Steel I-Girder Cross Frames

Considerations for Design & Constructability

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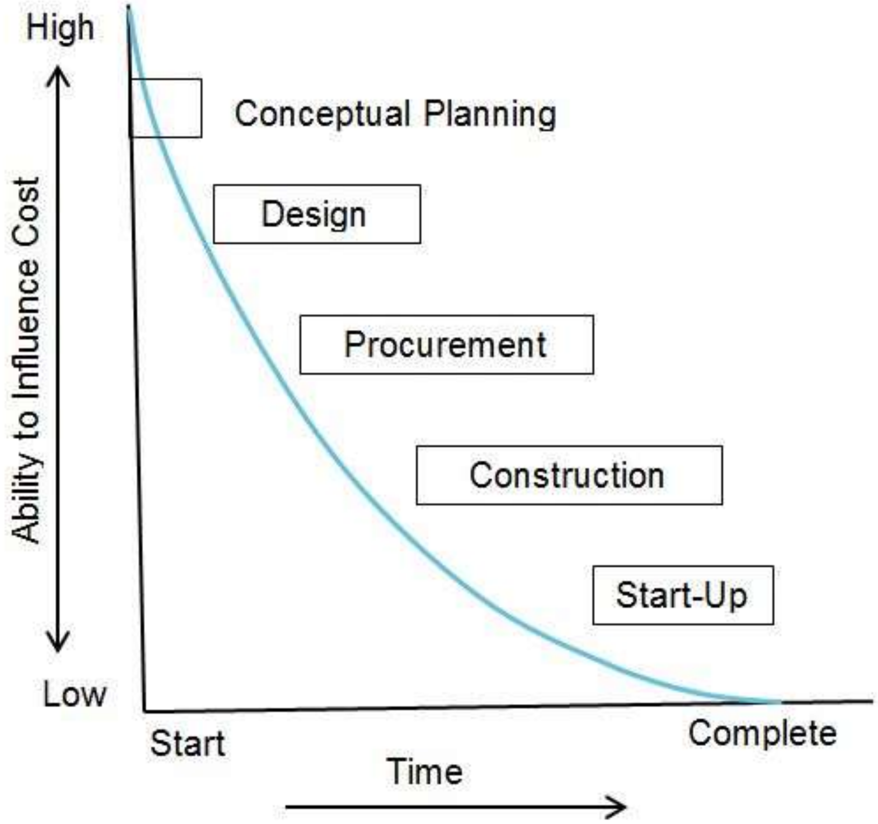
AECOM

Agenda

- **Design Considerations**
  - Bracing
  - Types of Cross Frames
  - Geometry & Layout
  - System Performance
  - Design Loads
  - Predicted Cambers & Deflections
  - Strength & Stiffness
  - Stability
- **Constructability Considerations**
  - Detailing
  - Coatings
  - Fit Condition

Design Considerations

Design Considerations



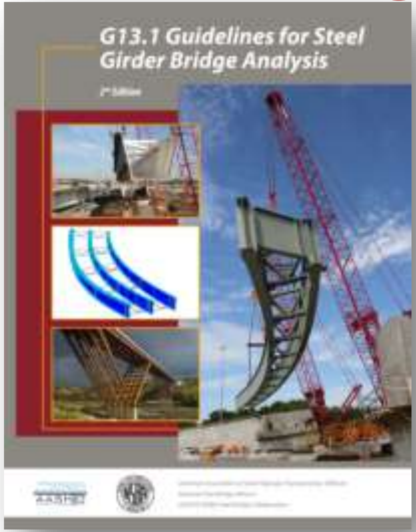
Cost-Influence

- Lightest bridge is not necessarily least cost bridge
- Balance between minimizing weight and minimizing labor
- On routine girder-bridges, fabricated cost of cross frames ranges 3x to 4x that of I-girders ($/lb)

Design Considerations

Bracing

Cross frame – *"a vertically oriented transverse truss framework connecting adjacent bending members" AASHTO/NSBA G13.1*



Two perspectives

- the girder
- the bridge (the "system")

Discrete braces (nodal torsional braces) which provide stability to the girders and system both during construction and in service

Design Considerations

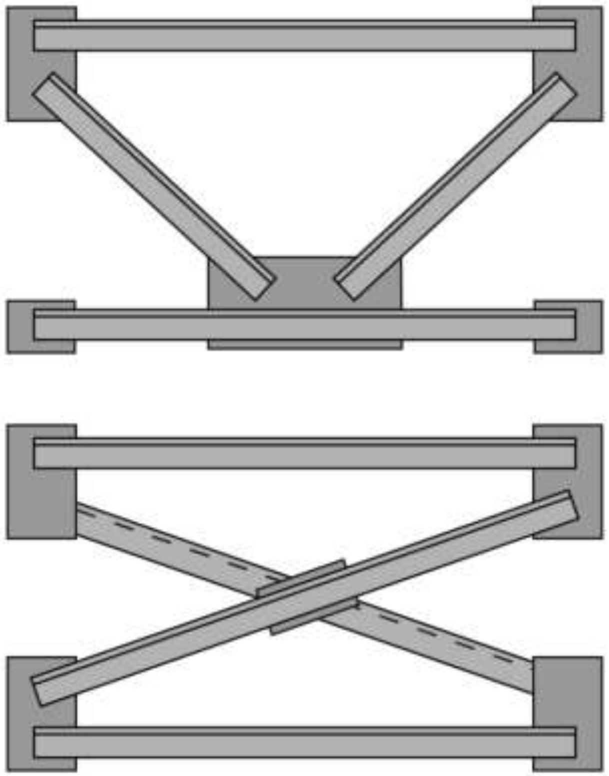
Bracing

Cross frame performs several functions:

- Provides stability to girders to resist buckling
- Provides stability to system to resist twist
- Transfers lateral wind loads from girders to the deck
- Transfers lateral wind loads from the deck to the supports
- Provides lateral support to the exterior girder during construction for the deck overhang brackets
- Transfers vertical dead load & live load (curved bridges)

Design Considerations

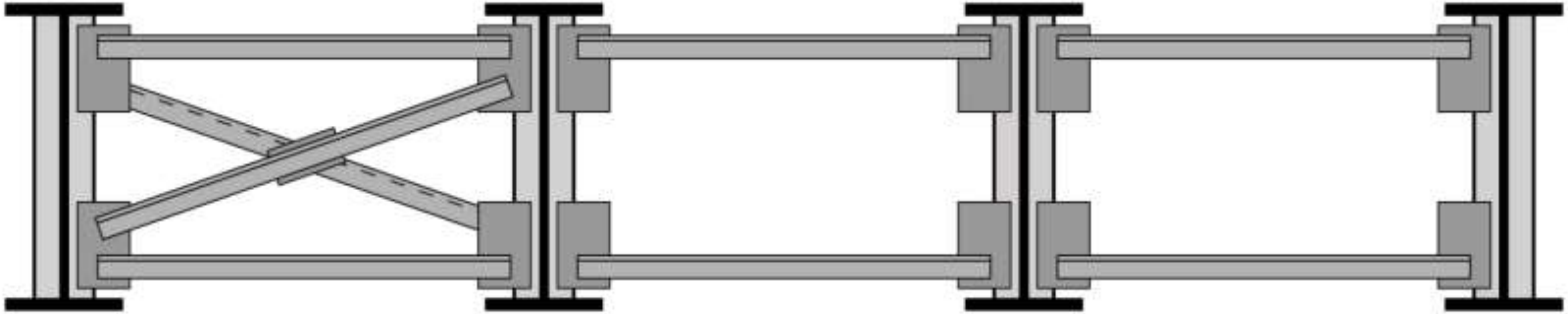
Types of Cross Frames



- K-type & X-type most common
- Provide flexibility in design and constructability
  - Angle of diagonal members based on girder depth & spacing
  - Length of diagonals and consideration of member buckling
  - Accommodation of utilities within a girder bay

Design Considerations

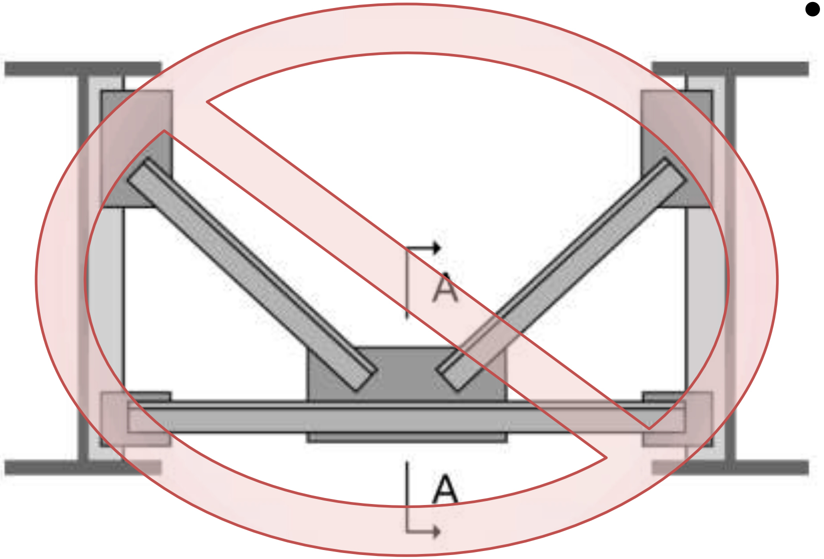
Types of Cross Frames



Lean-on Bracing

Design Considerations

Types of Cross Frames



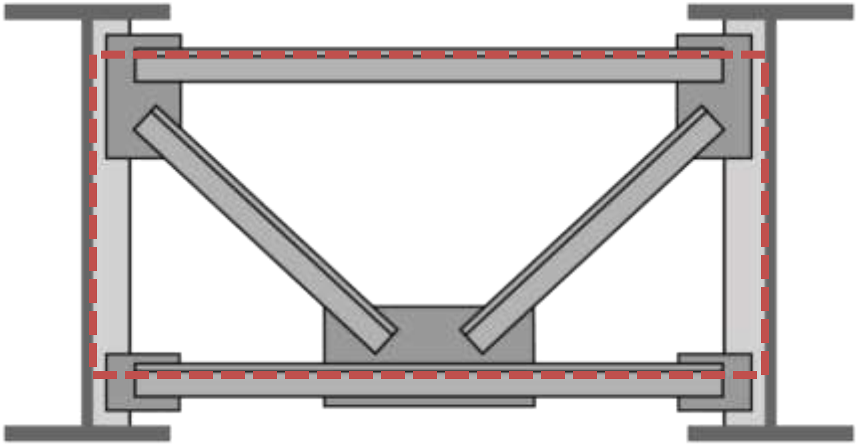
- K- or X-type cross frames should have top & bottom chord, even if analysis shows zero-force member

AASHTO/NSBA G13.1 & FHWA *Steel Bridge Design Handbook*

Stiffness is substantially reduced; essentially zero at middle ordinate (Section A-A)

Design Considerations

Types of Cross Frames

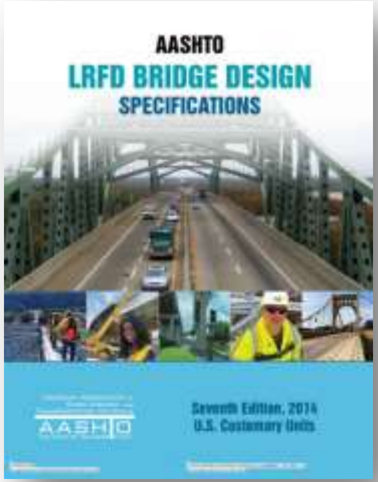


- Consider torsional resistance provided by an open and closed shape
- Open shape (e.g. I-girder) provides less torsional stiffness than closed shape (e.g. box girder)
- Pseudo-box shape

Design Considerations

Geometry & Layout

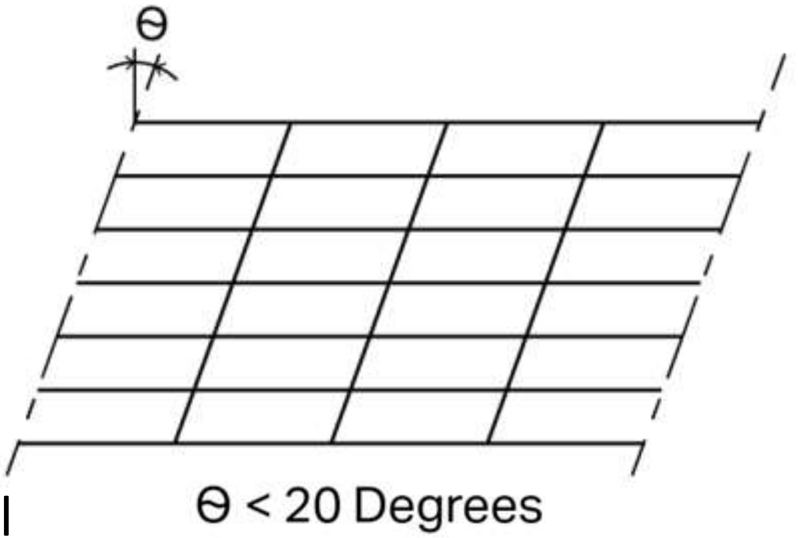
- Depth
  - Minimum of 75% Depth of I-Girder
- Spacing
  - No longer based on historical 25 feet
  - Reasonable spacing based on rational analysis
  - Reduces number of fatigue-prone attachments
  - Encouraged to follow analysis and investigation of strength & stiffness; both girder & system



Design Considerations

Geometry & Layout

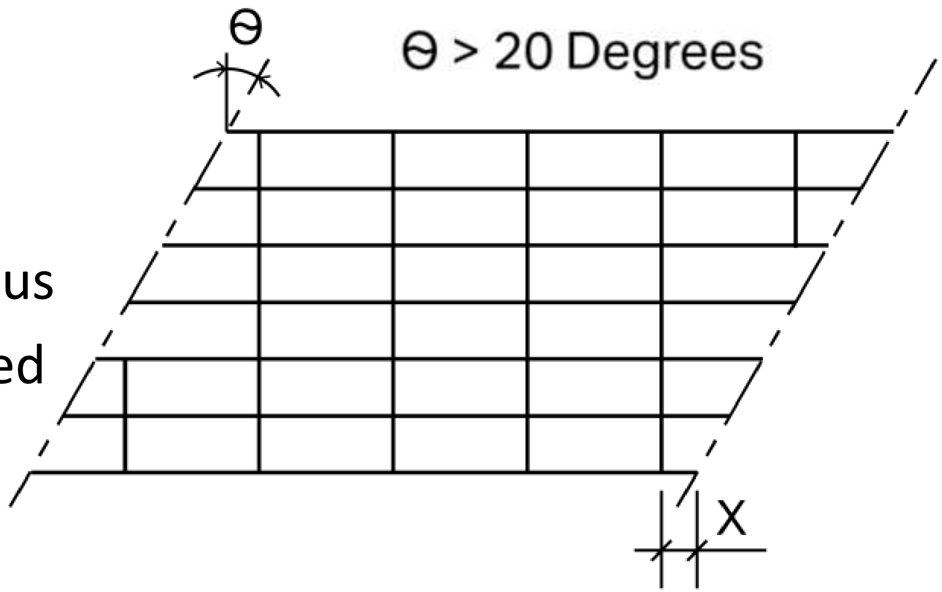
- No skew (square bridge)
  - Normal to girders
  - Contiguous
  - Promotes economy & satisfactory performance
- Less than 20 deg skew
  - Parallel to supports
  - Contiguous
  - Assist to mitigate girder differential deflections



Design Considerations

Geometry & Layout

- Greater than 20 deg skew
  - Normal to girders
  - Contiguous or staggered
  - Differential deflections
  - Less severe skew – contiguous
  - More severe skew - staggered

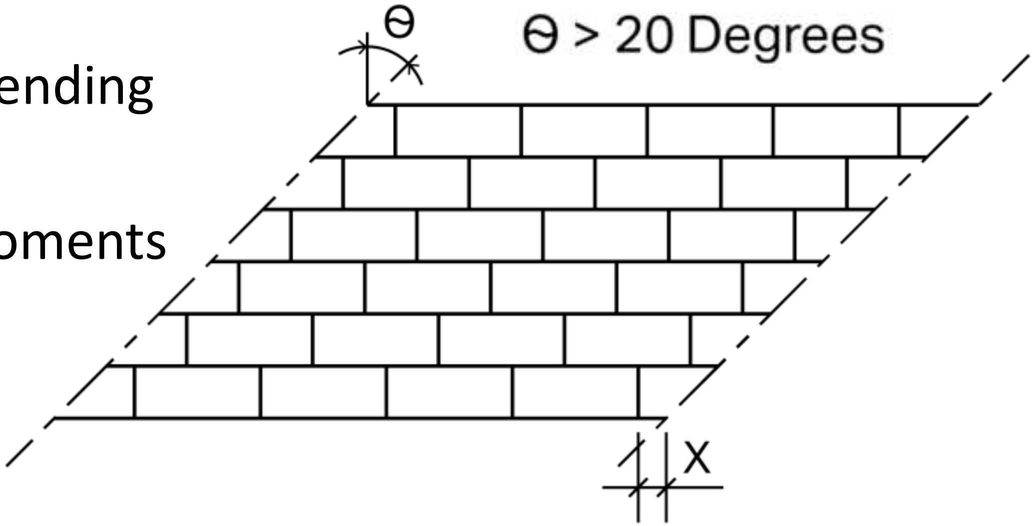


Contiguous Arrangement

Design Considerations

Geometry & Layout

- Staggered Arrangement
  - May be less susceptible to effects of differential deflections
  - Increases flange lateral bending moments
  - Flange lateral bending moments may differ from AASHTO; special analysis



Staggered Arrangement

Design Considerations

Response	Geometry	Worst-Case Scores		Mode of Scores	
		Traditional 2D-Grid	1D-Line Girder	Traditional 2D-Grid	1D-Line Girder
Major-Axis Bending Stresses	C ($I_C \leq 1$)	B	B	A	B
	C ($I_C > 1$)	D	C	B	C
	S ($I_S < 0.30$)	B	B	A	A
	S ($0.30 \leq I_S < 0.65$)	B	C	B	B
	S ($I_S \geq 0.65$)	D	D	C	C
	C&S ($I_C > 0.5$ & $I_S > 0.1$)	D	F	B	C
Vertical Displacements	C ($I_C \leq 1$)	B	C	A	B
	C ($I_C > 1$)	F	D	F	C
	S ($I_S < 0.30$)	B	A	A	A
	S ($0.30 \leq I_S < 0.65$)	B	B	A	B
	S ($I_S \geq 0.65$)	D	D	C	C
	C&S ($I_C > 0.5$ & $I_S > 0.1$)	F	F	F	C
Cross-Frame Forces	C ($I_C \leq 1$)	C	C	B	B
	C ($I_C > 1$)	F	D	C	C
	S ($I_S < 0.30$)	NA[a]	NA[a]	NA[a]	NA[a]
	S ($0.30 \leq I_S < 0.65$)	F[b]	F[c]	F[b]	F[c]
	S ($I_S \geq 0.65$)	F[b]	F[c]	F[b]	F[c]
	C&S ($I_C > 0.5$ & $I_S > 0.1$)	F[b]	F[c]	F[b]	F[c]

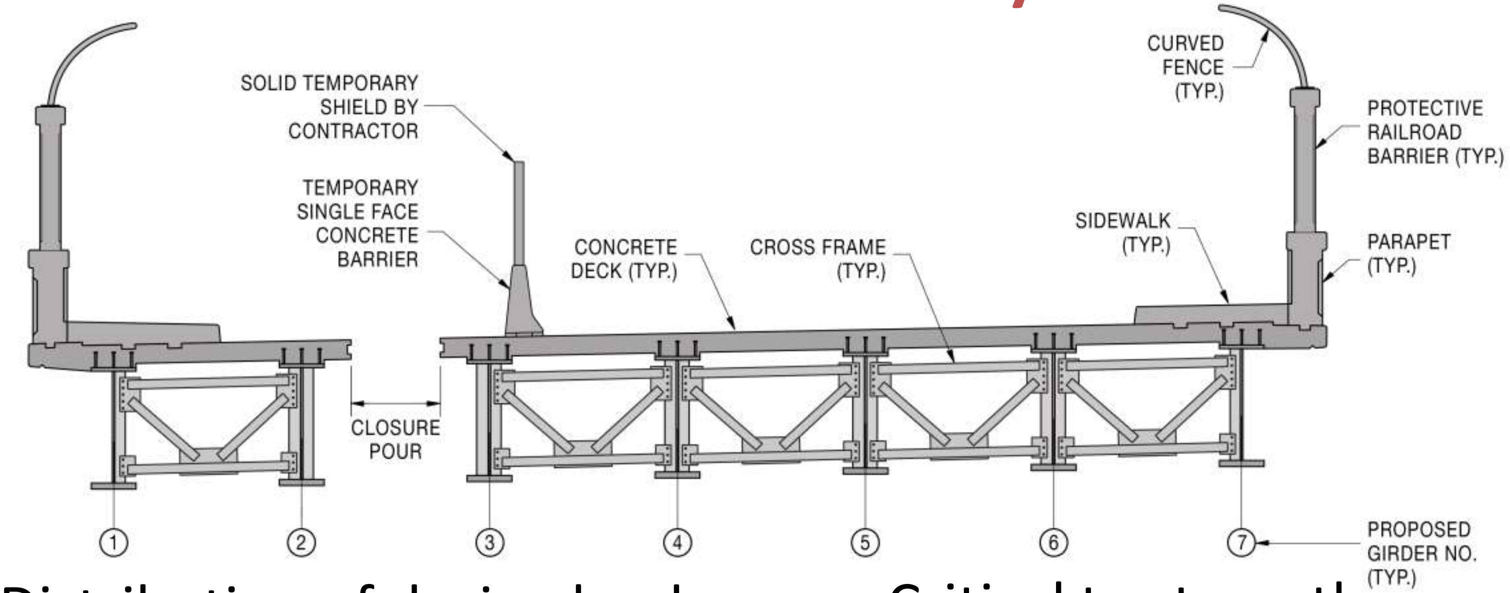
Excerpted from NCHRP Report 725

System Performance

- Location & orientation of cross frames influence behavior of system (stiffness)
- Consider location of cross frames w.r.t. supports
- Refer to NCHRP Report 725

Design Considerations

System Performance

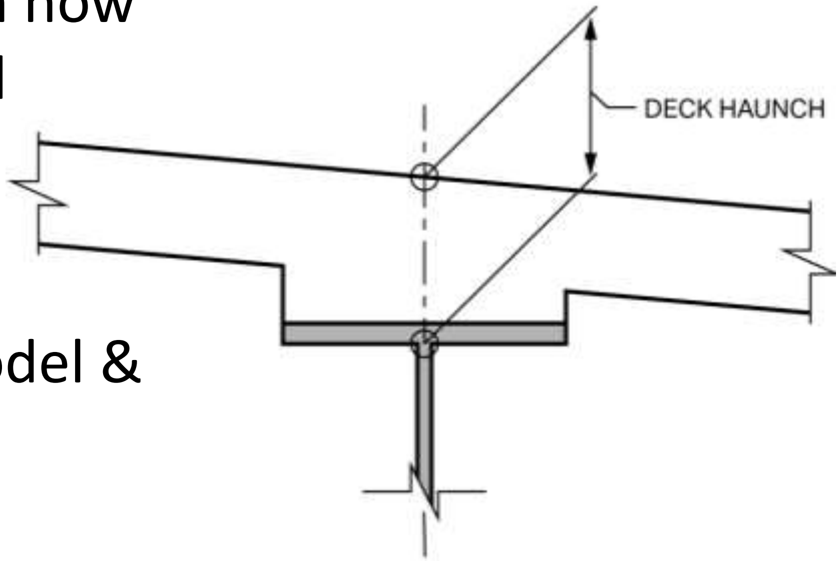


- Distribution of design loads largely influenced by **sequence of construction**
- Critical to strength assessment & prediction of **anticipated deflections**

Design Considerations

Predicted Camber

- Designer must be diligent in evaluating magnitude and timing of the loads
- Success of fit-up in structural steel & obtaining deck thickness relies on how well the deflections are predicted
- There is **no** "factor of safety" in predicting deflections
- Provide contingency between model & reality – Deck Haunch



Design Considerations

Strength & Stiffness

- Strength
  - Wind Load
  - Dead Load & Live Load (curved &…)
- Stiffness
  - Torsional brace system
  - FHWA *Steel Bridge Design Handbook* and AISC *Specification for Steel Buildings*
  - **Actual Stiffness > Required Stiffness**

$$\frac{1}{\beta_T} = \frac{1}{\beta_b} + \frac{1}{\beta_{sec}} + \frac{1}{\beta_g}$$

β_T = stiffness of torsional brace system

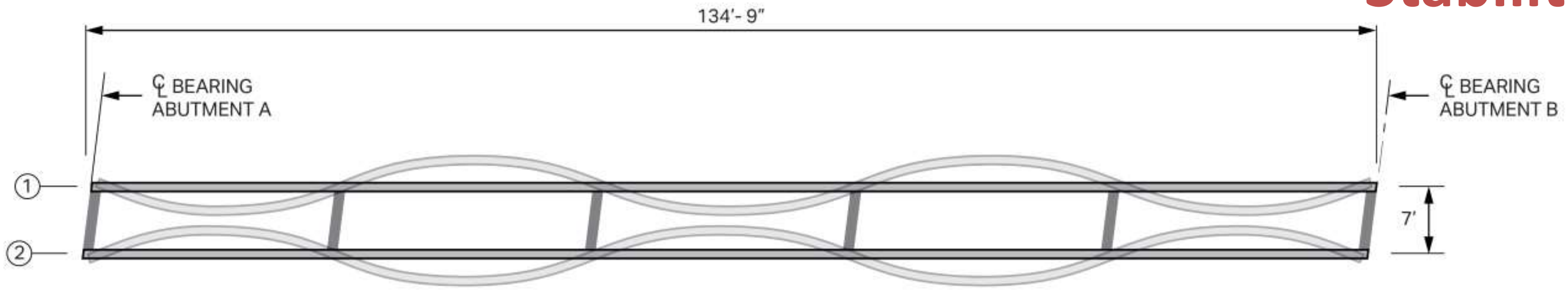
β_b = stiffness of cross frame and diaphragms

β_{sec} = distortional web stiffness

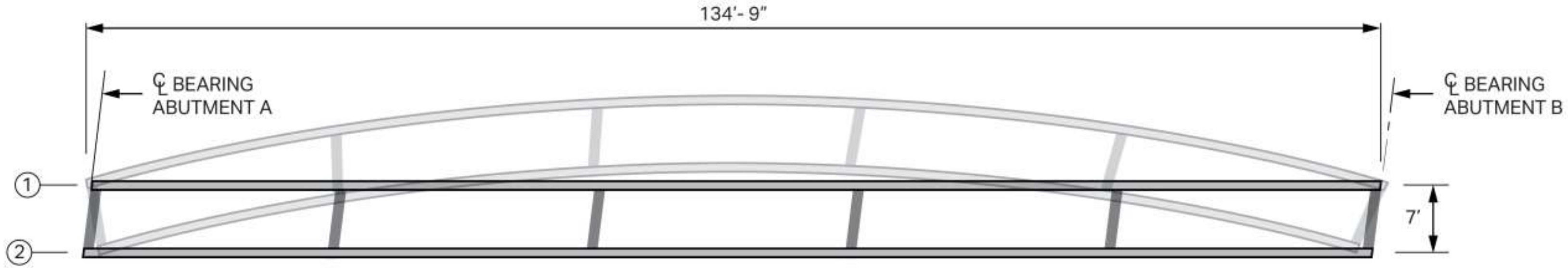
β_g = in-plane girder stiffness

Design Considerations

Stability



Individual Girder Buckling - Plan View



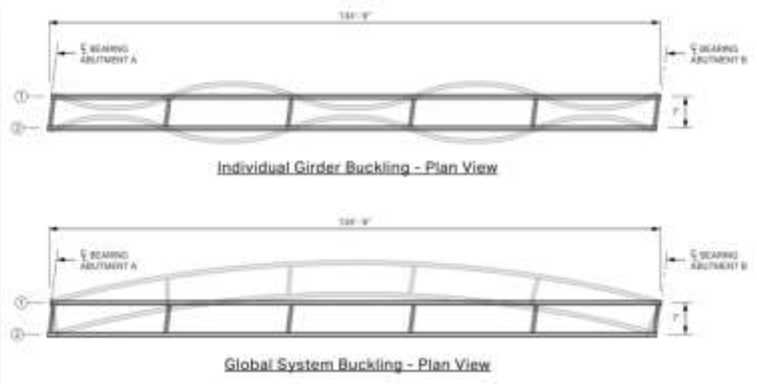
Global System Buckling - Plan View

Design Considerations

Stability

Narrow Systems

- 2-girder systems
- Length-to-spacing (L/s) ratio increases, girder and cross frames may potentially buckle as a single-unit
- 3 & 4-girder systems less likely to buckle but should be checked
- FHWA *Steel Bridge Design Handbook*



Constructability Considerations

Constructability Considerations

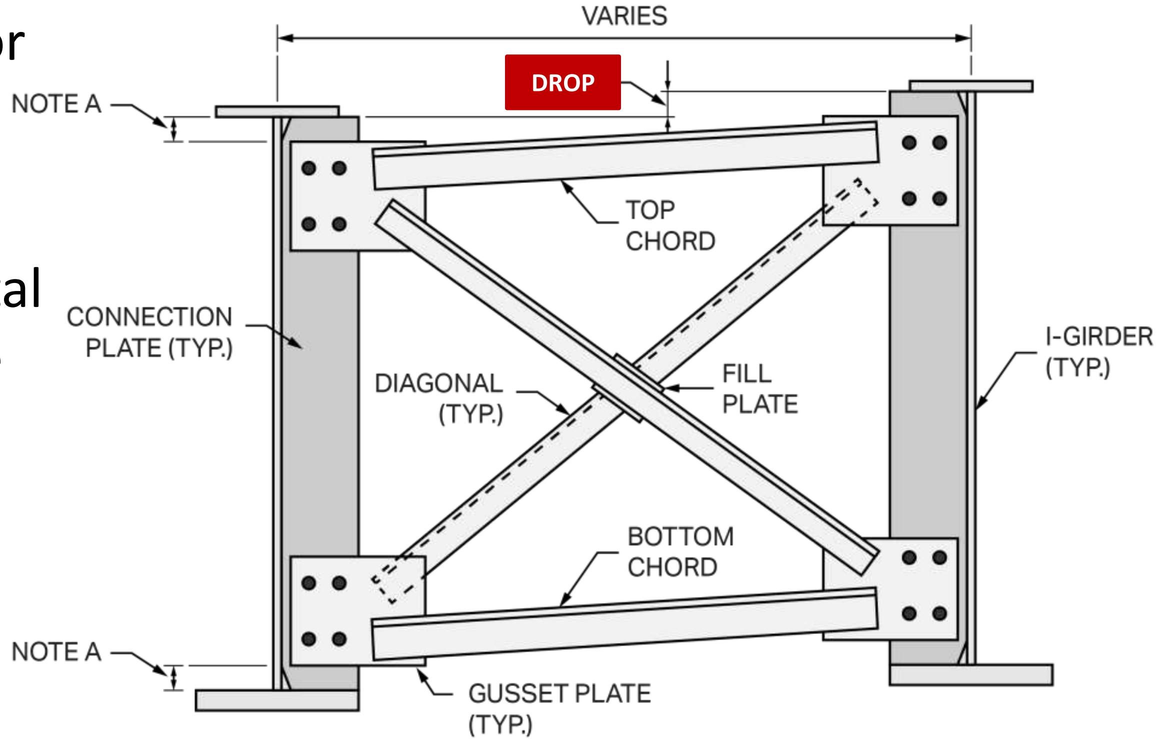
Geometry

Girders

- No-load camber used for web profile

Cross frames

- No-load, steel DL, or total DL used to compute the cross frame **drop**
- “Fit-Condition”

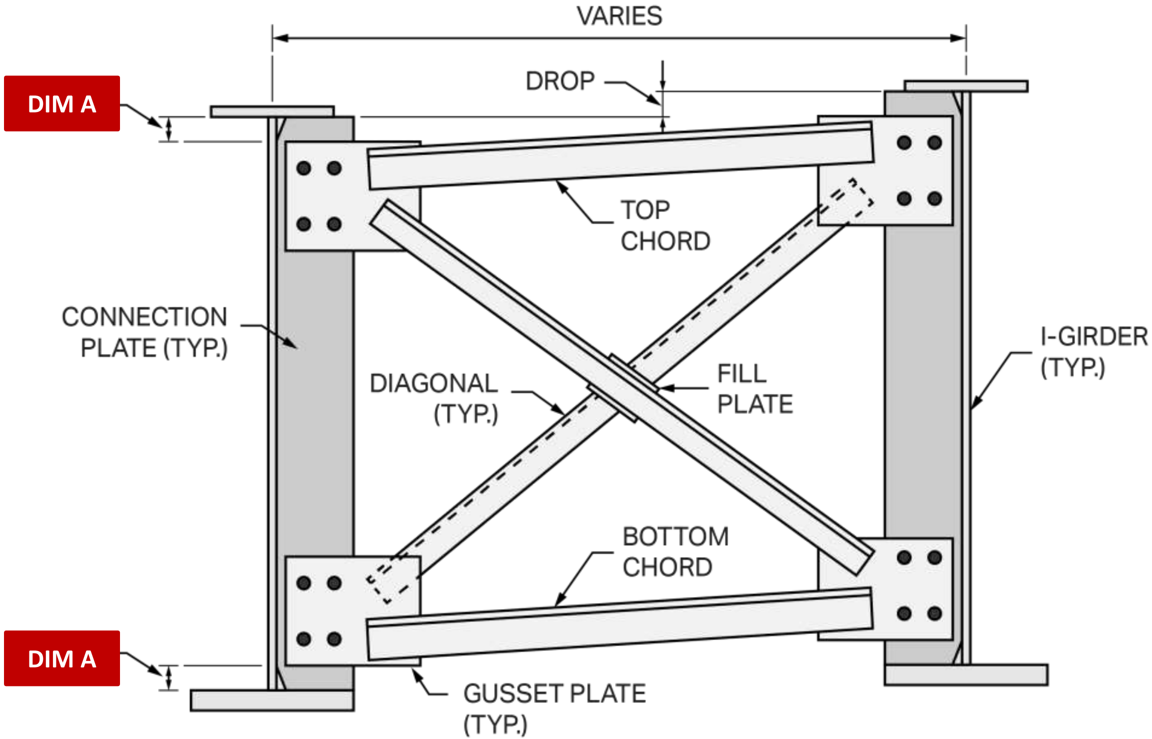


Constructability Considerations

Geometry

Cross frames

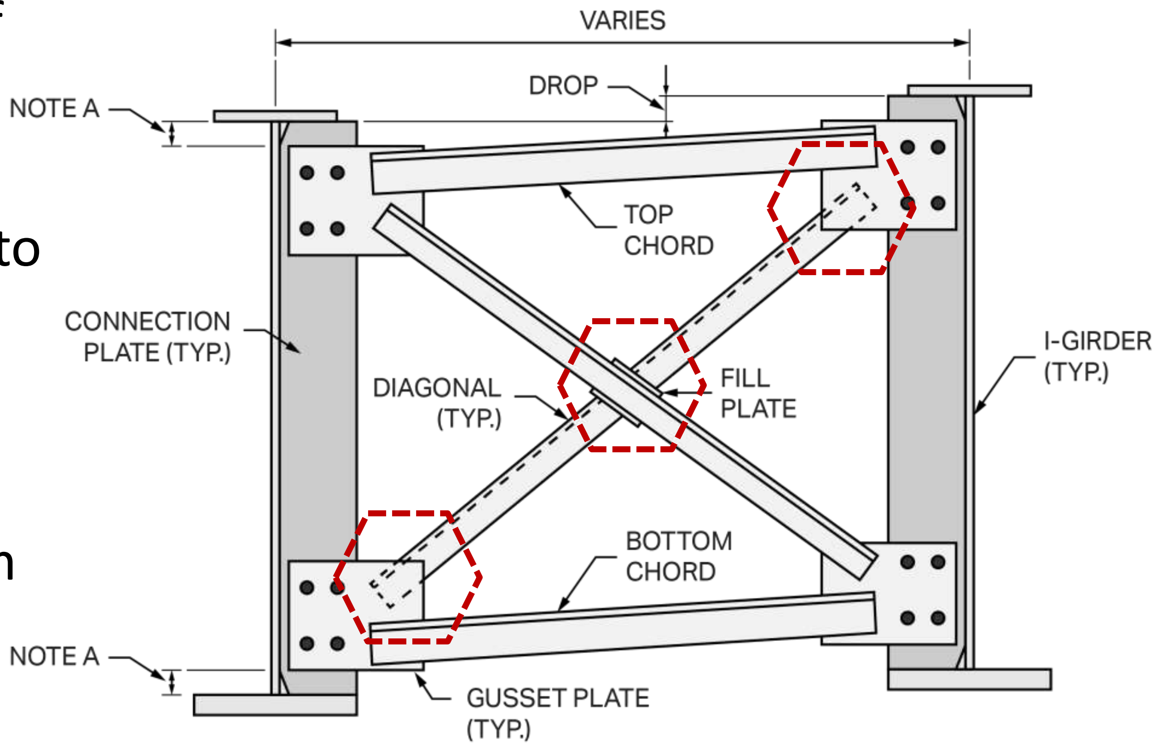
- Use constant dimension for all girders – top & bottom (**DIM A**)
- Facilitates fabrication for blocking in jig



Constructability Considerations

- Simple & Uniform
- Minimize the number of pieces, welding & shop handling
- Generally K-type easier to fabricate than X-type **(flipping the frame)**
- Maintain same type of cross frame to maximum extent possible

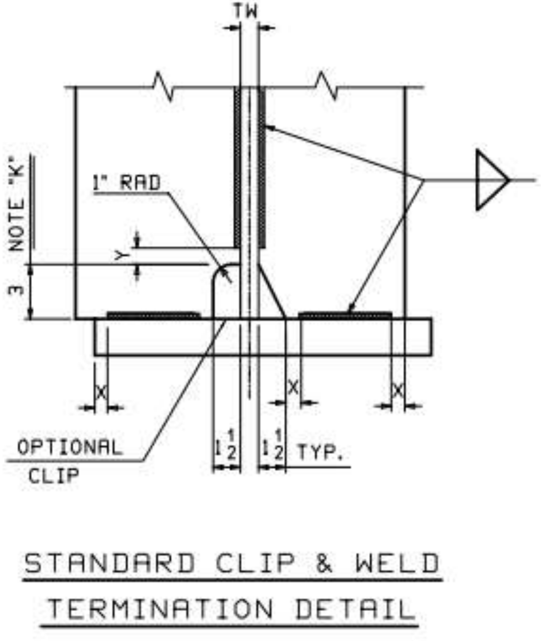
Members & Connections



Constructability Considerations

Members & Connections

- Use readily available shapes
- Single angles preferred
- Avoid back-to-back angles
- Avoid the use of structural tubes
- Minimize number of bolts & types of bolts
- Preferable to keep welding to one side

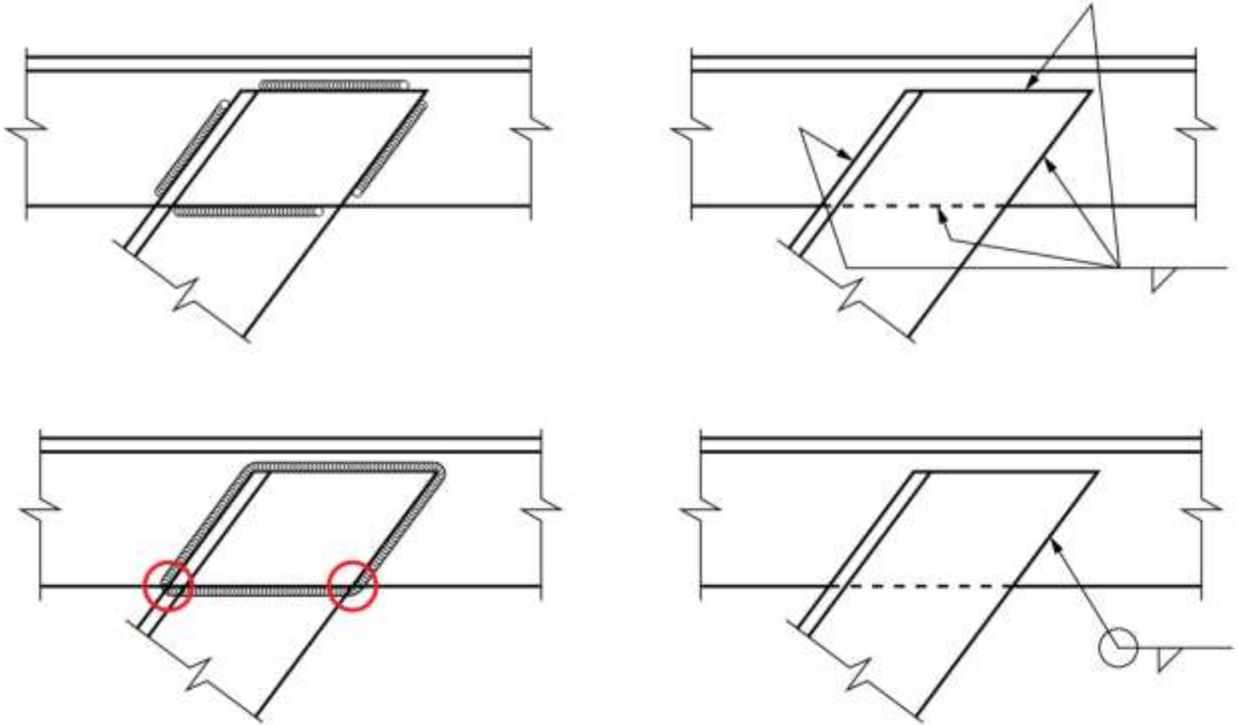


X=	1/4" +/- 1/8"
Y=	1/2" +/- 1/4"

AASHTO/NSBA G1.4-2006, p. 103

Constructability Considerations

Members & Connections

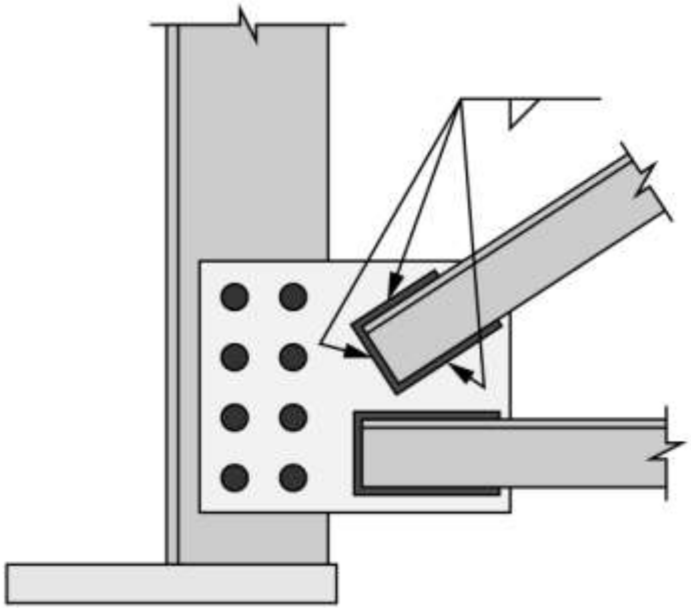


a) **Preferred** (welding through the corners not required)

b) **Not Preferred** (welding through the corners not preferred)

Constructability Considerations

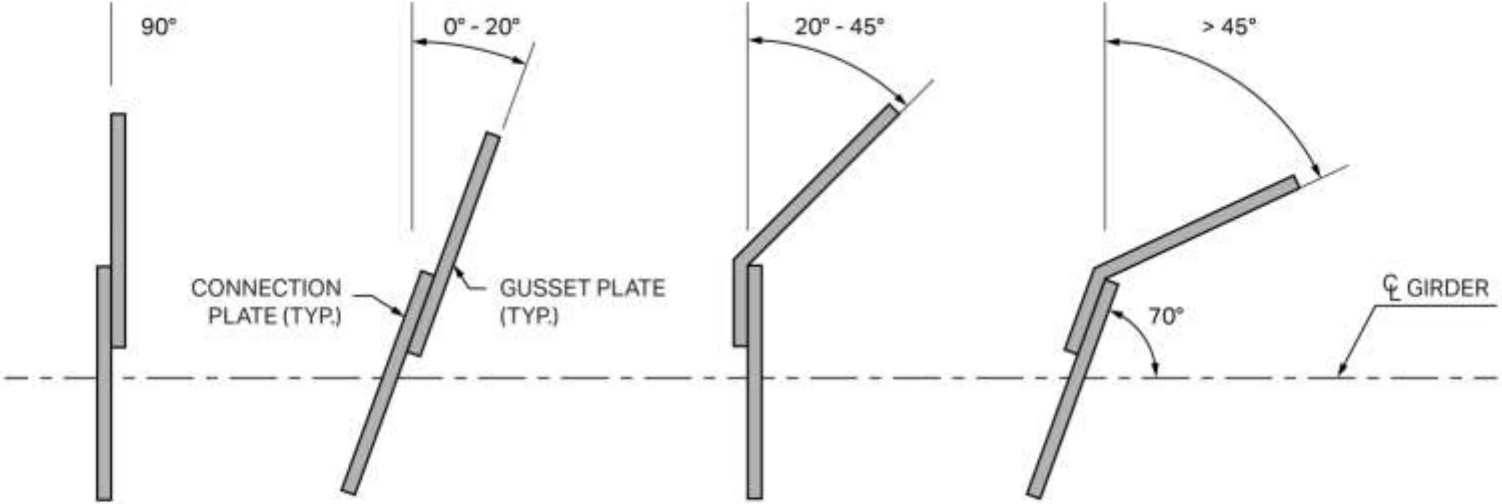
Members & Connections



Single-sided weld **preferred**

Constructability Considerations

Members & Connections



Skewed gusset to connection plate **(preferred)**

Constructability Considerations

Coatings

- Several Options
  - Painting
  - Galvanizing
  - Metalizing
- Slip Critical Connections
  - Clamping force by H.S. bolt pre-tensioned to load
  - Minimum slip coefficient of friction (μ)
- Design
  - Sized to determine number of bolts to prevent first slip
  - Checked for bearing

Painting
Galvanizing
Metalizing

Constructability Considerations

- Paint / PRIMER (Class A or B)
  - Primer qualified for use
  - Finish coat not applied to faying surfaces (masking)
  - Zinc-rich primers used today generally achieve Class B
- Galvanizing (Class C)
  - Hot dip galvanized in zinc bath
  - Consider for use on cross frames
  - Girders near the length of bath may be double-dipped

Coatings

Slip Coefficient

Class A (μ =0.33)

Class B (μ =0.50)

Class C (μ =0.33)

Constructability Considerations

Coatings

- Metalizing (***Class ?***)
  - Similar to paint where liquid zinc applied using spray-unit
  - Consider metalizing girders & galvanizing the cross frames
  - Porous coating with current practice recommending sealing
  - Do not seal the faying surfaces (masking)
  - ***Recently approved by AASHTO SCOBS in June 2016 for Class B Slip Coefficient…***

Slip Coefficient

Class A (μ =0.33)

Class B (μ =0.50)

Class C (μ =0.33)

Constructability Considerations

Fit Condition

- *Skewed and Curved Steel I-Girder Bridge Fit,* Chavel et al.
- NSBA White Paper on NSBA Website
- Recently Updated August 2016

Constructability Considerations

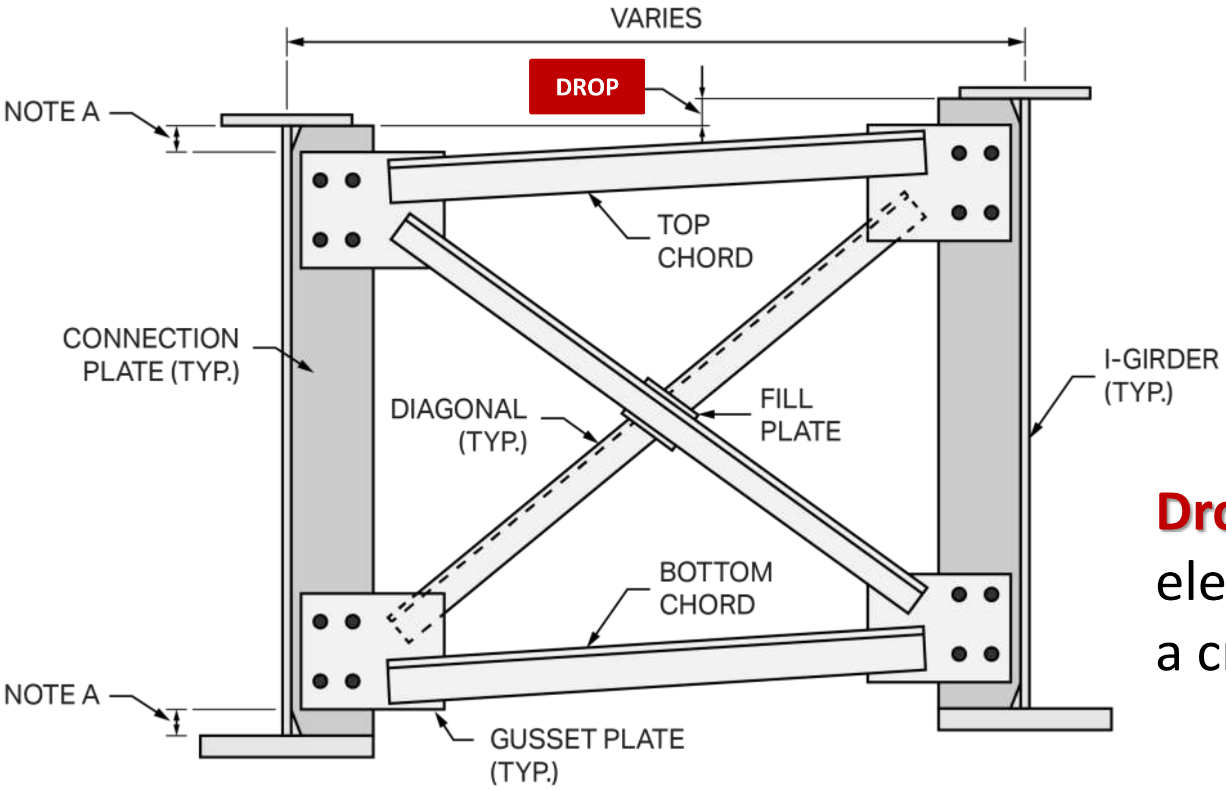
Fit Condition

Fit Condition – "refers to the deflected girder geometry with a specific load condition in which the cross-frames or diaphragms are detailed to connect to the girders"

Fit-up – assembly of the steel during erection

Constructability Considerations

Fit Condition



Drop – "difference in elevation on either side of a cross-frame"

Constructability Considerations

Fit Condition

Table 1 **Common Fit Conditions**

Loading Condition Fit	Construction Stage Fit	Description	Practice
No-Load Fit (NLF)	Fully-Cambered Fit	The cross-frames are detailed to fit to the girders in their fabricated, plumb, fully-cambered position under zero dead load.	The fabricator (detailer) sets the drops using the no-load elevations of the girders (i.e., the fully cambered girder profiles).
Steel Dead Load Fit (SDLF)	Erected Fit	The cross-frames are detailed to fit to the girders in their ideally plumb as-deflected positions under the bridge steel dead load at the completion of the erection.	The fabricator (detailer) sets the drops using the girder vertical elevations at steel dead load, calculated as the fully cambered girder profiles minus the steel dead load deflections.
Total Dead Load Fit (TDLF)	Final Fit	The cross-frames are detailed to fit to the girders in their ideally plumb as-deflected positions under the bridge total dead load.	The fabricator (detailer) sets the drops using the girder vertical elevations at total dead load, which are equal to the fully cambered girder profiles minus the total dead load deflections.

Ref: Chavel et al., 2016, *Skewed and Curved Steel I-Girder Bridge Fit*

Constructability Considerations

Fit Condition

Table 2 **Recommended Fit Conditions for Straight I-Girder Bridges (including Curved I-Girder Bridges with L/R in all spans ≤ 0.03)**

Square Bridges and Skewed Bridges up to 20 deg Skew			
	Recommended	Acceptable	Avoid
Any span length	Any		None
Skewed Bridges with Skew > 20 deg and $I_s \leq 0.30$ +/-			
	Recommended	Acceptable	Avoid
Any span length	TDLF or SDLF		NLF
Skewed Bridges with Skew > 20 deg and $I_s > 0.30$ +/-			
	Recommended	Acceptable	Avoid
Span lengths up to 200 ft +/-	SDLF	TDLF	NLF
Span lengths greater than 200 ft +/-	SDLF		TDLF & NLF

$$I_s = \frac{w_g \tan\theta}{L}$$

Ref: Chavel et al., 2016, *Skewed and Curved Steel I-Girder Bridge Fit*

Constructability Considerations

Fit Condition

Table 3 **Recommended Fit Conditions for Horizontally Curved I-Girder Bridges**
($(L/R)_{MAX} > 0.03$)

Radial or Skewed Supports			
	Recommended	Acceptable	Avoid
$(L/R)_{MAX} \geq 0.2$	NLF[1]	SDLF[2]	TDLF
All other cases	SDLF	NLF	TDLF

Note 1: The recommendation transitions to NLF at or above a maximum L/R of 0.2 because research on these types of bridges (NCHRP 2015) shows that the increase in the cross-frame forces from SDLF detailing can become more significant as the degree of curvature increases.

Note 2: SLDF detailing is considered acceptable in these cases if the additive locked-in force effects are considered (see Design and Analysis section below).

Ref: Chavel et al., 2016, *Skewed and Curved Steel I-Girder Bridge Fit*

Thank You

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Industry References

- AASHTO/NSBA G1.4-2006 *Guidelines for Design Details*
- AASHTO/NSBA S10.1-2014 *Steel Bridge Erection Guide Specification*
- AASHTO/NSBA G12.1-2003 (2016) *Guidelines for Design for Constructibility*
- AASHTO/NSBA G13.1-2014 *Guidelines for Steel Girder Bridge Design*
- FHWA/NSBA *Steel Bridge Design Handbook* (2015)
- NSBA White Paper *Skewed and Curved Steel I-Girder Bridge Fit* (Aug 2016)
- NCHRP 725 *Guidelines for Analytical Methods and Construction Engineering of Curved and Skewed Steel Girder Bridges* (2012)