiffness (kip-in./rad)
	=	$\dfrac{2.4\,L\,M_f^2}{\phi n\,E\,I_{eff}\,C_b^2}$ (4)
β_{sec}	=	web distortional stiffness (kip-in./rad). For full-depth cross-frame connection plates, β_{sec} can be taken equal to infinity. For this case, for illustration, the value of β_{sec} was calculated to be 12,910,512 kip-in./rad
L	=	span length (in.) = 147.5 ft = 1770 in.
M_f	=	maximum factored major-axis bending moment in the region (i.e. positive or negative moment region) and span under consideration for the Limit-State load combination under consideration (kip-in.)… see summary below
ϕ	=	resistance factor for bracing = 0.80
n	=	number of cross-frames within the span = 5
I_{eff}	=	effective moment of inertia (in.^{4}) = 981.5 in.^{4}
C_b	=	moment gradient modifier, conservatively taken as 1.0
L_b	=	unbraced length (i.e., cross-frame spacing) (in.) = 24.75 ft = 297 in.
h_o	=	distance between the flange centroids (in.) = 69.375 in.

Representative Calculations

- <u>Actual</u> cross-frame stiffness:

The required bracing stiffness, $(\beta_T)_{req}$, from Eq. (2) is checked against the actual overall brace system stiffness, $(\beta_T)_{act}$, given as:

$$(\beta_T)_{act} = \frac{1}{\left(\frac{1}{\beta_b}+\frac{1}{\beta_{sec}}+\frac{1}{\beta_g}\right)}$$

where, by separate calculations for the subject cross-frame:

β_b = cross-frame system stiffness (kip-in./rad) = 1,540,514 kip-in./rad
β_{sec} = web distortional stiffness (kip-in./rad) = 12,910,512 kip-in./rad
β_g = in-plane girder stiffness (kip-in./rad) = 339,863 kip-in./rad

thus:

$(\beta_T)_{act}$ = 272,557 kip-in./rad

- Representative Calculations
  - Required cross-frame stiffness
  - Maximum negative moments at the first cross-frame away from the support:
    - Strength I: 77,136 K-in.
    - Strength III: 36,696 K-in.
    - Strength V: 67,860 K-in.
  - By Eqs. (*4*) and (*2*), the required cross-frame stiffness, $\beta_T)_{req}$, is 225,883 kip-in./rad.
  - Actual cross-frame stiffness, $\beta_T)_{act}$, is 272,557 kip-in./rad.
  - Cross-frame has sufficient stiffness.

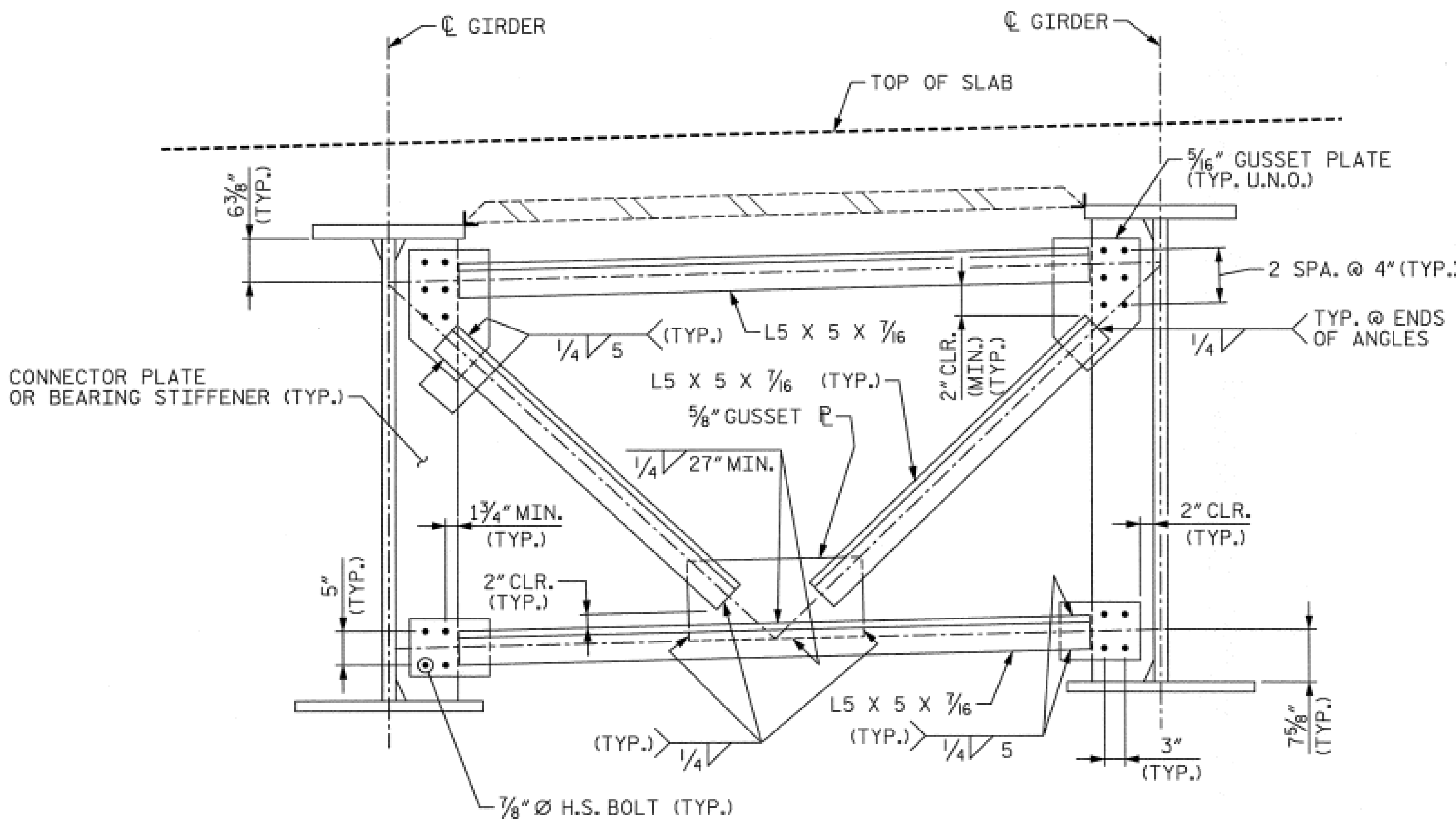
- Representative Calculations
  - Cross-frame strength requirements
  - Calculate bracing required strength per Eq. 3 (expressed as a moment value)
  - Convert to member force demands in chords and diagonals
  - Include consideration of wind loads
  - Select results for a cross-frame in a negative moment region:

Required bracing strength:

$$(M_{br})_{req} = \frac{(0.005) L_b\, L\, M_f^2}{n\, E\, I_{eff}\, C_b^2\, h_o}$$

Limit State	Load Factors				Wind Loading		Stability Bracing Forces		Total Loading	
	γ_{DC}	γ_{DW}	γ_{LL}	γ_{WS}	W_{chord} (kips)	W_{diag} (kips)	S_{chord} (kips)	S_{diag} (kips)	F_{chord} (kips)	F_{diag} (kips)
Str I	1.25	1.5	1.75	0.0	0.0	0.0	25.8	40.5	25.8	40.5
Str III	1.25	1.5	0	1.4	12.3	19.3	5.8	9.2	18.1	28.5
Str V	1.25	1.5	1.35	0.4	3.5	5.5	19.9	31.4	23.5	36.9

- Final Cross-Frame Design



Outline

- Stability Bracing
- Practical Implementation
- Design Example
- Summary

Outline

- Stability Bracing
- Practical Implementation
- Design Example
- Summary

Summary

- Discussed stability bracing strength and stiffness reqm'ts and implementation
- Yura's equations are simple, easy to use
- Interpretation for bridge use
  - Limit states, load combinations and factors
  - Consideration of negative moment regions
  - Practical design simplifications
- Design example
  - Forces not excessive
  - Member sizes reasonable
- Value of investigating stability bracing

Questions?