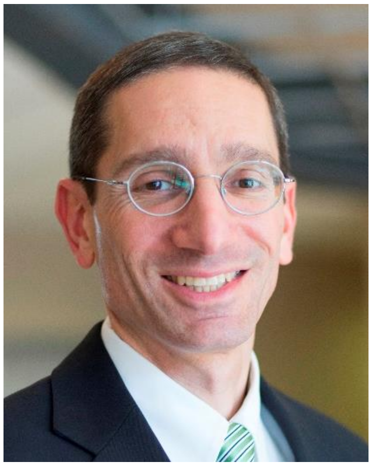
FIT-UP CONSIDERATIONS FOR STEEL I-GIRDER BRIDGES



DOMENIC A. COLETTI

DONALD W. WHITE

THANH V. NGUYEN

Domenic Coletti, PE, is a Principal Professional Associate with the Raleigh, NC office of HDR. He received his BSCE from Carnegie Mellon University and his MSCE from the University of Texas at Arlington. He is a member of several Task Groups of the AASHTO/NSBA Steel Bridge Collaboration and is Chair of TRB's Standing Committee on Steel Bridges, AFF20. He was a member of the NCHRP 20-07, Task 355 Research Team.

Don White is a Professor at the School of Civil and Environmental Engineering (CEE). He has been a member of the CEE faculty at Georgia Tech since 1997. Dr. White is a member of the AISC Technical Committees 4, Member Design, and 3, Loads, Analysis and Stability, the AISI Bridge Design Advisory Group, the AISC Specification Committee, and several AASHTO/NSBA Steel Bridge Collaboration Task Groups. He is past Chair of the SSRC Task Group 29, Second-Order Inelastic Analysis of Frames and currently serves on the Executive Committee of the SSRC. He was the Principal Investigator for NCHRP Research Project 20-07, Task 355.

Thanh Nguyen, PhD, PE is a Bridge Engineer with the Fort Lauderdale, FL office of RS&H. He received his BSCE, MSCE, and PhD degrees from Georgia Institute of Technology. He was a member of the NCHRP 20-07, Task 355 Research Team.

This paper summarizes research supporting the development of improved design, detailing and erection guidelines to ensure reliable fit-up of skewed and/or curved steel I-girder bridges. Twenty-one bridges, including multiple framing arrangements on a number of the bridges, were analyzed. The quantitative data of this research support recommended fit conditions as a function of the bridge geometry. Forces required to assemble the steel during erection were evaluated and difficult cases highlighted. Suggested erection considerations to facilitate fit-up were provided. In addition, the research investigated and specified beneficial staggered cross-frame arrangements for straight skewed bridges, as well as framing arrangements around bearing lines at interior piers in continuous-span bridges. The research placed an emphasis on identifying the impacts of the chosen fit conditions on girder elevations, girder layovers, cross-frame forces, girder stresses, and vertical reactions in completed bridge systems. Simplified methods of accounting for Steel Dead Load Fit (SDLF) and Total Dead Load Fit (TDLF) detailing effects were provided. In addition, procedures were developed and explained for direct calculation of the locked-in forces due to SDLF and TDLF detailing in cases where a more precise calculation of these effects may be beneficial. Lastly, construction inspection best practices were recommended to ensure that the erected geometry sufficiently meets the specified fit conditions, and recommended design specification provisions were developed that synthesize the key guidelines.

FIT-UP CONSIDERATIONS FOR STEEL I-GIRDER BRIDGES

BRANDON W. CHAVEL

Brandon Chavel, PhD, PE is a Senior Professional Associate and Bridge Section Manager with the Cleveland, Ohio office of HDR. He received his PhD from the University of Pittsburgh. He is a member of several Task Groups of the AASHTO/NSBA Steel Bridge Collaboration and is Chair of TG 11, Steel Bridge Design Handbook. He was a member of the NCHRP 20-07, Task 355 Research Team.

MICHAEL A. GRUBB

Michael Grubb, PE is a self-employed steel-bridge design consultant with M.A. Grubb & Associates, LLC in Wexford, PA. He has 39 years of experience in steel-bridge design, steel-bridge design specifications, straight and curved steel-bridge research, the development and delivery of training courses on steel-bridge design, and the development of comprehensive steel-bridge design examples. He was a member of the NCHRP 20-07, Task 355 Research Team.

CALVIN G. BORING, JR.

Calvin Boring, Jr. is the Operations Manager at Advantage Steel and Construction located in Saxonburg, PA. He received his BSCE at the University of Pittsburgh. He is a member of Iron Workers Local # 3, ESWP where he is on the Executive Committee of the IBC and served as General Chair in 2014, and Board Member of ASHE – SW PENN. He was a member of the NCHRP 20-07, Task 355 Research Team.

FIT-UP CONSIDERATIONS FOR STEEL I-GIRDER BRIDGES

Background

Achieving reliable fit-up of steel girder bridges with sharp curvature and/or significant skew is inherently challenging. To help inform the steel bridge design and construction industry, an ad-hoc task group affiliated with the National Steel Bridge Alliance (NSBA) published guidelines featuring fit-up considerations and design, detailing, and erection recommendations *(1)*. The basis for the recommendations was largely qualitative, being derived primarily from anecdotal accounts and the professional experiences of the authors. Further guidance, again largely qualitatively derived, was also presented in Reference *(2)*. While the guidance provided by these documents was helpful, it was recognized that conclusive, authoritative recommendations could only result from quantitative research. To this end, research was funded as NCHRP Research Project 20-07, Task 355, *Guidelines for Reliable Fit-Up of Steel I-Girder Bridges*, and reported in Reference *(3)*.

The research team first conducted a survey of current industry practice with regard to cross-frame framing arrangements, fit conditions / cross-frame detailing methods, erection procedures, and construction inspection practices; the results were synthesized and general trends were discussed. The survey revealed a wide range of practices and a similarly broad range of understanding of the key issues associated with fit-up of steel girder bridges.

Next, twenty-one steel I-girder bridges were analyzed to investigate the effects of structural steel framing arrangements, specified fit conditions, construction tolerances, and construction actions on ease of fit-up and locked-in stresses. The bridges investigated included radially supported curved girder bridges, straight girder bridges with skewed supports, and curved girder bridges with skewed supports. Both single span and multiple-span continuous bridges were investigated. A range of span lengths and bridge widths were examined, along with both parallel and non-parallel support conditions. Examples of framing plans for bridges studied are illustrated in Figure 1. In some cases, the configuration of the framing was varied for the same overall bridge geometry, typically to investigate the effects of contiguous versus staggered cross-frame patterns. The sequence of erection was considered in the analysis of each bridge, and in some cases more than one erection scheme per bridge was evaluated to investigate the effects of the various erection schemes on the difficulty of fit-up and the magnitude of locked-in stresses. The difficulty of fit-up was evaluated in terms of the magnitude of the "fit-up forces," i.e., the forces required to physically bring together a cross-frame and a girder to which the cross-frame is being connected.

A summary of key findings and recommendations of this research is presented in this paper. For more detailed discussion, the reader is encouraged to consult Reference *(3)*.

Cross-Frame Fit

The "fit" or "fit condition" of a skewed and/or curved I-girder bridge refers to the geometry in which the cross-frames are detailed to attach to the girders. The fit condition is selected for a given bridge to facilitate erection by offsetting, or compensating for (to different extents), the tendency of the I-girders in these bridge types to twist due to differential deflections. The selected fit condition corresponds to a specific targeted outcome of when the girder webs will be approximately plumb (vertical) in the field. "Fit-up" refers to the assembly of the structural steel during the bridge erection. It is desirable that the "fit-up" of the structural steel should be manageable, without the need for excessive jacking or pulling forces from the erector. The "fit condition" and the "fit-up" of the structural steel are interrelated, but these terms refer to different attributes of the construction.

Table 1 summarizes the three most common fit conditions considered in skewed and/or curved I-girder bridges. Alternate names for each potential fit condition, which are generally more familiar to fabricators and steel detailers, are also provided in the table; the names are used interchangeably in practice.

The term "Total Dead Load," typically is assumed to include either all dead loads that are present when the bridge is opened to traffic, or the as-constructed dead loads, taken as the weight of the structural steel plus the weight of the concrete deck, but not including the weight of barrier rails, sidewalks, etc.

TABLE 1 Common Fit Conditions

Condition	Alternate Name	Description
No-Load Fit (NLF)	Fully-Cambered Fit	The cross-frames are detailed to fit to the girders in their fabricated, fully-cambered and plumb position under zero dead load.
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 bridge steel dead load at the completion of the erection.
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.

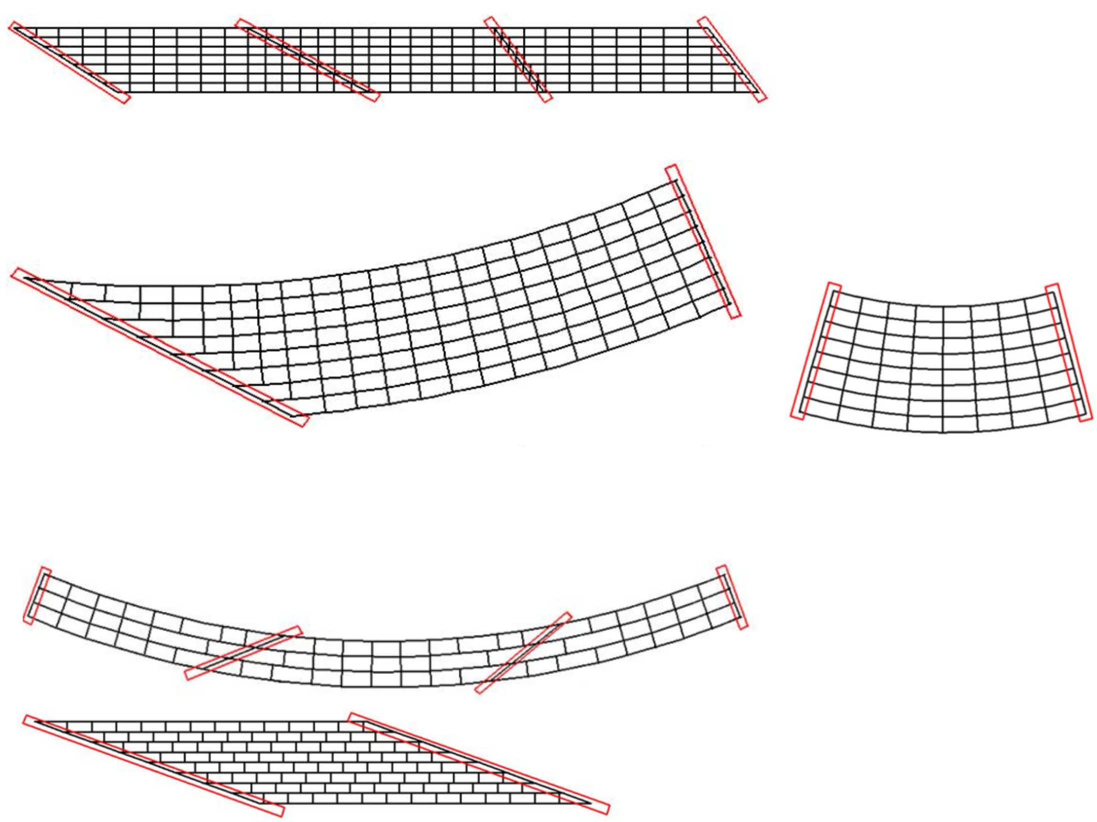


FIGURE 1 Framing plans for representative bridges studied in this research.

Forces Required to Assemble the Steel During Erection

A major focus of the NCHRP 20-07, Task 355 research was the ease of fit-up of the cross-frames during erection. In this work, cross-frame fit-up was estimated by calculating the forces induced at the cross-frame top and bottom connections, for the second girder to which the cross-frame is connected, as the cross-frame is installed. The fit-up force calculations performed in this research are accurate to the extent that the nominal assumptions generally employed in bridge design are satisfied. That is, the simulations to determine fit-up forces are based on the following assumptions:

- No yielding of the steel,
- No incidental restraint from friction, etc. at temporary or permanent supports,
- The girder geometries, support elevations, etc. are as specified in the bridge plans, and
- Negligible "play" in the connections.

There are various factors that can influence the actual bridge erection but cannot be accounted for in any detailed way within a practical engineering erection analysis, such as:

- Tolerances and the associated play at bolted connections,
- Adjustments of the crane and support elevations by the erector,
- Tolerances on support elevations, and
- Changes in the geometry of the steel due to thermal movements, etc.

These factors can cause differences between the actual fit-up forces encountered in the field compared to the erection analysis estimates. Connection tolerances and adjustment of crane and temporary support elevations can indeed make the fit-up forces somewhat smaller than the calculated estimates, as discussed in more detail in Reference *(3)*. However, the calculated fit-up forces determined in this research are forwarded as reasonable engineering estimates associated with the nominal design representation of the structures.

The fit-up forces required to assemble each bridge were evaluated at various stages of erection. In some cases, more than one erection scheme was investigated. For each bridge (and each erection scheme), typically three fit conditions (NLF, SDLF, and TDLF) were analyzed. The fit-up forces were recorded and the ease of assembly was characterized as a function of the magnitude of the fit-up forces. Erectors commonly use come-alongs and other local equipment, as necessary, to make the connections between the cross-frames and the girders. A typical come-along capacity was taken as 20 kips (some erectors indicate that 12 kips is more typical). For the purposes of evaluating various erection schemes and fit-up conditions, a calculated fit-up force significantly more than 40 kips was considered "difficult."

A full presentation of the specific findings regarding fit-up forces for each of the studied bridges is beyond the scope of this summary paper; the reader is directed to Reference *(3)* for presentation of all results. A sample of the results is presented in Table 2. Note the focus on correlation of difficulty of erection versus specific bridge geometries (e.g., span length, curvature, bridge width, erection scheme, etc.) and specific behavior (i.e., magnitude of differential deflections).

Suggested Erection Considerations

In addition to choosing an appropriate fit condition, determining an effective erection scheme is critical to ensure that a curved and/or skewed bridge is constructible and the maximum fit-up forces are maintained in a reasonable range. In some cases, site constraints such as a waterway, or availability, capacity, and allowed erection duration and location of cranes and shoring towers, can dictate the erection schemes.

A full discussion of erection considerations is provided in Reference *(3)*. A summary of selected key considerations is provided here.

Lifting Cranes, Hold Cranes, Shoring Towers, Tie-Downs

The lifting scheme for each girder (e.g., two-point pick, two-point pick with spreader beam, etc.) affects the orientation, deflection, and stresses in the girder during lifting, and can thus affect fit-up (as well as affecting stability of the girder during lifting). Hold cranes are often used during early stages of erection to reduce deflections and major-axis bending moments and facilitate fit-up of girders and cross-frames, especially in curved girder bridges. Shoring towers are often needed in the

TABLE 2 Sample Presentation of Summary of Maximum Cross-Frame Fit-Up Forces for Curved Radially-Supported Bridges												
Bridge	**Shoring Towers**	L_s **(ft)**	w_g **(ft)**	R **(ft)**	n_g	L_s/R	L_s/w_g	**Differential Deflections (in.)**		**Cross-Frame Fit-Up Force (kip)**		
								SDL	**TDL**	**NLF**	**SDLF**	**TDLF**
(A) EISCR1	0	90	17.5	200	3	0.45	5.1	**0.42**	**1.67**	**3.3**	**7.4**	**22.3**
(B) NISCR2, Scheme 1	0	150	24.0	438	4	0.34	6.2	**0.68**	**1.83**	**16.6**	**28.7**	**54.0**
(C) NISCR7	0	150	74.0	280	9	0.54	2.0	**0.42**	**1.19**	**21.3**	**35.9**	**75.3**
(D) NISCR10	1	225	74.0	705	9	0.32	3.0	**0.47**	**0.78**	**18.6**	**20.4**	**21.8**
(E) EICCR11	3 (in curved span)	322, 417, 322	40.4	∞, ∞, 411	4	0, 0, 0.80	8.0, 10.3, 8.1	**3.10**	**5.41**	**37.5**	**86.3**	**130.0**

Notes:

1. L_s = Span length(s)
2. W_g = Bridge width, measured between exterior girders
3. R = Radius of curvature at centerline of bridge
4. n_g = Number of girders in the cross-section
5. L_s/R = Subtended angle between bearing lines
6. L_s/w_g = Length to width ratio
7. Color coding of fit-up forces: A typical come-along capacity is taken as 20 kips (some erectors indicate that 12 kips is more typical). Calculated maximum fit-up forces between 30 and 40 kips are shown by light (blue) shading. Calculated maximum fit-up forces greater than 40 kips are considered difficult and are highlighted by dark (red) shading.
8. Bridge case (E) EICCR11 involved drop-in segments.
9. NLF = No-Load Fit; SDL = Steel Dead Load; SDLF = Steel Dead Load Fit; TDL = Total Dead Load; TDLF = Total Dead Load Fit

construction of long-span bridges and curved bridges. Multiple field splices may be required within longer spans. Shoring towers help limit deflections and facilitate the installation of field splices and cross-frames. The shoring towers should be used across the full width of the bridge cross-section where practicable to best facilitate erection of the structural steel. The number of shoring towers and cranes is generally selected to provide for a feasible, safe, and economical erection. Furthermore, tie-downs are typically provided for the girders at the shoring tower locations and/or the permanent supports to ensure girder stability before and after the splices are made within the spans.

The critical stages for fit-up often are stages that have the highest differential deflections between the girders. High differential deflections are indicative of the potential for development of large internal forces between the girders. Fit-up can potentially be the most difficult for the last girders installed in the bridge cross-section, and for drop-in segments installed in continuous spans.

Erection Schemes for Curved, Radially-Supported Bridges

For curved bridges, cranes and/or temporary supports are critical for stabilizing the partially completed systems, as well as for erecting the girders and cross-frames. Individual curved girders and narrow partially-erected curved bridge units have little stability on their own. The bridge cross-section generally over-rotates until all of its girders are installed. For most of the curved radially-supported bridges studied in this research, the bridges are erected from the outside to the inside of the curve. This is for the following reasons:

- The girder on the inside of the curve on the partially completed bridge cross-section deflects less than the outside girder.

- The girder that is being installed is supported by a lifting crane, and thus its deflections are typically small.
- Erecting from the outside to the inside of the curve requires smaller fit-up forces due to the smaller differential displacements between the inside girder and the girder being installed.
- Erecting from the outside to the inside of the curve avoids the need to lift the outside girder on the partially completed bridge cross-section to achieve fit-up with the next girder being installed on the outside of the curve, which is typically the case when the bridge is erected from the inside to the outside of the curve.
- For highly curved bridges, the crane and temporary support requirements for erection from the inside to the outside of the curve can be significantly greater than for erection from the outside to the inside of the curve.

In many cases, when a bridge is highly curved, a holding crane will be required on the girder on the outside of the curve until a number of the girders in the bridge cross-section have been installed. The erection schemes employed in this research install the bearing line cross-frames immediately after the girder is placed on its supports, to help provide torsional stability to the girder. Then the remaining intermediate cross-frames are sequentially installed.

Erection Schemes for Straight, Skewed Bridges

The potential fit-up considerations for straight skewed bridges are somewhat different than those discussed above for curved radially-supported bridges. A number of considerations for straight skewed simply-supported spans are as follows:

- For short straight skewed simply-supported spans that do not require a field splice within the span, and therefore would rarely require shoring towers, the cross-frames can be installed sequentially from one abutment to the other after each girder is lifted onto its vertical supports.
- Tie downs can be provided at the supports as necessary to maintain lateral-torsional stability of the girders.
- For longer spans that require a field splice within the span (because the field sections otherwise become too heavy), and often may require shoring towers, it is best to install only a few cross-frames or struts before the field splice is made, and to install the remaining cross-frames after the field splice is completed.
- If any temporary supports are still being employed when the cross-frames are being installed, positioning the temporary supports at the final girder steel dead load (SDL) elevations is often a good starting point to alleviate potential large fit-up forces.
- Typically, cranes are only used to lift the girders into place and are not critical to the erection of straight skewed bridges constructed in the above ways. This is in contrast to the discussion of curved bridge cases above.
- When the cross-frames are detailed for SDLF, their installation using the above type of erection scheme tends to result in the lowest level of fit-up forces.

For continuous-span straight skewed bridges, the erection schemes with the greatest ease of fit-up are typically similar to those for the simply-supported bridges described above. However, it is impractical for the erector to install each girder in all the spans, one at a time throughout the bridge length, to achieve the girder SDL elevation profiles. Instead, all the girders are typically erected in each span before moving to the next span. In these bridge types, a good option is to:

- Install only a minimal number of cross-frames to keep the bridge stable until all the girders are erected.
- Once all the girders in all spans have been erected, install the remaining cross-frames span-by-span.

This scheme limits the crane movement along the length of the bridge while keeping the bridge stable and the SDLF fit-up forces relatively small. In addition, this procedure appears to provide the best option to mitigate large fit-up forces in straight skewed bridges detailed for TDLF detailing. However, for longer spans with sharp skews, the larger fit-up forces associated with TDLF can be problematic in some cases.

Erection Schemes for Curved and Skewed Bridges

For the curved and skewed bridges studied in this research, the holding crane, lifting crane and shoring tower elevations were located at the no-load elevations. Fit-up forces in curved bridges can be reduced by varying the crane and shoring tower elevations from the no-load elevations. However, it was shown that the reduction in fit-up forces is relatively small. Also, iteratively adjusting the crane and shoring tower elevations to minimize the fit-up forces is not practical in typical erection engineering practice. However, in some cases, it can be beneficial for the erection personnel to install cross-frames at positions where the deflected geometries are most compatible, and for the crane operator to incrementally raise or lower a girder that is being installed after successive insertions of cross-frames, in effect to “button up” the cross-frames between the girder that is being installed and the structural steel that is already in place. From the studies of the erection schemes of several curved and skewed bridge cases, the following conclusions were drawn:

- For continuous-span cases, leaving the shoring towers in place during the erection of subsequent spans helps to reduce the overall deflections, which can facilitate fit-up.
- Similar to the recommended practice for curved radially-supported bridges, the erection scheme for curved and skewed bridges should also be from the outside to inside on tightly curved bridges, whenever practicable, to reduce the maximum fit-up forces.
- The cross-frames ideally should be installed sequentially from the radial bearing line (if there is a radial bearing line) to the skewed bearing line. This reduces the deflection incompatibilities when installing the cross-frames near the skewed end of the span.

Detailed Evaluation of Straight Skewed Bridge Responses Associated with the Use of LGA vs. 3D FEA Camber

It is common for girder camber profiles to be calculated from a 1D Line Girder Analysis (LGA) for some bridges, 2D Grid analysis for others, and in some cases from a 3D Finite Element Analysis (FEA). For a highly skewed I-girder bridge, however, the differences in the cambers obtained from LGA versus the other two methods can be substantial. Nonetheless, while the camber profiles calculated from LGA and 3D FEA for a straight sharply-skewed bridge can be substantially different, the final bridge geometries and responses obtained with either SDLF or TDLF detailing are similar. The use of cambers from LGA gives the closest match to the ideal zero girder layovers and flange lateral bending stresses under the targeted dead load conditions while the use of 3D FEA cambers gives girder layovers and internal stresses that are small, but non-zero, compared to the overall dead load responses under the targeted conditions. The final girder elevations due to TDLF detailing based on the LGA cambers closely match with the ideal targeted girder elevations under total dead load (TDL). However, the final girder elevations due to TDLF based on the 3D FEA cambers deviate only slightly from the ideal targeted elevations under TDL. Based on the studies synthesized by the research team, it was concluded that the 3D FEA results are close enough to matching the ideal values such that it is sufficient to use 3D FEA (or other accurate refined analysis) cambers for detailing of straight skewed bridges. For a full discussion of this issue, along with a comprehensive presentation of analytical studies of a single span, straight, wide (nine girder lines), severely skewed bridge, please see Reference *(3)*.

Influence of Framing Arrangements

The cross-frame framing arrangement can have a significant effect on the overall bridge behavior as well as the fit-up forces during the steel erection. In a number of the bridges studied in this research, specific improvements in the cross-frame framing arrangements were investigated. These improvements relate particularly to the alleviation of significant nuisance transverse stiffness paths associated with skew. These recommended improvements are summarized below.

Offsets between Intermediate Cross-Frames and Skewed Supports

References *(2)* and *(4)*, recommend the use of an offset of the intermediate cross-frames from the skewed bearing line cross-frames that is the larger of 1.5D or 0.4 L_b wherever practicable, where D is the girder web depth and L_b is the next or adjacent interior unbraced length. The provision of this offset locates cross-frames where girder differential displacements between the cross-frame ends are significantly reduced, leading to lower cross-frame forces.

Upon applying these rules to the suite of bridges selected for the NCHRP 20-07, Task 355 research, it became apparent that the above 1.5D rule was overly punitive and difficult to implement in longer-span highly-skewed bridges. This is because 1.5D is commonly a larger fraction of the other unbraced lengths for longer-span bridges, where the typical unbraced lengths of 30 ft or less are a smaller fraction of the overall span length. As such, the unbraced length on the fascia girders at the acute corners of the spans tended to be too long. The research team found that a length of 4b_f, where b_f is the largest girder flange width within the unbraced lengths on either side of the first cross-frame, serves as a better minimum limit that should always be met to ensure that offsets (and stagger distances) actually serve their intended purpose.

For bridges with sharply skewed bearing lines, the maximum (4b_f , 0.4L_b) offset rule may still result in a large L_b on the fascia girder near the acute corners of sharply skewed spans. The older AASHTO *Standard Specifications for Highway Bridges (5)* formerly recommended a maximum unbraced length of 25 ft. This has been replaced in the more recent AASHTO *LRFD Bridge Design Specifications (4)* by the requirement for a rational analysis to assess the cross-frame spacing, but cross-frame spacings larger than 30 ft are still relatively rare in straight I-girder bridges, and are not permitted for curved I-girder bridges.

At the simply-supported ends of a straight I-girder bridge, if the overhang loads do not cause excessive twisting of the fascia girder, unbraced lengths slightly larger than 30 ft can be accommodated easily in many cases. But at interior pier supports in multiple-span continuous bridges, where large negative moments occur, the use of cross-frame spacings larger than 30 ft at acute corners would adversely impact the lateral torsional buckling capacity of the fascia girders. To address torsional rotations due to overhang loads and provide lateral torsional buckling resistance, the first cross-frame in the exterior bays adjacent to the skewed bearing lines can be framed perpendicular to the girders with a small offset from the bearing on the interior girder and then the diagonal members of this cross-frame can be removed to reduce the resulting nuisance transverse stiffness, as shown in Figure 2. The cross-frames highlighted by an oval and labeled on this plan view as “CO” (for “chords only”) do not contain any diagonals. This allows for a small offset of these cross-frames relative to the skewed bearing lines without inducing large cross-frame forces from nuisance transverse stiffness effects, while reducing the large unbraced length on the adjacent girder at the acute corner of the bridge plan. This scheme may be considered as a variant of the lean-on bracing concept proposed by Romage *(6)* and Zhou *(7)*.

Cross-Frame Framing and Detailing Considerations for Severely Skewed Bridges

It is common practice to allow skewed intermediate cross-frames where the support lines are skewed by less than or equal to 20 degrees from normal. However, where the support lines are skewed more than 20 degrees from normal, the AASHTO *LRFD Bridge Design Specifications (4)* require that the cross-frames be framed orthogonal to the girders. In this case, it may be advantageous to place the intermediate cross-frames oriented normal to the girders in discontinuous lines, to selectively remove certain cross-frames, and/or to stagger the cross-frames in adjacent bays between the girders, in such a manner that the transverse stiffness of the bridge is reduced. Removal of highly stressed cross-frames, particularly in the vicinity of the obtuse corners of a span, reduces the stiffness of the corresponding transverse load path by forcing load transfer via girder flange lateral bending.

The above practices tend to decrease the cross-frame forces and increase the girder flange lateral bending. However, in certain cases involving excessively stiff transverse load paths, the cross-frame forces may be decreased to the extent that the associated flange lateral bending stresses are also reduced. The unbraced lengths between the cross-frame locations must still satisfy the flange resistance requirements of the design specifications. Where the flange sizes are increased due to the additional flange lateral bending, this increase typically is not significant. In fact, the increased cost resulting from the increased flange sizes is often much less than the increased cost of providing larger and/or more numerous cross-frames.

This research recommends framing of the cross-frames within straight skewed spans using arrangements such as those shown in Figure 3 to both dramatically reduce the number of cross-frames within the bridge as well as to reduce the overall transverse stiffness effects.

Effects of Fit Condition on Girder Stresses

In straight skewed bridges, the influence on the girder major-axis bending stresses due to SDLF and TDLF detailing based on refined analysis cambers is small and can be neglected, as long as the framing plan is configured in accordance with the recommendations presented earlier in this paper.

Effects of Fit Condition on Cross-Frame Forces

Although the use of refined analysis methods is not required for all curved and/or skewed I-girder bridges, these methods, when utilized, do allow for direct consideration of cross-frame forces and girder flange lateral bending stresses. However, it is important to recognize that the dead-load force effects, when determined from a refined analysis

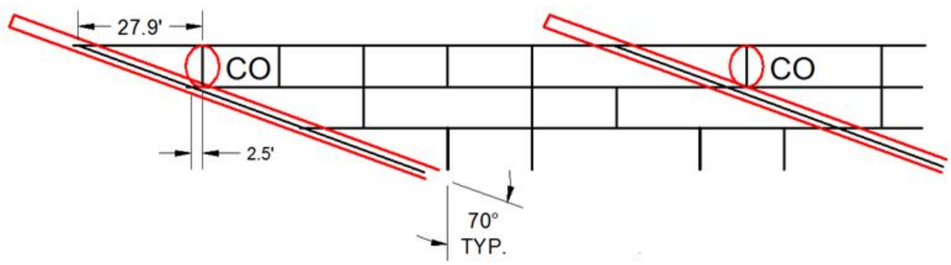


FIGURE 2 Use of intermediate cross-frames, with chords only, adjacent to skewed bearing lines.

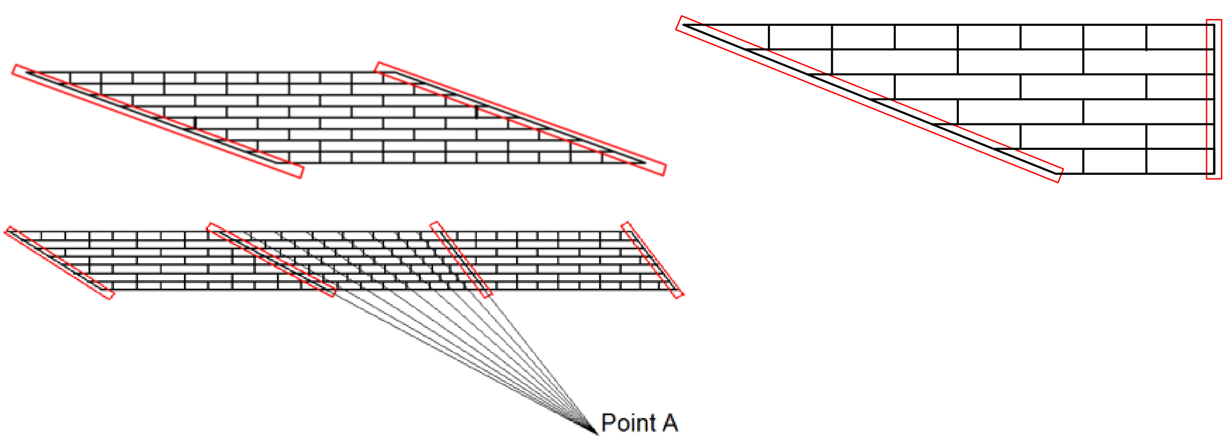


FIGURE 3 Recommended staggered cross-frame patterns for straight skewed bridges.

model, typically do not include the locked-in force effects from SDLF or TDLF detailing of the cross-frames. That is, the analysis model corresponds to the assumption of NLF.

In a straight skewed bridge, SDLF or TDLF detailing twists the girders in the direction opposite from that which they roll under dead load. However, in this case, the detailing relieves the dead load force effects in the cross-frames. This is because the dead load twist rotations in a straight skewed bridge are imposed on the girders via the compatibility of deformations with the cross-frames.

Conversely, in a curved radially-supported bridge, the intermediate cross-frames restrain or resist the tendency of the girders to twist and deflect excessively, which would occur if they were restrained from twisting only at the bearing lines. The intermediate cross-frames tie the girders into the overall structural system, and force the girders to work together to resist torsion via differential major-axis bending of the girders across the bridge cross-section. Therefore, the additional pulling or twisting of the girders in the opposite direction from that which they want to roll adds to the other dead load cross-frame forces in a curved radially-supported bridge, since the other dead load forces and the additional forces associated with the SDLF or TDLF detailing are both restraining or resisting the tendency of the individual girders to twist and deflect excessively.

As a result, in straight skewed bridges, it is conservative to design the cross-frames using the results from an accurate grid or 3D FEA model and neglecting the SDLF or TDLF effects. This is the current common practice when the engineer chooses to utilize more than a line girder analysis for the design. In certain I-girder bridges (those with severe skew and large width/span ratio) the cross-frame forces determined in this manner can be very conservative. This can lead to excessively large cross-frames. In lieu of a refined analysis that includes the lack-of-fit due to the SDLF or TDLF detailing, Reference *(3)* provides a range of simple reduction factors that may be applied to the cross-frame forces and the flange lateral bending stresses from a refined analysis that does not otherwise account for these effects.

In curved girder bridges, the girders require radial forces to be introduced by the cross-frames to satisfy equilibrium with their major-axis bending moments, and to restrain their tendency to twist. SDLF and TDLF detailing tends to increase these internal cross-frame forces, since the cross-frames are used to twist the girders back in the direction opposite to the direction that they naturally roll under the dead loads; this action effectively increases the restraint provided to the girders from the cross-frames.

It is possible to directly calculate the internal “locked-in forces” associated with SDLF or TDLF detailing directly within either a 2D grid or 3D Finite Element Analysis. The calculations simply involve the consideration of the initial lack-of-fit displacements between the cross-frame connection work points and the corresponding work points on the girders in the undeformed No-Load geometry of the structure. These lack-of-fit displacements are then used to calculate initial strains in the cross-frame members, or initial fixed-end forces in an overall beam element representation of the cross-frames. These initial strains or initial fixed-end forces induce nodal loads in the structural analysis model that account for the influence of the initial lack-of-fit. The response of the structure to these nodal loads is added to the above “initial effects” in the undeformed configuration of the structure to determine the corresponding internal forces and stresses that are “locked-in” to the structure due to the dead-load fit detailing.

Reference *(3)*, provides a detailed explanation of the above procedures, complete with benchmark 2D-grid and 3D FEA calculations for a basic straight skewed as well as a curved radially-supported bridge. It also explains how the results for the locked-in forces determined from this type of analysis may be included within design load combinations to properly satisfy AASHTO LRFD requirements.

At the present time, inclusion of the lack-of-fit effects from SDLF or TDLF detailing is not well supported in professional analysis and design software. An engineer who wishes to include these effects typically must do significant calculations outside of the software, then input information such as, for example, pseudo temperature changes in the cross-frame members that produce the same initial strains as the initial lack-of-fit displacements. Until this situation is improved, and for sanity checking of the results from these types of analysis calculations when they are performed, the basic estimates recommended in Table 3 may be employed to estimate the locked-in force effects associated with SDLF and TDLF detailing. This table is based on the studies conducted in Reference *(3)*.

Table 3 Recommended estimates of factored dead load bridge responses for curved and/or skewed bridges in their final constructed condition, in lieu of including lack-of-fit directly within the structural analysis.

Responses	**(1) Curved Radially-Supported**	**(2) Straight Skewed**	**(3) Curved and Skewed**
Cross-frame forces	γ_p (2.0 SDL + ADL) for SDLF [a], except γ_p (SDL + ADL) for chords of X-Type cross-frames	γ_p TDL for SDLF, (γ_p – 0.4) TDL for TDLF	Same as (1)
Flange lateral bending	γ_p (1.2 SDL + ADL) for SDLF [b]	(γ_p – 0.5) SDL + γ_p ADL for SDLF (γ_p – 0.4) TDL for TDLF	Same as (1)
Major-axis bending	γ_p TDL for SDLF [a]	γ_p TDL for SDLF [b] γ_p TDL for TDLF [c]	Same as (1)
Vertical Reactions	γ_p TDL for SDLF [a] For simply supported bridges, SDLF and TDLF tend to increase the smallest reactions at the girders on the inside of the curve [d]	γ_p TDL for SDLF [b, e] γ_p TDL for TDLF [c, e] For simply-supported bridges the tendency for uplift on the girder bearings at the obtuse corners of the bridge plan is lessened by the use of SDLF or TDLF detailing based on refined analysis cambers (compared to the use of LGA cambers)	For simply-supported bridges [d, f]: Worst-case maximum reactions [g]: • γ_p (1.2 SDL + ADL) for SDLF [a], when the length of girder on the inside of the curve is increased by the skew • γ_p (1.6 SDL + ADL) for SDLF [a], when the length of girder on the outside of the curve is increased by the skew

Definitions and Acronyms:

- SDL = Steel Dead Load, SDLF = Steel Dead Load Fit
- TDL = Total Dead Load, TDLF = Total Dead Load Fit
- ADL = Additional Dead Load = TDL – SDL
- LGA = Line Girder Analysis
- γ_p = Permanent Dead Load Factor

Notes:

a) TDLF detailing is strongly discouraged for curved bridges with $L_s/R > 0.03 \pm$, where L_s is the span length along the centerline of the bridge and R is the radius of the centerline of the bridge cross-section.
b) Contingent on the use of discontinuous cross-frame lines with an unbraced length $L_b >$ max of ($4b_f$, $0.4L_{b.adj}$) for all unbraced lengths within the span, where b_f is the largest girder flange width within on either side of a given cross-frame, and $L_{b.adj}$ is the smallest adjacent unbraced length.
c) Contingent on $I_s \leq 1.0 \pm$, and $L_b \geq$ max of ($4b_f$, $0.4L_{b.adj}$), where I_s is the "skew index" in Eq. 4.6.3.3.2-2 of Reference *(4)*
d) The influence of SDLF or TDLF detailing on the reactions for curved and skewed continuous-span bridges is relatively complex; if potential uplift and/or increases in the reactions are a concern, a SDLF or TDLF refined analysis is recommended.
e) If potential uplift at obtuse corners of the bridge plan is a concern, the uplift condition can be estimated conservatively by using LGA for the targeted dead load condition and NLF refined analysis for additional dead and/or live loads.
f) In curved and skewed I-girder bridges, the cross-frame lines need to be contiguous within the spans to develop the width of the structural system; in some cases, this requirement can exacerbate potential uplift conditions at obtuse corners of the bridge plan that are on the inside of the curve.
g) If potential uplift at obtuse corners of the bridge plan is a concern, a SDLF or TDLF refined analysis should be considered.

In curved I-girder bridges, the locked-in force effects from SDLF and TDLF detailing tend to be additive with the corresponding dead load effects. Calculation of adjustments to force effects is recommended for curved, radially-supported bridges with a maximum L_s/R greater than or equal to 0.2. The additional forces associated with TDLF detailing tend to be prohibitive for highly-curved I-girder bridges, and thus TDLF detailing of these types of structures is strongly discouraged. Therefore, Table 3 does not address estimates for curved bridges detailed for TDLF.

Construction Inspection Best Practices

As can be seen from the discussions in this research, the behavior of curved and/or skewed steel I-girder bridges can be quite complicated, and the constructed geometry can change significantly through the various stages of construction. However, this research has also shown that this behavior is also predictable within reasonable accuracy, and that properly designed, detailed, and fabricated bridges, when properly assembled, can achieve their constructed geometry at all significant milestones in the construction sequence.

Due to the complex nature of the behavior of these types of structures, it is advisable that construction inspectors have some knowledge of that behavior, and some understanding of the significance of the various notes and information presented on the plans. Inspectors should have a clear understanding of the meaning of, and differences between, NLF, SDLF, and TDLF detailing. They should also understand the various synonymous terms such as Fully Cambered Fit, Erected Fit, and Final Fit. They should know how to evaluate the constructed geometry

It is critical that inspectors be able to properly assess the constructed geometry of a bridge at two key stages of construction: at the completion of steel erection, and at the completion of deck placement. Properly assessing the constructed geometry at these key stages, and taking proper action (or properly taking no action) will help ensure successful construction and minimize problems, delays, and unnecessary costs. With a small amount of instruction, inspectors can achieve this goal.

Common Items

Here are a few items which are common to any curved and/or skewed steel I-girder bridge, regardless of geometric configuration or specified detailing method:

1. Web Plumbness /Girder Layover Tolerance

   Tolerances for girder layover are specified in the AASHTO/NSBA Guide Specification S10.1-2014, Steel Bridge Erection Guide Specification (*8*).

2. Effect of Girder Layover on Girder Stresses and Strength

   Multiple studies have demonstrated that the effects of girder layover on girder stresses and girder strength are negligible, including (*2*), (*9*), (*10*), and (*11*).

   Inspectors should not be concerned about the strength or stresses in girders which are out of plumb.

3. Girder Camber at End of Steel Erection

   Most owners require that the tops of girders be surveyed in the as-erected position, prior to installing deck formwork, and the contractor use this survey information to determine the correct position of the deck forms.

   The surveyed profiles of the girder top flanges are compared to the camber profiles on the plans to check for general conformance. The surveyed profile information is also used to determine the appropriate position of the deck formwork relative to the girder top flanges; the anticipated dead load deflection is subtracted from the surveyed elevation of the top of the girder and then compared to the desired final roadway profile and deck thickness to determine the correct position of the deck formwork relative to the top flange.

   Generally, if the top flange is a little higher or a little lower than anticipated, the contractor can compensate by setting the deck formwork a little lower or a little higher respectively. If the needed adjustments appear to be excessive, i.e., if the haunch will be too deep or too shallow, other actions may be required, such as providing haunch reinforcing (for an excessively deep haunch), adjusting the final roadway profile (for an excessively over-cambered girder with a "negative" haunch, i.e., girder flange would be embedded in the deck), or other actions.

Owners should clearly specify the required field survey and calculation procedures, and should have clearly identified minimum and maximum haunch values so that inspectors can easily review this information and make appropriate decisions on whether to allow construction to continue, to require adjustments to deck forms, or to contact the Engineer to discuss more significant remedial actions.

4. Uplift at Bearings

   Uplift at bearings may or may not represent a problem; inspectors should be provided with sufficient information in the plans to assess the nature of any observed uplift, and should be sufficiently informed about this issue so as to know if and when to involve the engineer in discussions about possible remedial actions.

   Generally, uplift is considered undesirable by most owners, under any conditions. However, some leeway is generally given in allowing temporary uplift during construction, provided that in the final condition there is no uplift.

   If temporary uplift is anticipated at some interim stage of erection or deck placement it should be clearly indicated in the plans or specifications, or clearly communicated at a preconstruction meeting or by other means. The locations where uplift is anticipated, and the specific conditions under which uplift is anticipated, should be clearly presented. If feasible and appropriate, some measure of anticipated uplift might also be presented. This information will allow the inspector to compare the as-built condition of the bridge under those same stages of erection or construction to the anticipated conditions. If the observed behavior of the structure is significantly different from the anticipated behavior, the engineer should be contacted and an investigation undertaken to determine the causes and possible consequences of this behavior, and to determine what, if any, remedial actions may be necessary.

   Inspectors should understand that *anticipated* uplift during interim stages of construction is not necessarily a sign of a problem. The inspector should not undertake remedial action to "correct" what may be perceived to be a "problem" with uplift. For example, if uplift is anticipated at some interim stage of construction and if the designer evaluated this condition and found no long-term problems associated with it, the inspector should not attempt to remediate the uplift by means of shims, counterweights, etc., as these actions would interfere with the subsequent behavior of the structure and may cause long-term problems.

5. Effects of Deviations from Anticipated Web Position or other Anticipated Constructed Geometry Measurements

   Layover and web position for various bridge geometries and detailing methods will be discussed further later in this section. The possible consequences of unintended layover or deviations from anticipated web position are discussed here in general terms. Inspectors should be familiar with these possible consequences so that they can have informed discussions with the contractor and the engineer as appropriate. The possible consequences of unintended layover or deviations from anticipated web position, and some possible remedial actions, are listed below. The list of possible remedial actions is not meant to be comprehensive; other actions may be warranted or necessary in specific situations.

   - Increased Rotational Demand on Bearings: In some cases this may be a minor effect, especially if it is determined that the effects are temporary (occurring only during an interim stage of construction). For cases of temporary increased rotational demand on bearings, one possible solution might be to temporarily support the girders on blocking (removing all load from the bearings), or otherwise providing additional support to reduce demand on the bearings in the interim condition.
   - Girder/Cross-Frame Fit-Up Problems: Unintended layover or other deviations from the anticipated constructed geometry (such as excessive deflection, particularly excessive differential deflection between adjacent girders) at interim stages of steel erection may be a sign that the contractor is

losing control of the constructed geometry. This problem is sometimes difficult to recognize since specific constructed geometry information at each and every stage of erection typically does not exist. However, if such information is available, the inspector should evaluate the constructed geometry at interim stages of erection. If significant deviations from constructed geometry are observed, the inspector and the contractor should discuss the matter and verify that the problems can be corrected in the next stage of erection. If the structure continues to deviate further from its anticipated constructed position in the next stage of erection that could be a sign that eventually the contractor will be unable to fit-up the remainder of the structural steel. Inspectors should evaluate compliance with the anticipated constructed geometry throughout the erection of the structural steel. The sooner issues are identified and diagnosed, the better the chances that simpler, easier actions will be able to correct the problem.

- Misaligned Joints and Barriers: Unintended layover or deviations from anticipated web position at supports under TDL conditions can result in misaligned joints or barriers. The best time to assess the position of the web is at the end of steel erection, prior to deck placement, since there is still a reasonable opportunity to take remedial actions at that time. If problems with web position are not identified until after deck placement, the range of possible remedial actions is very limited and generally very costly. Inspectors should carefully evaluate the position of the webs at supports at the end of steel erection, prior to deck placement.

Items Related to Straight Skewed Bridges

Straight, skewed steel I-girder bridges will often exhibit noticeable changes in their web position (i.e., noticeable layover) throughout construction. Girder webs will be plumb under only one loading condition. Girder webs that are plumb at the end of erection (prior to deck placement) will not be plumb after deck placement, and vice versa. It is important that inspectors evaluate girder layover at supports both at the end of steel erection (prior to deck placement) and also after deck placement.

Most straight, skewed steel I-girder bridges will be detailed for one of two possible types of fit:

- Steel Dead Load Fit (SDLF, also known as Erected Fit): For bridges which are detailed for SDLF the girder webs should be plumb (within reasonable construction tolerance) at the end of steel erection, prior to deck placement. If they are not plumb at the end of steel erection (prior to deck placement), the engineer should be consulted and remedial action should be considered. Later, when the deck is placed, the webs will lay over and be out of plumb. This sequence of webs being plumb prior to deck placement and out of plumb after deck placement is normal and generally does not represent a problem.
- Total Dead Load Fit (TDLF, also known as Final Fit): For bridges which are detailed for TDLF the girder webs should be plumb (within reasonable construction tolerance) at the end of deck placement. The webs will be out of plumb at the end of steel erection, prior to deck placement. If the webs are plumb at the end of steel erection (prior to deck placement), or are out of plumb in the wrong direction or beyond reasonable construction tolerances, remedial action should be considered. If the webs are in their correct, anticipated out of plumb position prior to deck placement, then when the deck is placed the webs will rotate (twist) to a plumb position (within reasonable construction tolerance), at least at the supports. This sequence of webs being out of plumb prior to deck placement and plumb after deck placement is normal and generally does not represent a problem.

Some owners/designers may present web orientation information on the plans; if so, the inspector can use this data to evaluate the positions of the webs at the end of steel erection (prior to deck placement). If this information is not on the plans, the web orientation (out of plumbness) at the end of steel erection (prior to deck placement) can be estimated using a simple geometric formula commonly used by steel detailers. Depending on the owner's specification requirements, the inspector may be able to request this information from the contractor, or may only be able to encourage the contractor to perform their own evaluation at the end of steel erection. In either case, both the magnitude and direction of out-of-plumbness of the webs at the end of steel erection should be considered.

Items Related to Curved Radially-Supported Bridges

Curved, radially supported steel I-girder bridges will exhibit noticeable changes in their web position (i.e., noticeable layover) throughout construction, but only within the span. At the supports the girders will be plumb both at the end of steel erection (prior to deck placement) and after deck placement. Out in the span, the girder webs will be plumb under only one loading condition. Girder webs may be plumb when shored, or they may be plumb at the end of erection (after shoring is removed but prior to deck placement). It is highly unlikely that the webs will be plumb after deck placement. It is important that inspectors evaluate web plumbness at supports at all stages of the construction process, including under shored conditions (if shoring is used), at the end of steel erection (prior to deck placement), and after deck placement.

Most curved, radially supported steel I-girder bridges will be detailed for one of two possible types of fit:

- No-Load Fit (NLF, also known as Fully Cambered Fit): For bridges which are detailed for NLF, the girder webs should be plumb under shored conditions throughout the length of the bridge. Later, when the shoring is removed at the end of steel erection (prior to deck placement) the webs should still be plumb at the supports, but will be out of plumb in the span. Generally the girders should be expected to twist so that the top flange is deflected toward the outside of the curve. Later, when the deck is placed, the webs should still be plumb at the supports, but will be further out of plumb in the span. Again, the girders should be expected to twist so that the top flange is deflected toward the outside of the curve. If the girder webs are out of plumb at the supports at any stage of construction the engineer should be consulted and remedial action should be considered. Girder layover in the span at the end of construction is normal in a curved, radially supported bridge and generally does not represent a problem.
- Steel Dead Load Fit (SDLF, also known as Erected Fit): For bridges which are detailed for SDLF the girder webs should be plumb (within reasonable construction tolerance) at the end of steel erection, prior to deck placement, throughout the length of the bridge. If they are not plumb at the end of steel erection (prior to deck placement), the engineer should be consulted and remedial action should be considered. Later, when the deck is placed, the webs should still be plumb at the supports, but will be further out of plumb in the span. Again, the girders should be expected to twist so that the top flange is deflected toward the outside of the curve. Girder layover in the span at the end of construction is normal in a curved, radially supported bridge and generally does not represent a problem.

The use of Total Dead Load Fit detailing (TDLF, also known as Final Fit) for curved, radially supported steel I-girder bridges is strongly discouraged as its use in these types of bridges generally results in excessive fit-up forces.

Items Related to Curved and Skewed Bridges

Curved and skewed steel I-girder bridges are very complicated structures. They will exhibit noticeable changes in their web position (i.e., noticeable layover) throughout construction. Girder webs may be plumb when shored, or they may be plumb at the end of erection (after shoring is removed but prior to deck placement). It is highly unlikely that the webs will be plumb after deck placement. It is important that inspectors evaluate web plumbness at supports at all stages of the construction process, including under shored conditions (if shoring is used), at the end of steel erection (prior to deck placement), and after deck placement.

Most curved and skewed steel I-girder bridges will be detailed for one of two possible types of fit:

- No-Load Fit (NLF, also known as Fully Cambered Fit): For bridges which are detailed for NLF, the girder webs should be plumb under shored conditions throughout the length of the bridge. Later, when the shoring is removed at the end of steel erection (prior to deck placement) the webs will be out of plumb in the span, and possibly also at the supports, particularly at any and all skewed supports. Generally the girders should be expected to twist so that the top flange is deflected toward the outside of the curve, but this may not be true if the geometry is particularly complicated. Later, when the deck is placed, the webs which were plumb at the supports prior to deck placement will likely still be plumb after deck placement, but will be further out of plumb in the span. Again, the girders should be expected to twist so that the top flange is deflected toward the outside of the curve, but this may not be true if the geometry is particularly complicated. Girder layover at the end of construction is normal and generally does not represent a problem.
- Steel Dead Load Fit (SDLF, also known as Erected Fit): For bridges which are detailed for SDLF the girder webs should be plumb (within reasonable construction tolerance) at the end of steel erection, prior to deck placement, throughout the length of the bridge. If they are not plumb at the end of steel erection (prior to deck placement), the engineer should be consulted and remedial action should be considered. Later, when the deck is placed, the webs should still be plumb at the supports, but will be further out of plumb in the span. Again, the girders should be expected to twist so that the top flange is deflected toward the outside of the curve, but this may not be true if the geometry is particularly complicated. Girder layover in the span at the end of construction is normal in a curved, radially supported bridge and generally does not represent a problem.

The use of Total Dead Load Fit detailing (TDLF, also known as Final Fit) for curved and skewed steel I-girder bridges is generally discouraged unless the degree of curvature is very small.

Conclusions

Improved design, detailing and erection guidelines to ensure reliable fit-up of skewed and/or curved steel I-girder bridges, based on detailed analytical studies of twenty-one bridges, including multiple framing arrangements on a number of the bridges, are provided in the full report which is summarized in this paper. The report provides quantitatively-based recommendations regarding the choice of fit condition (aka, cross-frame detailing method) and the selection of erection schemes as a function of the bridge geometry, based on the goal of minimizing fit-up forces and facilitating erection. In addition, the report recommends beneficial staggered cross-frame arrangements for straight skewed bridges, as well as framing arrangements around bearing lines at interior piers in continuous-span bridges. Simplified methods of accounting for Steel Dead Load Fit (SDLF) and Total Dead Load Fit (TDLF) detailing effects, as well as procedures for direct calculation of the locked-in forces due to SDLF and TDLF detailing, are provided. Lastly, construction inspection best practices are recommended to ensure that the erected geometry sufficiently meets the specified fit conditions. Recommended design specification provisions have been developed and incorporated into the 8th Edition *AASHTO LRFD Bridge Design Specifications* (*12*) that synthesize the key guidelines that resulted from this research.

Acknowledgements

The research discussed in this paper was funded as NCHRP Research Project 20-07, Task 355. The support and input of Technical Committee T-14 (Structural Steel) of the AASHTO Subcommittee on Bridges and Structures, the NCHRP 20-07, Task 355 Project Panel, and Dr. Waseem Dekalbab of the Transportation Research Board, are greatly appreciated. The substantive input on the project considerations by Mr. Joshua Orton of Heath & Lineback Engineers, Inc., and the prior contributions of Dr. Cagri Ozgur and Dr. Telmo Andres Sanchez leading to NCHRP Report 725, are also gratefully acknowledged.

References

1) Chavel, B.W., Coletti, D.A., Frank, K.H., Grubb, M.A., McEleney, W., Medlock, R.D., White, D.W., *Skewed and Curved Steel I-Girder Bridge Fit,* White Paper prepared for the National Steel Bridge Alliance (NSBA), August 2016.
2) White, D. W., D. A. Coletti, B. W. Chavel, T. A. Sanchez, C. Ozgur, J. M. M. Chong, R. T. Leon, R. D. Medlock, R. A. Cisneros, T. V. Galambos, J. M. Yadlosky, W. J. Gatti, G. T. Kowatch, *NCHRP Report 725 - Guidelines for Analytical Methods and Construction Engineering of Curved and Skewed Steel Girder Bridges*, Prepared for the Transportation Research Board of the National Academies under the auspices of the National Cooperative Highway Research Program, February 29, 2012.
3) White, D.W., Nguyen, T.V., Coletti, D.A., Chavel, B.W., Grubb, M.A., Boring, C.G., *Guidelines for Reliable Fit-Up of Steel I-Girder Bridges*, Final Report of NCHRP Research Project 20-07, Task 355, Prepared for the Transportation Research Board of the National Academies under the auspices of the National Cooperative Highway Research Program, October 26, 2015.
4) American Association of State Highway Transportation Officials (AASHTO), *LRFD Bridge Design Specifications*, 7th Edition, 2014, with Interim Revisions through 2016.
5) American Association of State Highway Transportation Officials (AASHTO), *Standard Specifications for Highway Bridges,* 17th Edition, 2002.
6) Romage, M.L., "Field Measurements on Lean-On-Bracing for Steel Girder Bridges with Skewed Supports," M.S. thesis, University of Texas, Austin, TX, 2008.
7) Zhou, C., "Utilizing Lean-On Cross-Frame Bracing for Steel Bridges," Ph.D. dissertation, University of Houston, Houston, TX, 2006.
8) American Association of State Highway Transportation Officials/National Steel Bridge Alliance (AASHTO/NSBA) Steel Bridge Collaboration, *Steel Bridge Erection Guide Specification,* 2nd Edition, 2014.
9) Domalik, D. E, Linzell, D. G, and Shura, J. F, "Design and Field Monitoring of a Horizontally Curved Steel Plate Girder Bridge," *HDR Bridgeline*, Vol.14, No.1, 2005.
10) Domalik, D. E, Shura, J. F, and Linzell, D. G, "The Design and Field Monitoring of a Horizontally Curved Steel Plate Girder Bridge," in *Proc., 84th Annual Meeting of the Transportation Research Board,* 2005.
11) Howell, T. and Earls, C. "Curved Steel I-Girder Bridge Response during Construction Loading: Effects of Web Plumbness," *ASCE Journal of Bridge Engineering*, Volume 12, No. 4, July, 2007, pp. 485–493.
12) American Association of State Highway Transportation Officials (AASHTO), *AASHTO LRFD Bridge Design Specifications*, 8th Edition, 2017.