Illinois Department of Transportation

Memorandum

To:	ALL BRIDGE DESIGNERS	19.4
From:	D. Carl Puzey	
Subject:	Steel Structure Analysis and Cross-Frame/Diaphragm Policy Updates	
Date:	April 15, 2019	

AASHTO LRFD Bridge Design Specifications, 8th Edition (AASHTO) commentary C6.10.1 contains guidance regarding simplifications of lateral stress calculations in steel beams for skewed bridges with discontinuous diaphragms. The commentary provides engineers an estimate of lateral stresses, while still allowing a line girder analysis using the live load distribution factors found in Article 4.6.2.2 of the AASHTO code. IDOT has further investigated the use of discontinuous diaphragms and cross frames on skewed structures. 3D finite element analyses were performed on various bridge lengths, widths, skews, and span ratios, and compared to the results of the distribution factors utilized in a line girder analysis. This research has resulted in the following policy changes regarding analysis procedures and cross-frame/diaphragm details.

Analysis Procedures for Non-Curved Skewed Steel Structures

- For straight steel structures (or equivalently straight structures as per AASHTO Article 4.6.1.2.4b) with skews less than or equal to 60 degrees, a line girder analysis shall be used. This is consistent with the practices used by the Bureau of Bridges and Structures Ratings Unit when performing bridge ratings.
- For straight steel structures with skews greater than 60 degrees, a higher level of analysis such as a 2D grid analysis shall be performed. The results of this higher-level analysis shall be used for all force effects on the bridge, both lateral and vertical. Vertical force effects from a line girder analysis and lateral force effects from a higher level of analysis shall not be combined.

Designers should note that use of a higher level of analysis will require diaphragm and cross-frame members and connections to be designed, as they will be considered primary members. The design shall be in accordance with AASHTO Article 6.7.4. Therefore, for bridges with skews exceeding 60 degrees, the Department's standard cross-frame/diaphragm details may be insufficient. The force effects used to design the diaphragms and cross-frames shall be those generated by the higher-level analysis. Typically, a design will result in cross-frames with top chords and larger members (e.g. L5x5 members instead of the typical L4x4 members), larger bolt groups for the cross-frame connections (e.g. a 5x2 bolt pattern instead of the standard 3x1 bolt pattern), and longer weld lengths to accommodate the higher loads. Primary members and connections in tension are also required to use Charpy V-Notch (CVN) tested steel, and this shall be noted on the plans. Diaphragms and cross-frames which are primary members shall have all elements, including the connection plates or stiffener plates, so designated.

Designers should be aware that, when performing a higher-level analysis, use of 2D analyses such as grillage or plate-and-eccentric-beam may result in inaccurate values for lateral force effects because of simplifications that are inherent in these analysis types. Moreover, most design software will output the envelope of the most conservative values, meaning the results of the analysis from the software will typically be inaccurate on the conservative side. NCHRP Report 725: Guidelines for Analysis Methods and Construction Engineering of Curved and Skewed Structures gives recommendations to account for this and may be used as a guide to help produce more accurate lateral force effects should the results of a 2D grid analysis yield outcomes that appear to be inaccurate or excessive. This report is referenced in AASHTO commentary C6.10.1 as "White et al. (2012)."

Lateral Flange Stresses for Skewed Steel Structures

AASHTO commentary C6.10.1 states that, for bridges with skews greater than 20 degrees, lateral stresses (f_l) of 10 ksi may be assumed in lieu of performing a more rigorous analysis. The Department has performed research to determine the accuracy of this value. The research has shown that, for structures with discontinuous diaphragms that utilize Illinois diaphragm/cross-frame connection details, this 10 ksi value is accurate or conservative for structures with skews between 45 and 60 degrees. For skews less than or equal to 45 degrees with typical staggered diaphragms, this additional stress may be ignored. Therefore, the following policy shall be used:

- For structures with skews less than or equal to 45 degrees, f_l shall be assumed to be 0 ksi.
- For structures with skews greater than 45 degrees and less than or equal to 60 degrees, f_l shall be assumed to be 10 ksi, which includes both dead load and live load. For Fatigue load combinations, only live load applies, and the lateral flange stress shall be taken as 5 ksi. The lateral stresses are considered factored; thus, no further load factors need be applied.
- For structures with skews greater than 60 degrees, a higher level of analysis is required, and the lateral flange stress results of that analysis shall be used when designing the beams.

When lateral flange stresses are included in the design of the beam, they shall be included on the Beam Moment Tables on the design plans. See attached Moment Table examples, Figures 4 and 5, which have been revised from ABD memo 15.3.

Interior Diaphragm/Cross-Frame Orientation for Bridges with Skews Less than or Equal to 20 Degrees

Current IDOT practice is that, for bridges with skews less than or equal to 10 degrees, diaphragms and cross-frames shall be oriented in a continuous (i.e. not staggered) manner, parallel to the skew. The intent of this policy was to avoid detail congestion and possible stress concentrations at locations where two non-staggered diaphragms/ cross-frames may tie into the beams at close proximity to one another. To better follow the guidance in AASHTO Article 6.7.4 and commentary C6.10.1, this skew limit shall be increased to 20 degrees. Therefore, for all bridges with skews less than or equal to 20 degrees, the designer shall orient the diaphragms and cross-frames along the skew, forming one continuous line. Please see the attached Figures 1 through 3 for details of this connection.

Interior Diaphragm Connection Detail Clarification for Rolled Beams

The current Bridge Manual Figure 3.3.22-1 details a diaphragm connection with only a bent plate connection to the web, and Figure 3.3.22-2 is also not compliant with the previous AASHTO requirements discussed. These details shall be replaced with the new details on the attached Figure 2. The interior cross frame details of Bridge Manual Figure 3.3.22-3 have also been updated and included in Figure 3.

Bearing Stiffeners and End Diaphragms/Cross-Frames

To maintain consistency and comply with the previously discussed AASHTO requirements, end diaphragms or cross-frames for bridges with skews less than or equal to 20 degrees shall have similar details to interior diaphragms or cross-frames.

Bearing stiffeners shall now be required for all wide flange beams and plate girders, whereas previously they were only required for plate girders. The bearing stiffeners shall serve as the connection plates for the diaphragms or cross-frames. To allow for some level of corrosion loss at beam ends near the abutments with joints, minimum bearing stiffener thickness at these locations shall be 1", but may be thicker if required by design. For skews less than or equal to 20 degrees, the bearing stiffeners shall be placed along the skew.

Wide flange beams and plate girders with web depths less than 40" and with skews greater than 20 degrees shall both have the centerline of the diaphragms offset from the centerline of bearing to one continuous centerline of diaphragms along the entire support. This shall be achieved by adding an additional connection plate to the beam. Plate girders with cross-frames shall use a similar detail for skews up to 45 degrees. Plate girders with cross-frames and skews greater than or equal to 45 degrees shall use the attached cross-frame details in Figures 10 through 12. These are similar to the existing Bridge Manual details, except various cross frame members and plate sizes have been adjusted to reduce steel congestion. All current Bridge Manual figures for Section 3.3.23 shall be replaced by the attached end diaphragm/cross-frame details, see Figures 6 through 17.

These policies shall be implemented on bridges with TSL's approved after June 1, 2019 and are encouraged to be implemented where feasible on bridges under design where plans have not been submitted for approval.

If you have any questions, please contact Mark Shaffer of the Policy, Standards, and Final Plan Control Unit at (217) 785-2914.

MDS/kktABD19.4-20190415

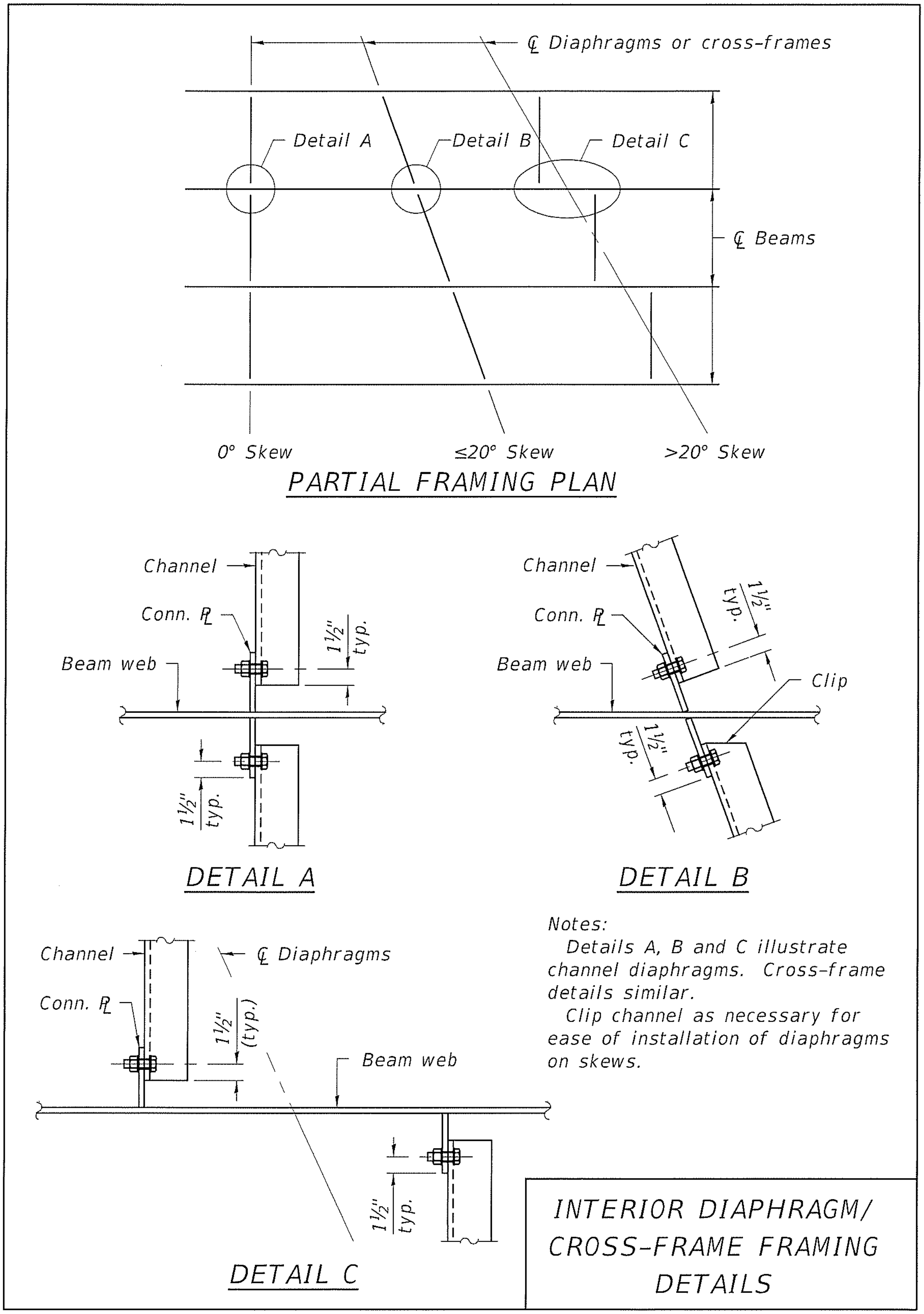
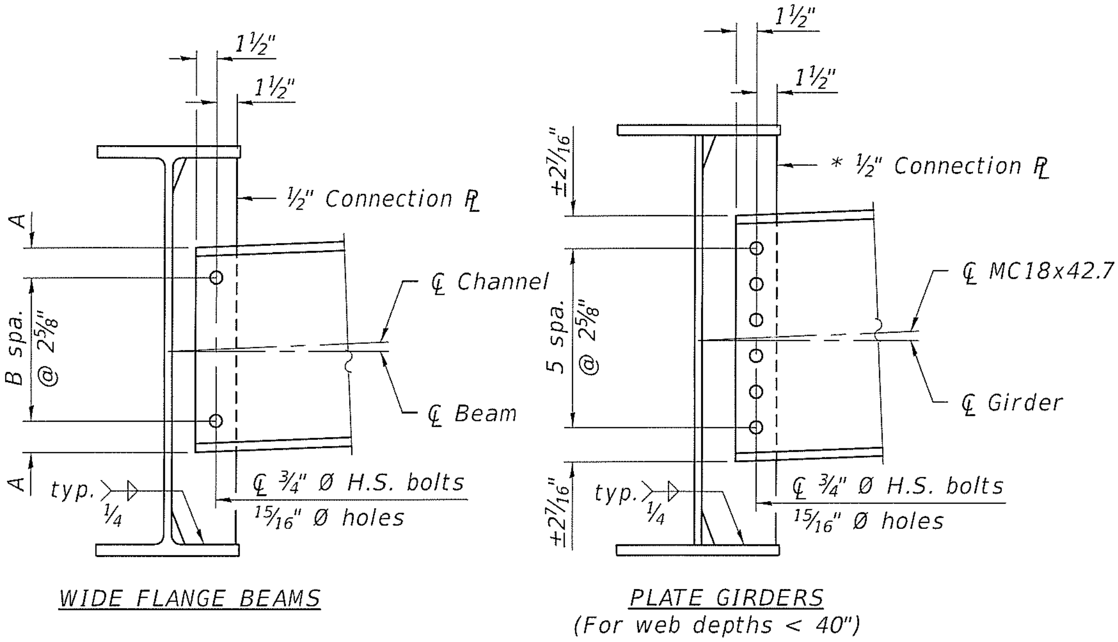

℄ Diaphragms or cross-frames
Detail A
Detail B
Detail C
℄ Beams
0° Skew
≤20° Skew
>20° Skew
PARTIAL FRAMING PLAN
Channel
Conn. ℘
Beam web
1½" typ.
DETAIL A
Channel
Conn. ℘
Beam web
Clip
1½" typ.
DETAIL B
Channel
℄ Diaphragms
Conn. ℘
1½" (typ.)
Beam web
1½" typ.
DETAIL C
Notes:
Details A, B and C illustrate channel diaphragms. Cross-frame details similar.
Clip channel as necessary for ease of installation of diaphragms on skews.
INTERIOR DIAPHRAGM/ CROSS-FRAME FRAMING DETAILS

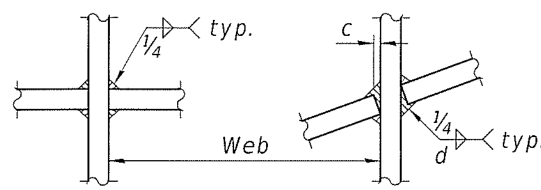
Figure 1



INTERIOR DIAPHRAGMS

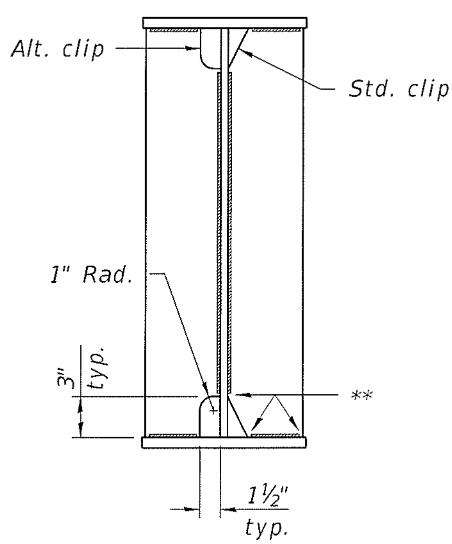
* May also function as transverse stiffener or bearing stiffener. In these cases, plate thickness and weld size by design.

Beam Size	Channel	A	B
W21 to W24	C12 x 25	±2 1⁄16"	3
W27 to W30	C15 x 40	±2¼"	4
W33 to W36	MC18 x 42.7	±2 7⁄16"	5



WEB WELD DETAIL

d = ¼ + c



WELD LIMITS AND CLIP DETAILS

** Stop welds ¼" (±⅛") from edges as shown. Typical.

Notes:

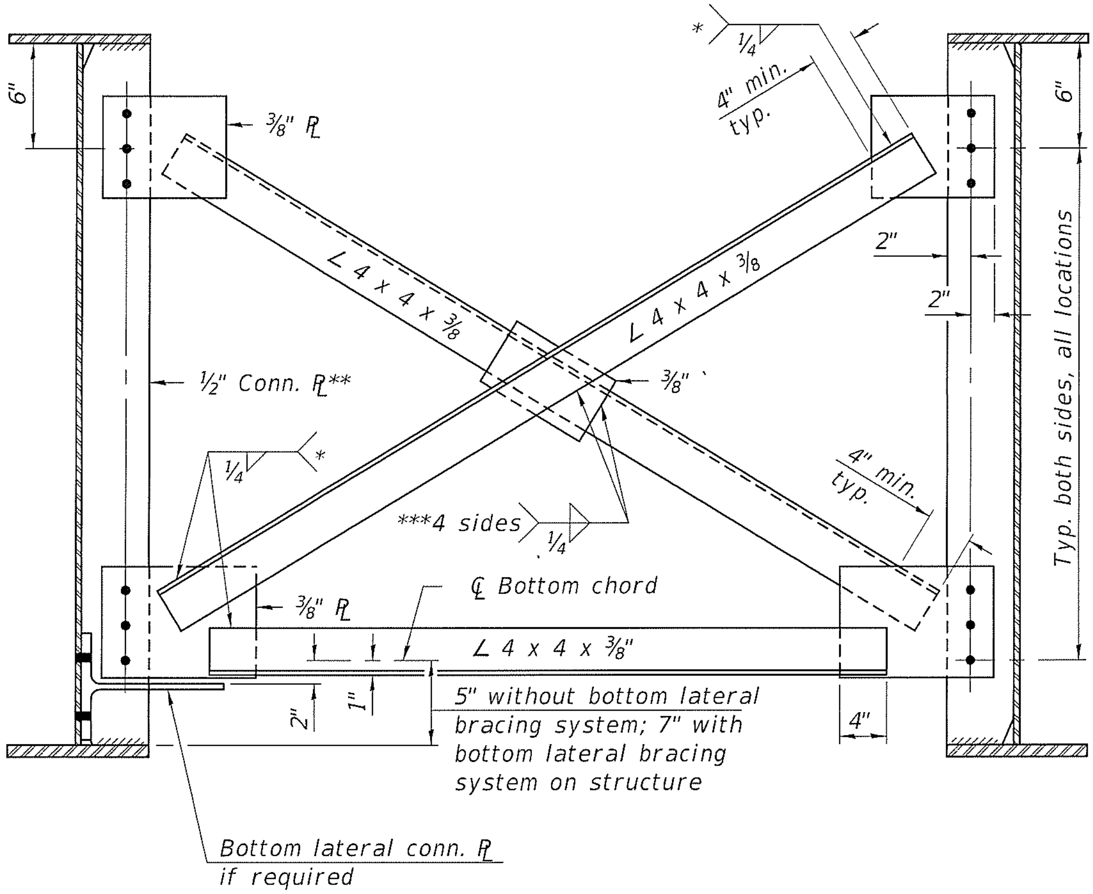
Two hardened washers required for each set of oversized holes.

Alternate channels of equal depth and larger weight are permitted to facilitate material acquisition. Alternate channels, if utilized, shall be provided at no additional cost to the Department.

See Interior Diaphragm/Cross-Frame Framing Details for connection plate orientation.

INTERIOR DIAPHRAGM CONNECTION DETAILS

Figure 2



TYPICAL INTERIOR CROSS-FRAME

(Detail for welded girders ≥ 40" in depth).

* Fillet weld angles along 3 sides on one face of gusset plate; however, if cross-frames are galvanized, weld all-around.

** May also function as transverse stiffener. Plate thickness and weld size by design.

*** If cross-frames are galvanized, weld all-around.

Notes:

Detail 15/16" Ø holes for all 3/4" Ø bolts (1 1/16" Ø holes for all 7/8" Ø bolts only if required by design).

Two hardened washers required for each set of oversized holes.

See Interior Diaphragm/Cross-Frame Framing Details for connection plate orientation.

See Interior Diaphragm Connection Details for weld and clip details.

INTERIOR CROSS-FRAME CONNECTION DETAILS

Figure 3

Moment table – Symmetrical composite 2 span
(Composite in positive and negative moment areas)

INTERIOR GIRDER MOMENT TABLE			
		0.4 Sp. 1 or 0.6 Sp. 2	Pier
I_s	(in^4)		
$I_c(n)$	(in^4)		
$I_c(3n)$	(in^4)		
$I_c(cr)$	(in^4)		
S_s	(in^3)		
$S_c(n)$	(in^3)		
$S_c(3n)$	(in^3)		
$S_c(cr)$	(in^3)		
DC1	(k/')		
M_{DC1}	('k)		
DC2	(k/')		
M_{DC2}	('k)		
DW	(k/')		
M_{DW}	('k)		
LLDF			
M_{LL+IM}	('k)		
* f_ℓ (Strength I)	(ksi)		
$M_u + \frac{1}{3} f_\ell S_{xc}$	('k)		
$\phi_f M_n$	('k)		
f_s DC1	(ksi)		
f_s DC2	(ksi)		
f_s DW	(ksi)		
f_s (LL+IM)	(ksi)		
* f_ℓ (Service II)	(ksi)		
$f_s + \frac{f_\ell}{2}$ (Service II)	(ksi)		
$0.95 R_h F_{yf}$	(ksi)		
$f_s + \frac{f_\ell}{3}$ (Total)(Strength I)	(ksi)		
$\phi_f F_n$	(ksi)		
V_f	(k)		

* f_ℓ = 10ksi. Factors are already included.
Applicable only for skews > 45 and ≤ 60
For skews >60°, f_ℓ is as per design.

GIRDER REACTION TABLE					
		Abut.		Pier	
		Interior	Exterior	Interior	Exterior
LLDF					
OCF		———		———	
R_{DC1}	(k)				
R_{DC2}	(k)				
R_{DW}	(k)				
R_{LL}	(k)				
R_{Im}	(k)				
R_{Total}	(k)				

LRFD DESIGN DATA TABLES
FOR TYPICAL BRIDGES

Figure 4

Moment table – Symmetrical composite 2 span
(Composite in positive and negative moment areas)

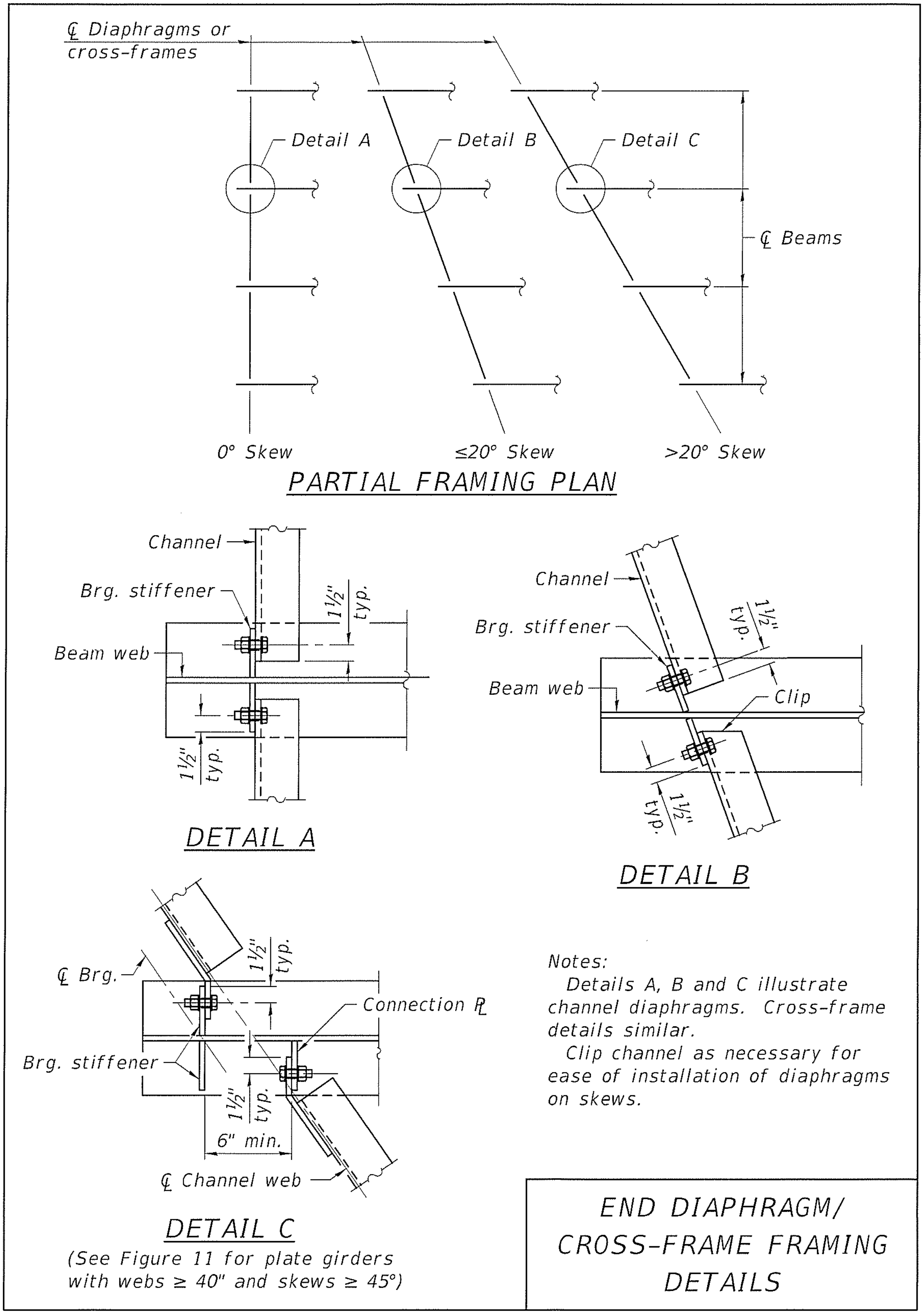
GIRDER MOMENT TABLE						
		0.4 Span 1 or 0.6 Span 2		Pier		
		Interior	Exterior	Interior	Exterior	
	I_s	(in^4)				
	$I_c(n)$	(in^4)				
	$I_c(3n)$	(in^4)				
	$I_c(cr)$	(in^4)				
	S_s	(in^3)				
	$S_c(n)$	(in^3)				
	$S_c(3n)$	(in^3)				
	$S_c(cr)$	(in^3)				
	DC1	(k/')				
	M_{DC1}	('k)				
	DC2	(k/')				
	M_{DC2}	('k)				
	DW	(k/')				
	M_{DW}	('k)				
	LLDF					
	M_{LL+IM}	('k)				
*	f_ℓ (Strength I)	(ksi)				
	$M_u + \frac{1}{3} f_\ell S_{xc}$	('k)				
	$\varnothing_f M_n$	('k)				
	f_s DC1	(ksi)				
	f_s DC2	(ksi)				
	f_s DW	(ksi)				
	f_s (LL+IM)	(ksi)				
*	f_ℓ (Service II)	(ksi)				
	$f_s + \frac{f_\ell}{2}$ (Service II)	(ksi)				
	$0.95 R_h F_{yf}$	(ksi)				
	$f_s + \frac{f_\ell}{3}$ (Total)(Strength I)	(ksi)				
	$\varnothing_f F_n$	(ksi)				
	V_f	(k)				

* f_ℓ = 10ksi. Factors are already included.
Applicable only for skews > 45 and ≤ 60
For skews >60°, f_ℓ is as per design.

GIRDER REACTION TABLE					
		Abut.		Pier	
		Interior	Exterior	Interior	Exterior
LLDF					
OCF		———		———	
R_{DC1}	(k)				
R_{DC2}	(k)				
R_{DW}	(k)				
R_{LL}	(k)				
R_{Im}	(k)				
R_{Total}	(k)				

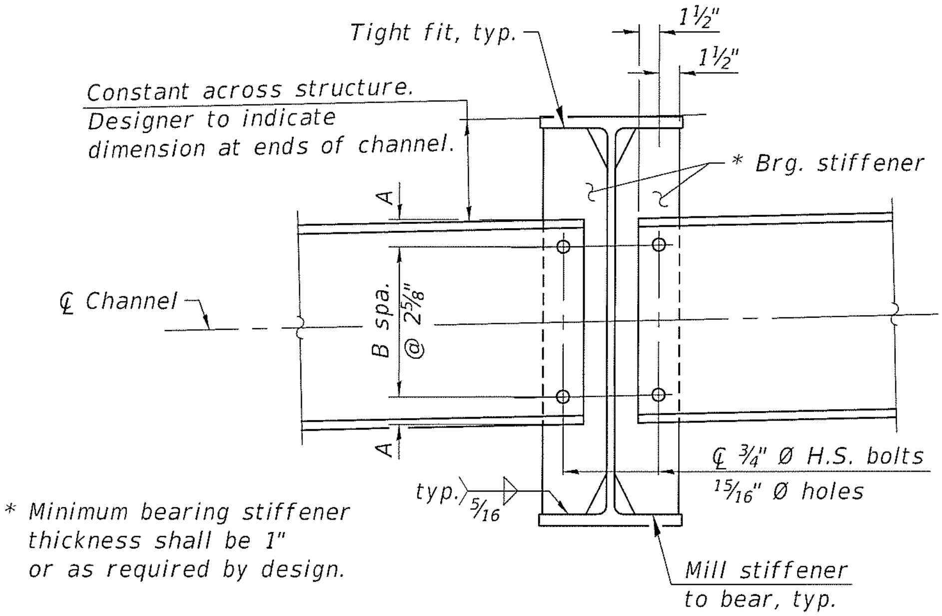
LRFD DESIGN DATA TABLES
FOR ATYPICAL BRIDGES

Figure 5



℄ Diaphragms or cross-frames
Detail A
Detail B
Detail C
℄ Beams
0° Skew
≤20° Skew
>20° Skew
PARTIAL FRAMING PLAN
Channel
Brg. stiffener
Beam web
1½" typ.
1½" typ.
DETAIL A
Channel
Brg. stiffener
Beam web
Clip
1½" typ.
1½" typ.
DETAIL B
℄ Brg.
Brg. stiffener
Connection PL
1½" typ.
1½" typ.
6" min.
℄ Channel web
DETAIL C
(See Figure 11 for plate girders with webs ≥ 40" and skews ≥ 45°)
Notes:
Details A, B and C illustrate channel diaphragms. Cross-frame details similar.
Clip channel as necessary for ease of installation of diaphragms on skews.
END DIAPHRAGM/ CROSS-FRAME FRAMING DETAILS

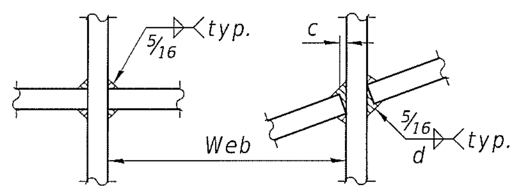
Figure 6



END DIAPHRAGMS

(Wide flange beam shown, plate girder with web depths < 40" similar)

Beam Size	ℙ Girder Web	Channel	A	B
W21 to W24	< 24"	C12 x 25	±2¹⁄₁₆"	3
W27 to W30	≥ 24", < 30"	C15 x 40	±2¼"	4
W33 to W36	≥ 30", < 40"	MC18 x 42.7	±2⁷⁄₁₆"	5



WEB WELD DETAIL

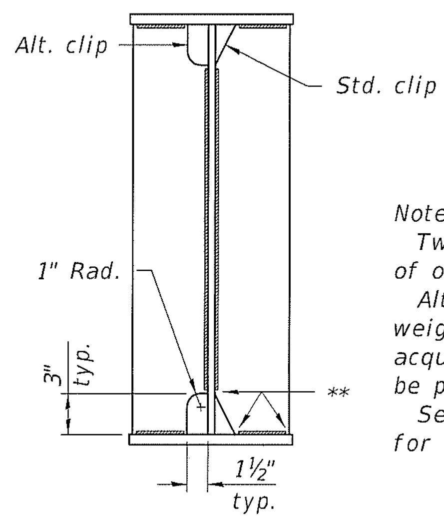
$d = 5/16 + c$

Notes:

Two hardened washers required for each set of oversized holes.

Alternate channels of equal depth and larger weight are permitted to facilitate material acquisition. Alternate channels, if utilized, shall be provided at no additional cost to the Department.

See End Diaphragm/Cross-Frame Framing Details for connection plate orientation.

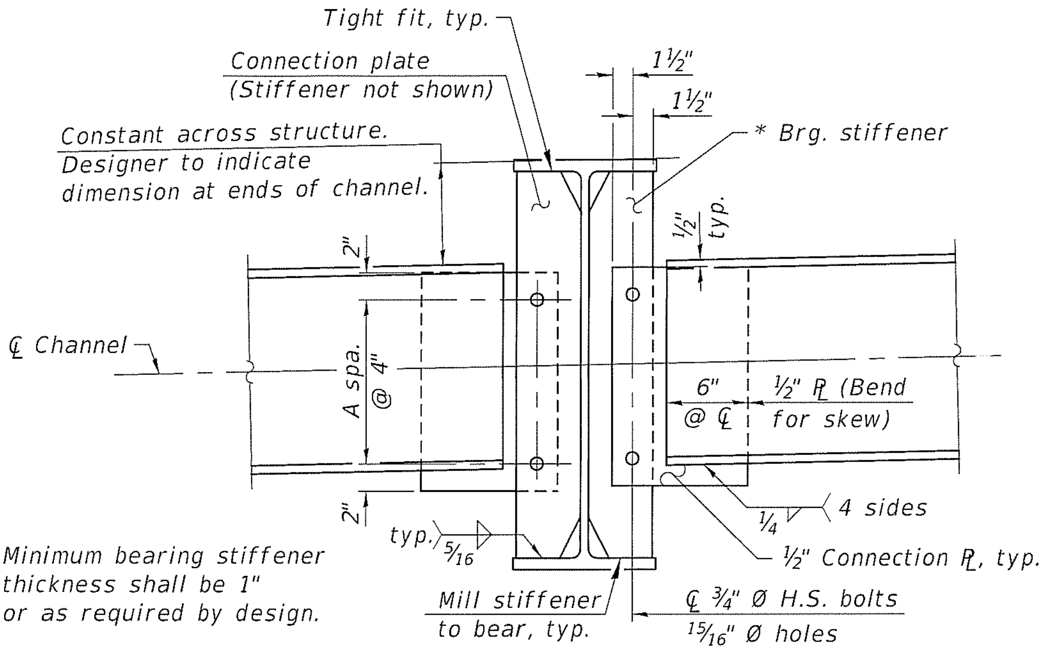


WELD LIMITS AND CLIP DETAILS

** Stop welds ¼" (±⅛") from edges as shown. Typical.

END DIAPHRAGM
CONNECTION DETAILS
FOR SKEWS < 20°

Figure 7

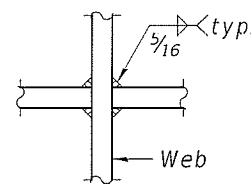


* Minimum bearing stiffener thickness shall be 1" or as required by design.

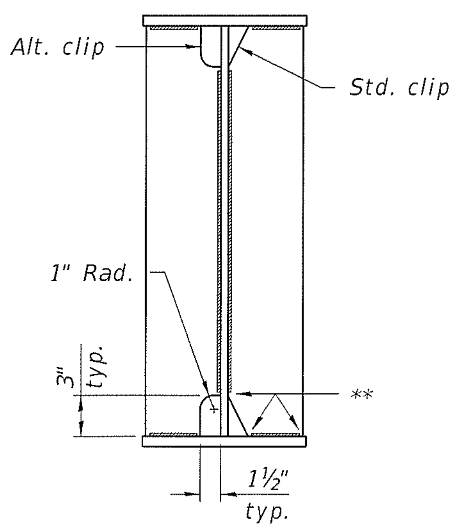
END DIAPHRAGMS

(Wide flange beam shown, plate girder with web depths < 40" similar)

Beam Size	℞ Girder Web	Channel	A
W21 to W24	< 24"	C12 x 25	2
W27 to W30	≥ 24", < 30"	C15 x 40	3
W33 to W36	≥ 30", < 40"	MC18 x 42.7	4



WEB WELD DETAIL



WELD LIMITS AND CLIP DETAILS

** Stop welds ¼" (±⅛") from edges as shown. Typical.

Notes:

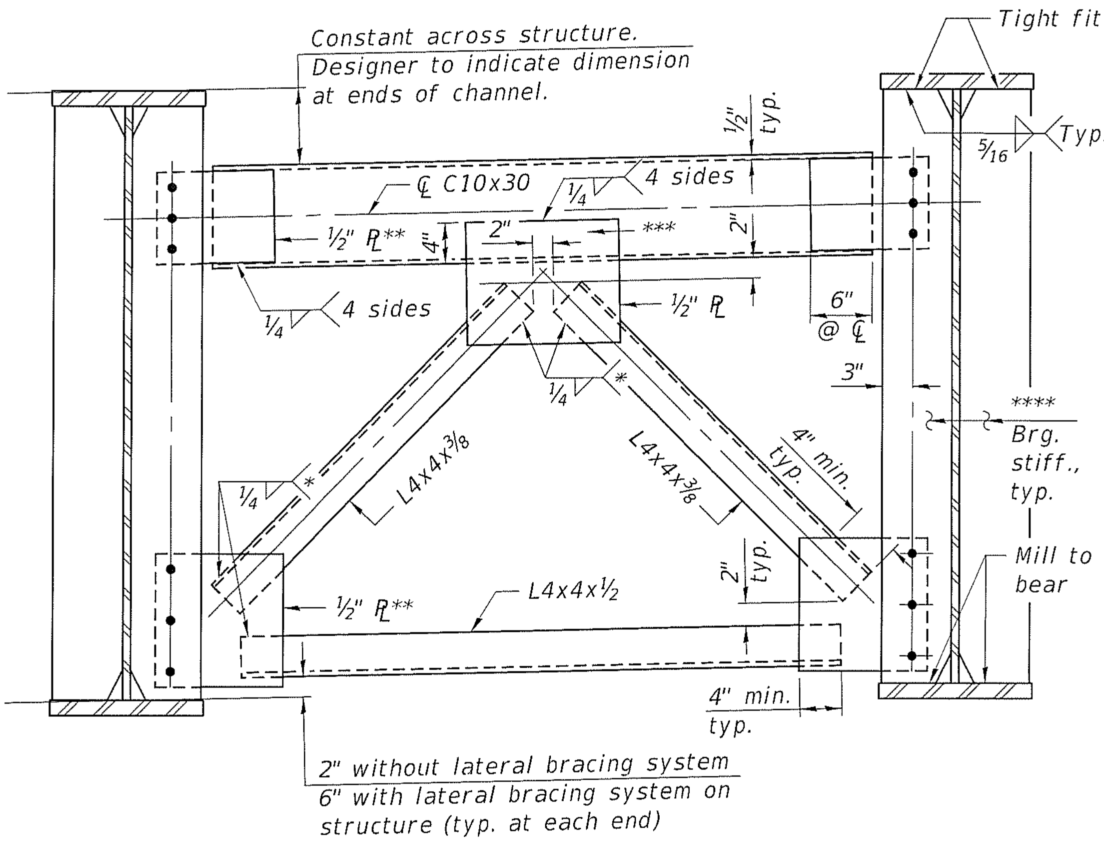
Two hardened washers required for each set of oversized holes.

Alternate channels of equal depth and larger weight are permitted to facilitate material acquisition. Alternate channels, if utilized, shall be provided at no additional cost to the Department.

See End Diaphragm/Cross-Frame Framing Details for connection plate orientation.

END DIAPHRAGM CONNECTION DETAILS FOR SKEWS ≥ 20°

Figure 8



TYPICAL END CROSS-FRAME

(Detail for welded girders ≥ 40" web depth).

* Weld angles along 3 sides on one face of gusset plate; however, if cross-frames are galvanized, weld all-around.

** 1/2" plate to be bent for skewed structures.

*** Use bolted connection for stage construction, 3 bolts minimum.

**** Minimum bearing stiffener thickness shall be 1" or as required by design.

Notes:

Detail 15/16" Ø holes for all 3/4" Ø bolts (1 1/16" Ø holes for all 7/8" Ø bolts only if required by design).

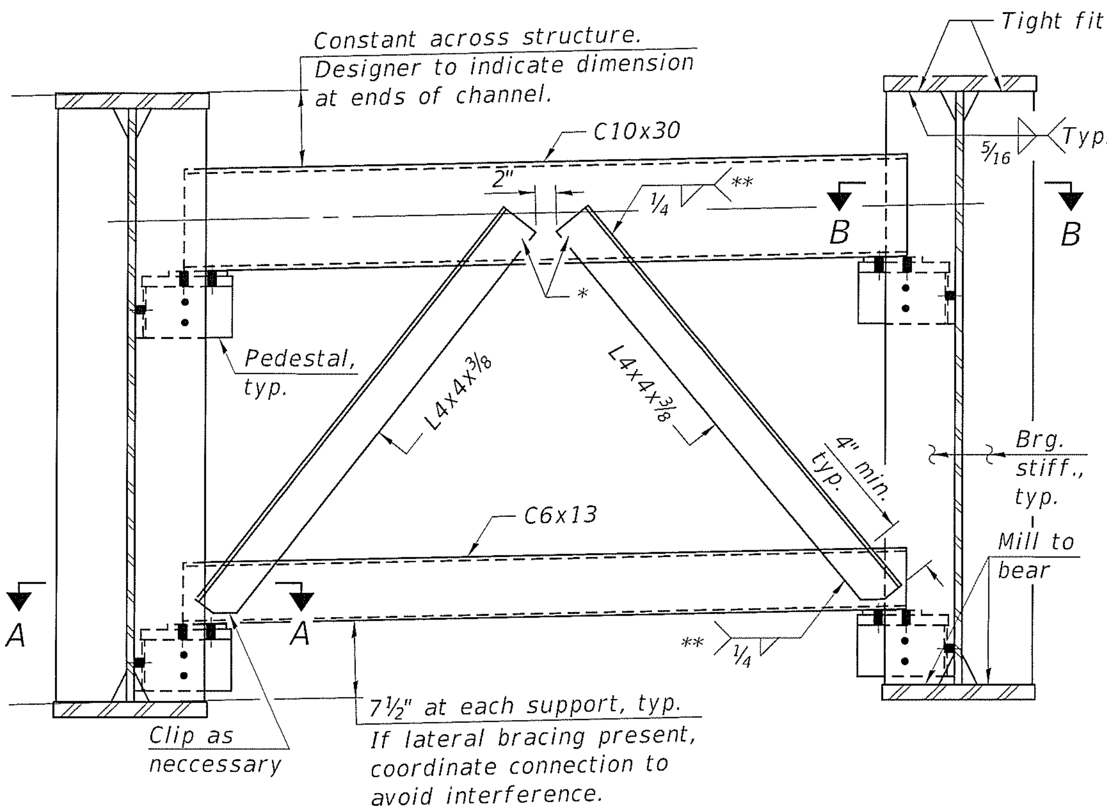
Two hardened washers required for each set of oversized holes.

See End Diaphragm/Cross-Frame Framing Details for connection plate orientation.

See End Diaphragm Connection Details for weld and clip details.

END CROSS-FRAME CONNECTION DETAIL FOR SKEWS < 45°

Figure 9



TYPICAL END CROSS FRAME

(Detail for welded girders ≥ 40" web depth)

Notes:

Detail 15/16" Ø holes for all ¾" Ø bolts (1 1/16" Ø holes for all ⅞" Ø bolts only if required by design).

Two hardened washers required for each set of oversized holes.

Place diaphragm with channel flanges outward from abutment backwall.

For Sections A-A and B-B, see End Cross-Frame Plan for Skews ≥ 45°.

See End Diaphragm Connection Details for weld and clip details.

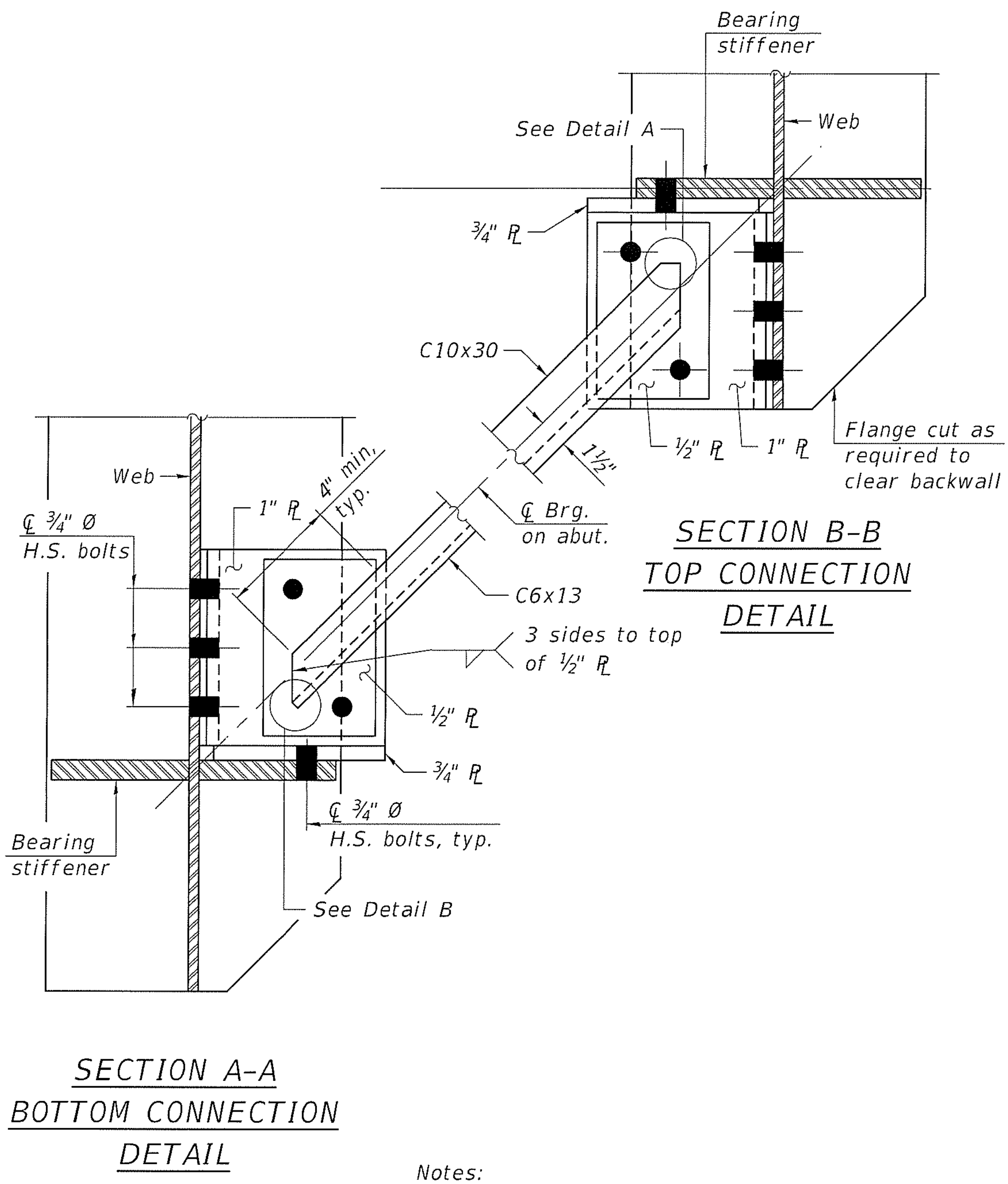
For pedestal details, see End Cross-Frame Details for Skews ≥ 45°.

* Use a minimum 2 bolt connection for stage construction.

** Weld angles along 3 sides to back face of channel: however, if cross frames are galvanized, weld all-around.

END CROSS-FRAME CONNECTION DETAILS FOR SKEW ≥ 45°

Figure 10



Notes:

For Details A & B, see End Cross-Frame Details for Skews ≥ 45°

Place bolts to maintain minimum 1½" clearance between channel and edge of ½" PL.

END CROSS-FRAME PLAN FOR SKEWS ≥ 45°

Figure 11

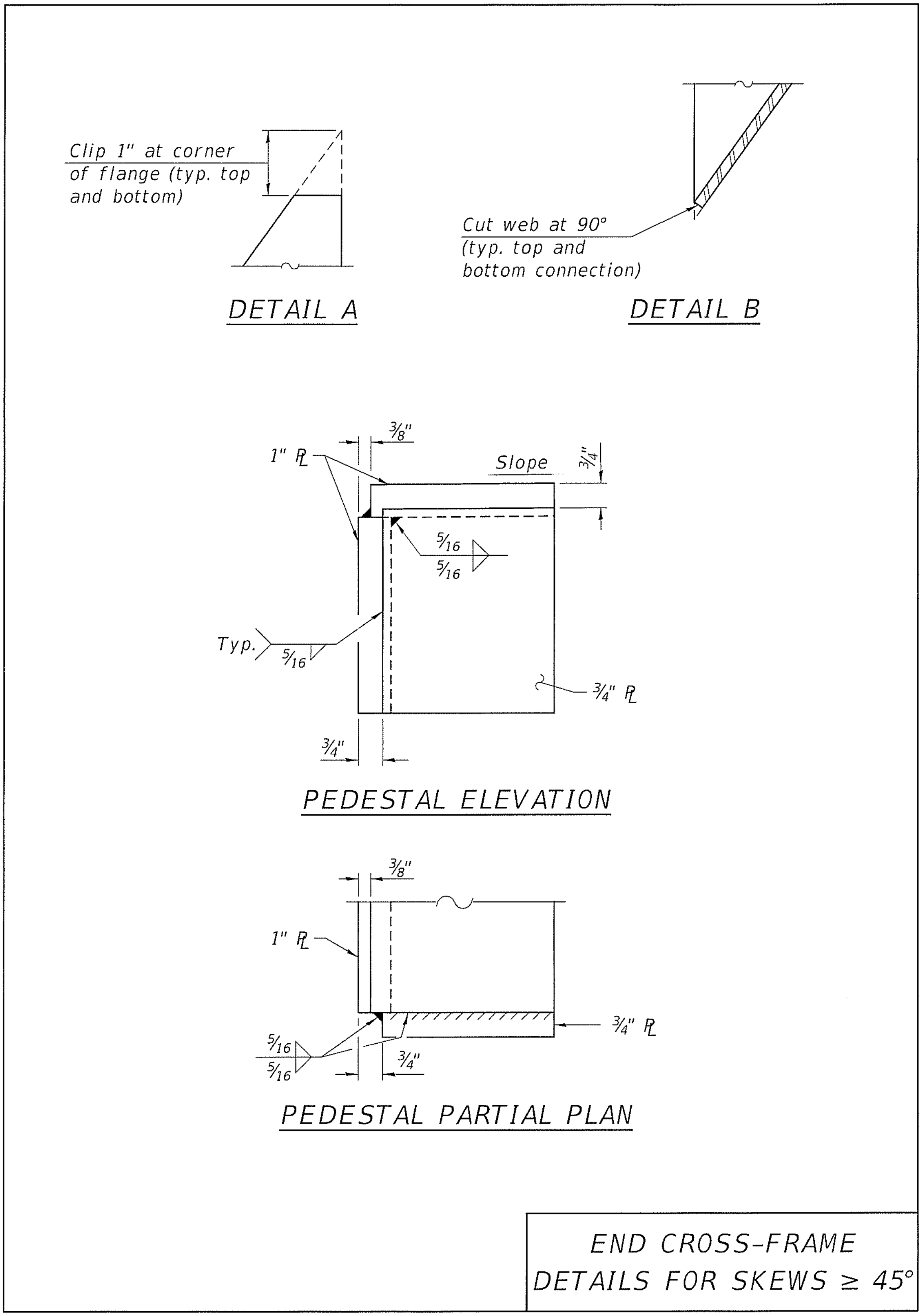
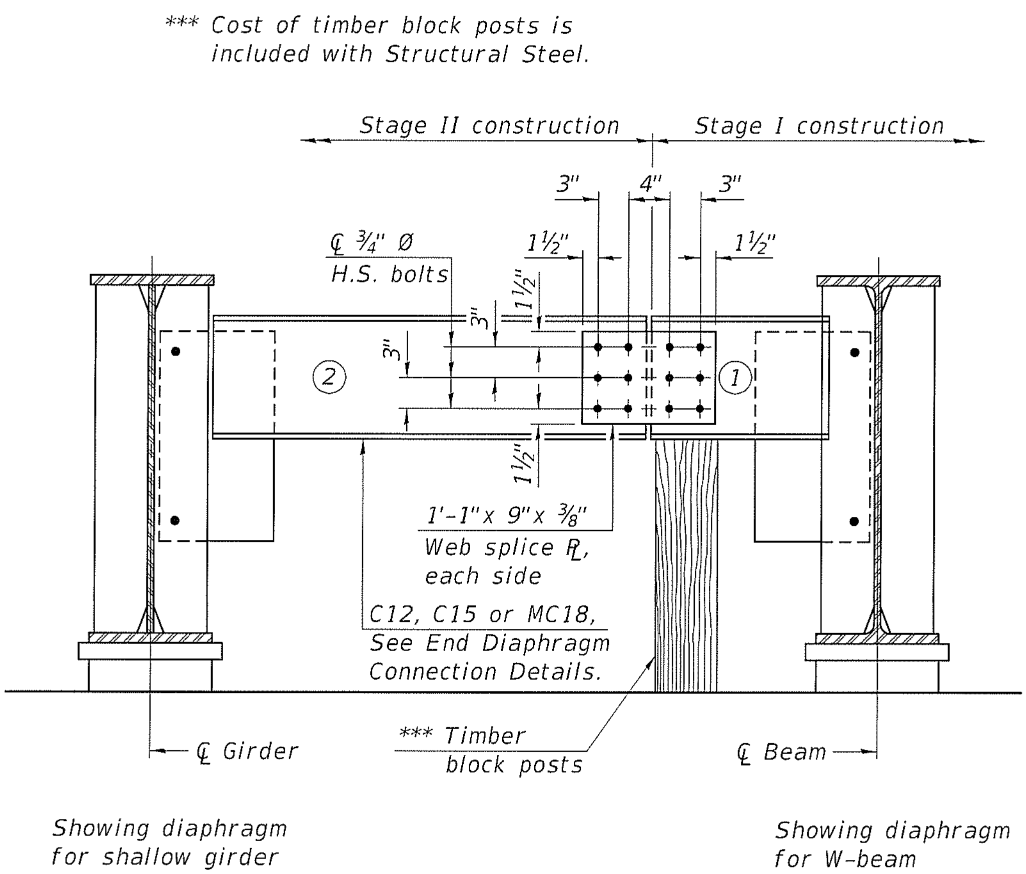

Clip 1" at corner of flange (typ. top and bottom)
DETAIL A
Cut web at 90° (typ. top and bottom connection)
DETAIL B
3/8"
1" PL
Slope
3/4"
5/16
5/16
Typ.
5/16
3/4" PL
3/4"
PEDESTAL ELEVATION
3/8"
1" PL
3/4" PL
5/16
5/16
3/4"
PEDESTAL PARTIAL PLAN
END CROSS-FRAME
DETAILS FOR SKEWS ≥ 45°

Figure 12



END DIAPHRAGM

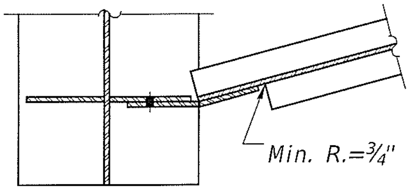
END DIAPHRAGM STAGE CONSTRUCTION SEQUENCE

1.) Order diaphragm in two sections.
2.) Attach section (1) of diaphragm to beam .
3.) Place timber block posts between section (1) of diaphragm and abutment bearing section.
4.) Attach section (2) of diaphragm to both beam and section (1) of diaphragm during stage II construction with splice plates.
5.) Remove timber block posts.

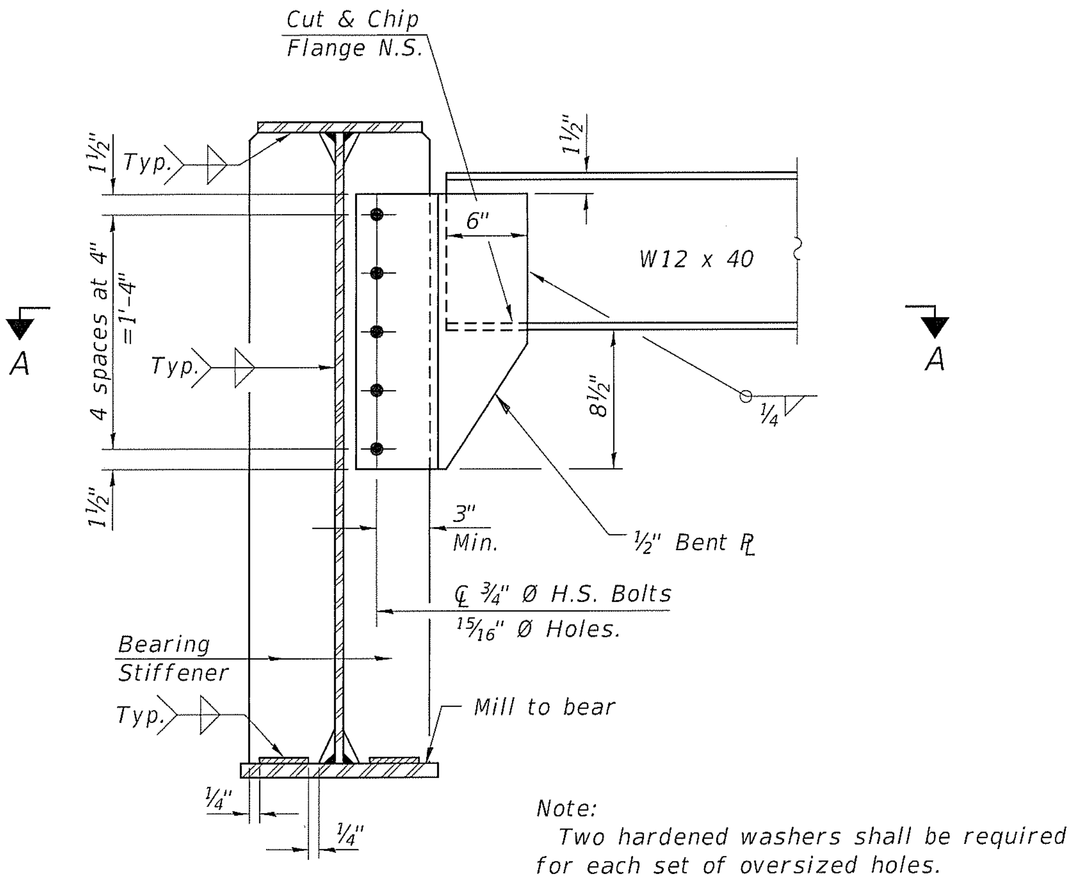
Note:
For PL girder ≥ 40" web, use detail above with top C10 only and install lower portion of CF after stage II.

END DIAPHRAGM STAGE CONSTRUCTION SEQUENCE

Figure 13



SECTION A-A

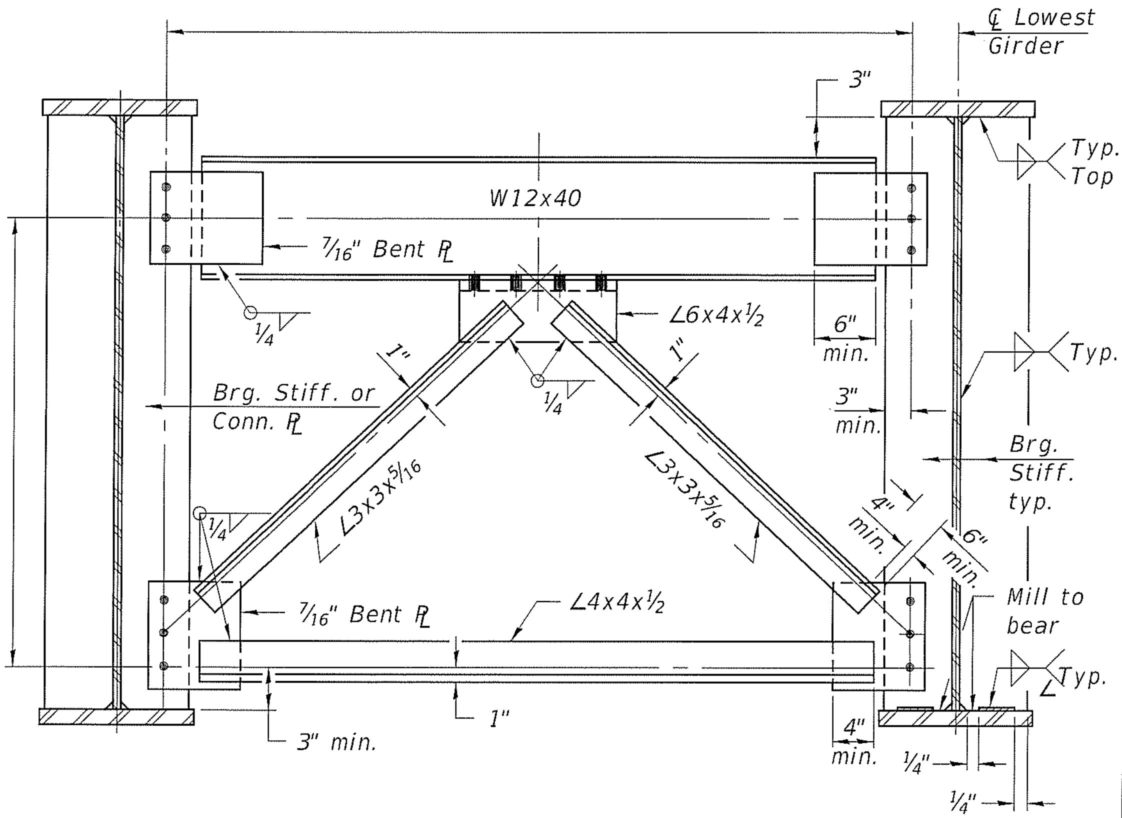


END DIAPHRAGM

(For skews ≥ 45° use a connection as shown in fiqure 3.3.23.1-3).

DIAPHRAGM CONNECTION
FOR FINGER PLATE AND
MODULAR JOINTS

Figure 14



TYPICAL END CROSS FRAME

(For Welded Girders ≥ 40" in depth)

Notes:

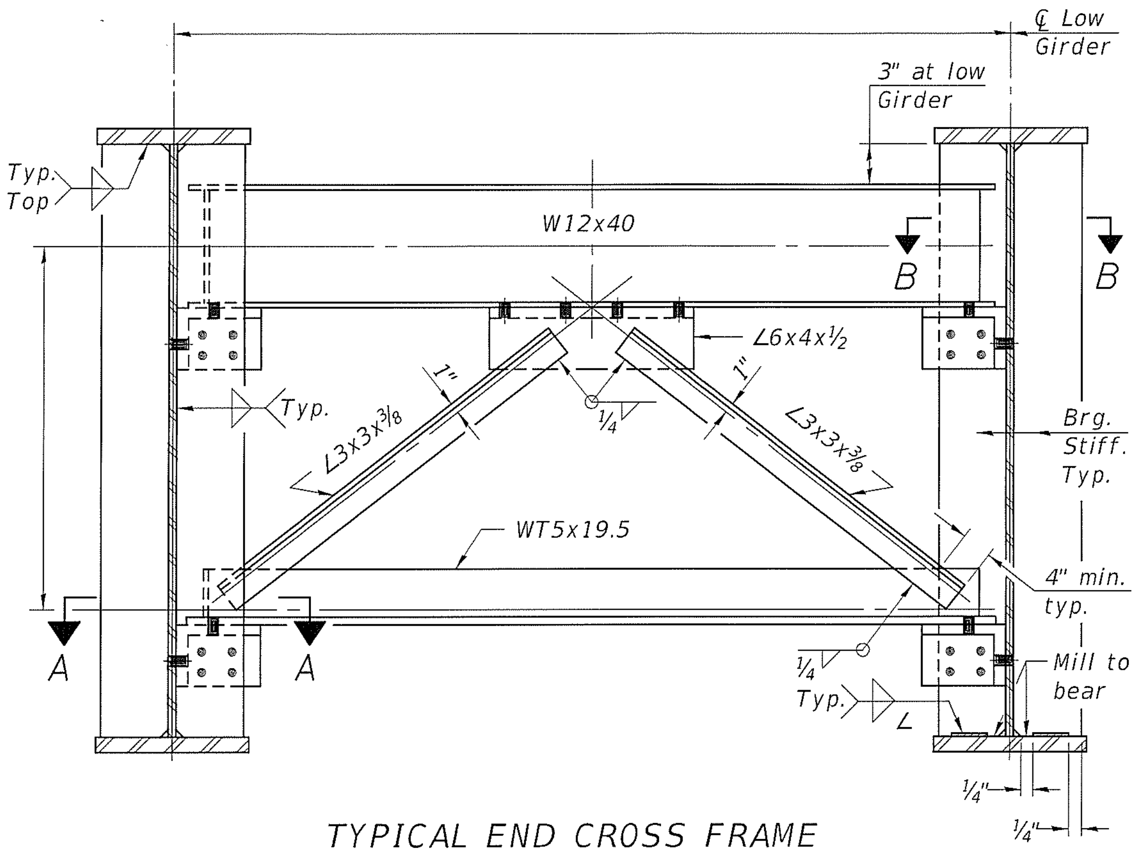
Detail 15/16" Ø holes for all 3/4" Ø bolts, 1 1/16" Ø holes for all 7/8" Ø bolts.

Two hardened washers shall be required for each set of oversized holes.

Bearing stiffeners shall be welded when these stiffeners are used as connection plates. See Section 3.3.16.

END CROSS FRAME FOR FINGER PLATE AND MODULAR JOINTS (SKEW < 45°)

Figure 15



TYPICAL END CROSS FRAME

(For Welded Girders ≥ 40" in depth)

Notes:

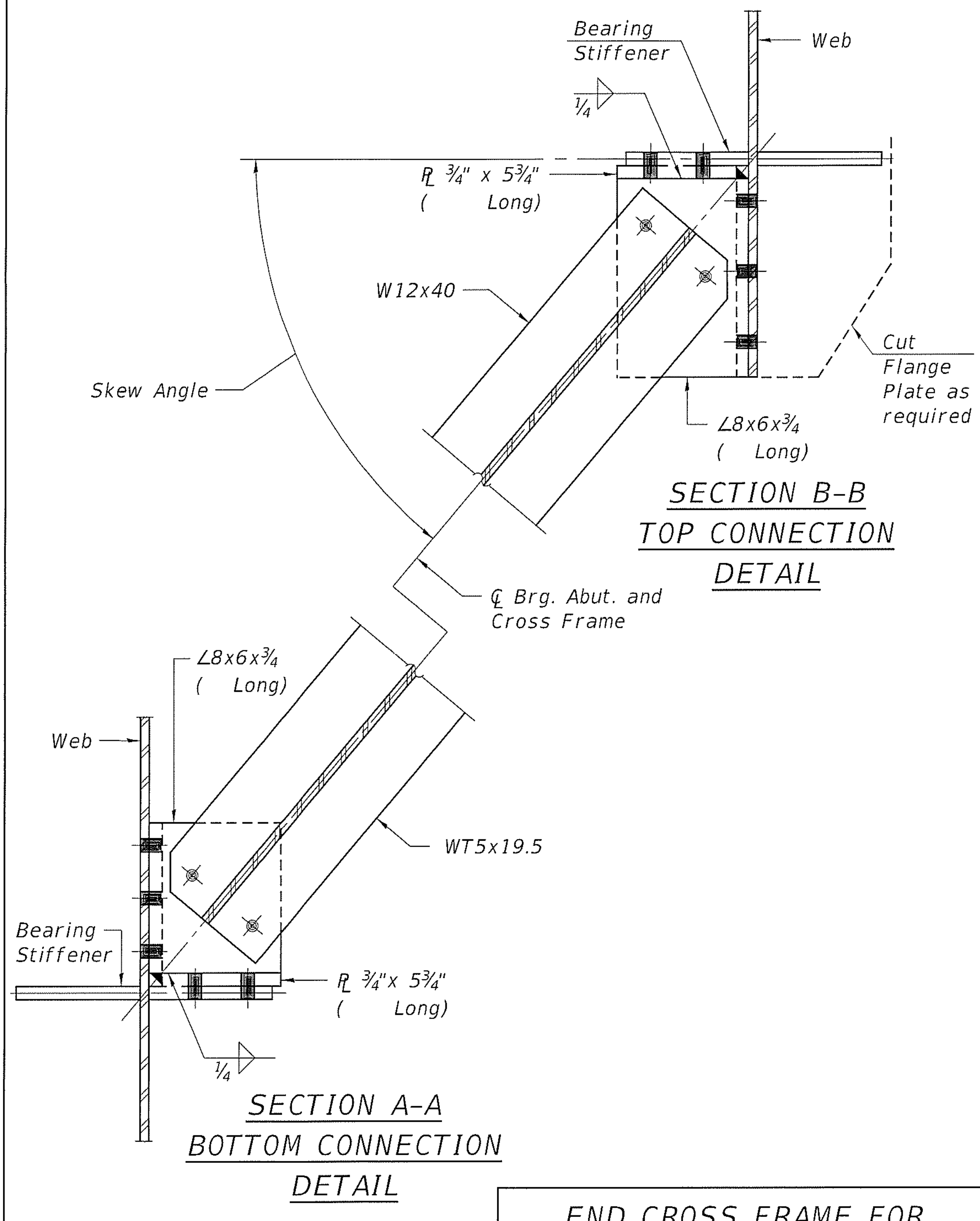
Detail 1⁵⁄₁₆" Ø holes for all ¾" Ø bolts, 1¹⁄₁₆" Ø holes for all ⅞" Ø bolts.

Two hardened washers shall be required for each set of oversized holes.

For Sections A-A and B-B see Fig. 3.3.23.1-4.

END CROSS FRAME FOR FINGER PLATE AND MODULAR JOINTS (SKEW ≥ 45°)

Figure 16



END CROSS FRAME FOR FINGER PLATE AND MODULAR JOINTS (SKEW ≥ 45°)

Figure 17