technical resource

Skewed and Curved Steel I-Girder Bridge Fit

NSBA TECHNICAL COMMITTEE, FIT TASK FORCE: BRANDON CHAVEL, DOMENIC COLETTI, KARL FRANK,
MIKE GRUBB, BILL McELENEY, RONNIE MEDLOCK, AND DON WHITE

WHAT IS FIT AND WHY IS IT IMPORTANT?

The "fit" or "fit condition" of an I-girder bridge refers to the deflected girder geometry associated with a specific load condition in which the cross-frames or diaphragms are detailed to connect to the girders. Consideration of the fit condition is important because the appropriate fit decision can provide a significant benefit to the constructability and the overall performance of the bridge system.

In all bridge systems (trusses, arches, etc.) the steel components change shape between the fabricated condition, the erected condition, and the final condition. Therefore the associated relationship, or fitting, of the members also changes. When the changes are small, the fit choice can be inconsequential, but when the changes are large, the proper fit choice is essential for achieving a successful project.

Article 6.7.2 of the AASHTO *LRFD Bridge Design Specifications* (8th Edition, 2017) specifies that the contract documents should state the fit condition for which the cross-frames or diaphragms are to be detailed for the following I-girder bridges:

- Straight bridges where one or more support lines are skewed more than 20 degrees from normal;
- Horizontally curved bridges where one or more support lines are skewed more than 20 degrees from normal and with an L/R in all spans less than or equal to 0.03; and
- Horizontally curved bridges with or without skewed supports and with a maximum L/R greater than 0.03.

where L is the span length bearing to bearing along the centerline of the bridge and R is the radius of the centerline of the bridge cross-section.

A fit decision always must be made so that the fabricator/detailer can complete the shop drawings and fabricate the bridge components in a way that allows the erector/contractor to assemble the steel and achieve a desired geometry in the field. The fit decision also affects design decisions regarding the rotation demands on the bearings as well as the internal forces for which the cross-frames and girders must be designed. The fit condition generally should be selected to accomplish the following objectives, in order of priority: 1. facilitate the construction of the bridge; 2. offset large girder dead load twist rotations and corresponding lateral movements at the deck joints and barrier rails, which occur predominantly at sharply skewed abutment lines; 3. in straight skewed bridges, reduce the dead load forces in the cross-frames or diaphragms and the flange lateral bending stresses in the girders, and in horizontally curved bridges, limit the magnitude of additive locked-in dead load force effects.

The question, then, is in what condition should an I-girder bridge be detailed to fit? Certainly, the final condition is of great interest: to perform effectively in service, girders and cross-frames need to be in place, properly connected and properly supporting the roadway and traffic. Therefore, one might infer that bridges should be detailed simply to fit in their final constructed condition. For some bridges fitting the cross-frames to the final condition is fine and indeed may be the best choice; however, for others, fitting to the final condition significantly increases the internal cross-frame forces and can potentially make the bridge unconstructable. For every bridge, the fit condition must be selected to effectively manage the structure's constructed geometry and internal forces, and to facilitate the construction of the bridge.

It should be noted that, in practice, I-girder bridge fit is accomplished by the choice the detailer makes in setting the "drops" for the cross-frame and connection plate fabrication. The drop is defined as the difference in elevation on either side of a cross-frame. Since the fit decision directly influences the cross-frame fabricated geometry, as well as the bridge constructability and subsequent internal forces, the fit condition ideally should be selected by the engineer, who best knows the loads and capacities of the structural members. To facilitate an informed decision regarding detailing and constructability, the engineer can consult with experienced fabricators, and/or erectors prior to completing the contract documents.

Common Fit Conditions

The fit of an I-girder bridge is influenced by the difference in deflection between the sides of the cross-frames: the greater the skew, the sharper the curve, the greater the variation in the girder lengths, and the greater the span lengths, the greater this differential deflection will be. In fact, a quick way to evaluate potential constructability issues is to note the differences in the deflections across the width of the bridge at each stage of loading.

Given that dead loads cause deflections, and differences in girder deflections affect fit, it follows that the common fit conditions are associated with different bridge dead load conditions. These are shown in Table 1. Engineers tend to be more familiar with names associated with loading conditions; fabricators tend to be more familiar with terms associated with stages of construction. The setting of drops discussed in the "Practice" column of the table refers to the detailer establishing the relative position of each cross-frame to each girder.

This is a stand-alone summary that is complimentary to a larger guide document on fit published by the NSBA.

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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.

Since differential deflections cause twisting of the girders when they are connected by cross-frames, the girders can be plumb only in the load condition in which the bridge is fit. That is, if a bridge is detailed for Steel Dead Load Fit (SDLF), the girders will be approximately plumb at the completion of the steel erection, but not when the remaining dead loads are ap-plied. Furthermore, if a bridge is detailed for Total Dead Load Fit (TDLF), the girders will not be plumb at erection but will theoretically be plumb after all the dead loads are applied. Hence, another way to refer to the fit condition is to speak of when the girders are approximately plumb: plumb at no-load, plumb at erection, or plumb in the final condition.

Although the above terminology is commonly used, it is not the best way to refer to fit conditions for two reasons. First, the natural answer to the question "when should the girders be plumb?" is "at the end." However, choosing plumb "at the end" is not always best and can lead to significant problems in some bridges. Second, the question of "how plumb is plumb enough?" cannot be answered effectively. Due to tolerances and constraints, the girders will not be truly plumb in the associated fit condition. For example, if TDLF is used, the deck casting sequence and hardening of the deck during casting may cause the girders to be somewhat out of plumb after the total dead load is applied unless the associated changes in stiffness are estimated sufficiently in the camber calculations. Likewise, the sequence of erection, cross-frame connection tolerances, and shoring conditions can influence the actual plumb condition at the erection of the girders in a bridge detailed for SDLF.

Customary Practice

Fabricators use the fit condition prescribed in the plans (AASHTO 6.7.2 specifies that this direction should be provided for significantly curved and/or skewed I-girder bridges, although the actual provision of such direction is not universal). A key element to consider when choosing the fit condition is the girder differential deflections between the locations where they are connected by cross-frames (i.e., what are the drops?). If the deflection of the girders at each side of the cross-frames is about the same, then the structure is not sensitive to the fit choice. For example on straight, non-skewed bridges with uniformly spaced girders and typical overhangs, the girders will deflect essentially equally at all dead load stages without producing any differential deflections. Conversely, the larger the difference in girder deflection between the locations where they are connected by the cross-frames, the more the fit choice matters.

For straight bridges (skewed and non-skewed), both SDLF and TDLF are common and effective. SDLF gives approximately plumb girder webs once the erection of the steel is completed and is favored for ease of construction. Since the steel dead load corresponds to the condition when all the girders are erected and all the cross-frames are connected, skewed bridges detailed for this condition require little force to fit the cross-frames to the girders. However, on skewed bridges, the application of subsequent dead loads (due to the weight of the deck, barriers, etc.) will introduce a final and permanent twist into the girders. Conversely, TDLF gives approximately plumb girder webs once the bridge is subjected to its total dead load; but for skewed bridges, the cross-frames do not match the geometry of the girders during erection, so the cross-frames must be forced into position and the girders will be tilted after the steel is erected until the final dead loads are applied.

Note that although Table 1 refers to girder elevations, major-axis girder rotations also affect fit. Although intuition might suggest that fit issues associated with differential deflections can be avoided by framing the cross-frames along the skew, doing so results in similar fit responses because the axis of the skewed cross-frames (which have high in-plane shear stiffness, or high racking stiffness) is not normal to the girder webs. As the girders undergo major-axis rotations, the cross-frames roll about their own axis, and since they have high in-place shear stiffness, they resist racking deformations and cause the girders to twist (or lay over).

For curved bridges, the use of SDLF is most common. Furthermore, practice has demonstrated that the use of TDLF on curved bridges can potentially render the bridge unconstructable. This is because curved girders cannot be twisted as readily as girders in straight bridges to facilitate erection. Therefore, as specified in AASHTO 6.7.2, the use of TDLF detailing should not be specified for horizontally curved bridges with or without skew and with a maximum *L/R* greater than 0.03. TDLF detailing may be specified but is not recommended for horizontally curved bridges when the supports are skewed more than 20 degrees from normal, spans are less than or equal to about 200 feet in length, and *L/R* in all spans is less than or equal to 0.03.

Article 6.7.2 further specifies that horizontally curved bridges with or without skew and with a maximum *L/R* greater than 0.03 may be detailed for a NLF or a SDLF, unless the maximum *L/R* is greater than or equal to 0.2. In this case, either the bridge should be detailed for a NLF, or the additive locked-in force effects associated with the SDLF detailing should be considered (refer to the section on Design and Analysis below). The additive locked-in force effects tend to be particularly significant for bridges with a maximum *L/R* greater than or equal to 0.2 that are detailed for a SDLF (NCHRP 2015). Detailing these bridges for a NLF avoids the introduction of these additional locked-in force effects. Furthermore, such bridges are likely to require temporary shoring and support during the erection as a matter of course—as such, the bridge is erected in a "quasi" NLF condition as a general practice and the cross-frames can be easily installed in this shored condition. For curved bridges with smaller *L/R* that are detailed for a SDLF, the horizontal curvature effects are smaller, and hence the additive locked-in force effects are smaller and may be neglected.

Recommended Fit Conditions

I-girder bridges have been detailed for fit for as long as steel stringers, including rolled beams, have been used in bridges. However the challenge of making a good fit choice has increased as bridge geometries have become more complex, and as greater skews, longer span lengths, and sharper curves have resulted in greater differential deflections. Tables 2 and 3 provide general fit recommendations which reflect historic experience blended with improved understanding of fit-up forces from recent research:

1. To facilitate fit-up (i.e., assembly of the steel) during erection;
2. To limit bearing rotation demands and to facilitate deck joint alignment and barrier rail alignment at skewed bearing lines; and
3. In straight skewed bridges, to reduce the dead load forces in the cross-frames and diaphragms and the flange lateral bending stresses in the girders, and in horizontally curved bridges, to limit the magnitude of additive locked-in dead load force effects.

The generalized terms used in Tables 2 and 3 are described as follows:

- L = span length, bearing to bearing along the centerline of the bridge
- R = radius of the centerline of the bridge cross-section
- The skew index, I_s, in Table 2 is defined as follows (AASHTO Eq. 4.6.3.3.2-2):

$$I_s = \frac{w_g \tan \theta}{L} \tag{1}$$

where:

- w_g is the bridge width perpendicular to the centerline, fascia girder to fascia girder, and
- θ is the maximum skew angle of the bearing lines at the end of a given span measured from a line perpendicular to the span centerline (equal to zero for no skew).

For continuous-span bridges, I_s is defined as the largest value for any of the spans. Equation 1 has been found to be a useful indicator of the influence of skew on the potential development of transverse load paths in the bridge system in straight skewed bridges (NCHRP, 2012). A strong correlation was found between the skew index and the general magnitude of the cross-frame forces caused by skew. For highly curved bridges, there is a complex interrelationship between the direction of the skew and the direction of the horizontal curvature when considering the fit behavior, and the associated effects are more involved than just the consideration of I_s. For the various recommended fit conditions presented in Tables 2 and 3, the span length and skew index limits should be considered as approximate guidelines and should be evaluated in the full context of the geometric and structural complexity of a given bridge.

Both SDLF and TDLF are customary long-used industry practices for straight bridges, but they are not used universally for all situations. That is, there are trade-offs between the two approaches. TDLF results in a bridge whose webs are nominally plumb after construction and produces smaller rotation demands at the bearings. However, at the end of the steel erection there will be an initial girder layover (until final dead loads are applied), and the girders and cross-frames must be forced together during erection. The use of such force is common, but may not be workable in some cases for longer span highly-skewed bridges. Conversely, SDLF makes straight skewed bridges easier to erect and results in webs that are plumb after erection; however, after the final dead loads are applied, some girder layover will be present. This final layover is not known to cause any particular girder behavior problems, but the bearings must be able to accommodate the associated girder rotations. Generally NLF is not recommended for straight skewed bridges because NLF would lead to a need to accommodate girder twist rotations at the abutment bearings that can otherwise be avoided, and it does not facilitate fit-up or improve the final plumb condition. In the limiting condition of a bridge that is straight with no skew in any of the supports, (i.e., a "square" bridge), the fit-up effects become small and essentially inconsequential and the results of the different cross-frame detailing methods are all the same.

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 $I_s \le 0.30$ +/-			
	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

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

Radial or Skewed Supports			
	Recommended	Acceptable	Avoid
$(L/R)_{MAX} \ge 0.2$	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: SDLF detailing is considered acceptable in these cases if the additive locked-in force effects are considered (see Design and Analysis section below).

The emphasis of the above discussion is on straight skewed bridges. Additional considerations regarding horizontally curved bridges, with or without skew, are addressed in the following discussions.

Special Considerations

The following are key points to consider regarding fit. Although there are many fit considerations, these are highlighted here because they reduce the chances for construction problems:

- To facilitate construction at skewed abutments and piers, keep the first intermediate normal cross-frames a minimum of the larger of $4b_f$ and $0.4L_{b.adj}$ away from the support where practicable when laying out the cross-frames in design as noted in AASHTO C6.7.4.2, where b_f is the largest girder flange width within the unbraced lengths on either side of the intermediate cross-frame, and $L_{b.adj}$ is the adjacent unbraced length to the offset under consideration (NCHRP, 2015).
- Be cautious using oversize or slotted holes in the cross-frame to girder connections in straight skewed bridges; oversize holes (or

slots) can be used to facilitate assembly of discrete pieces that are difficult to frame in, but use of oversize or slotted holes throughout the system can compromise the bridge geometry. AASHTO 6.13.1 states that "Unless otherwise permitted by the contract documents, standard-size bolt holes shall be used in connections in horizontally curved bridges."

- Be sure to tighten fasteners in girder-to-cross-frame connections before casting the deck.
- As reflected in the tables above, avoid TDLF in curved bridges unless the supports are skewed and the degree of curvature is small. Given the stiffness and coupled vertical and torsional deflections of curved girders under load, there is no practical way to assemble some TDLF curved bridges (since substantial extra loads would need to be applied to account for the missing dead loads during erection).
- When TDLF is used on straight skewed bridges, note the expected initial layover (under steel dead load) in the design plans or shop drawings. This practice is recommended so that the layover does not cause alarm and delays when it is noticed during the steel erection.

Design and Analysis

Two different types of forces are influenced by the selected fit condition: 1. the bridge internal dead load forces and 2. the "fit-up" forces, which are external forces the erector may need to apply to assemble the structural steel during erection.

For SDLF/TDLF on a straight skewed bridge, the cross-frame internal forces due to the SDLF/TDLF detailing are opposite in sign to and a significant fraction of the internal steel dead load/total dead load (SDL/TDL) forces calculated by building an accurate grid (as defined in NCHRP, 2012) or 3D FEA model, and simply turning the corresponding gravity loads on (or which are nominally present in the cross-frames if the bridge were built with NLF detailing). Since the locked-in forces due to the SDLF/TDLF detailing are opposite in sign to and a significant fraction of the above SDL/TDL internal forces, the total internal dead load forces in the cross-frames of a straight skewed bridge detailed for SDLF are relatively small under the SDL (at the completion of the steel erection), and the total internal dead load forces in the cross-frames of a straight skewed bridge detailed for TDLF are relatively small under the TDL (at the completion of the bridge construction).

It is conservative to design the cross-frames in a straight-skewed bridge 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 I-girder bridges having a particularly large skew index, I_s, the cross-frame forces estimated in this way can be overly conservative. In some cases, this can lead to excessively large cross-frame member designs. Due to the eccentricity of the cross frame connection plates to the centroid of the members, the axial stiffness of the angles and tee sections typically used as cross frame members is reduced. Stiffness reduction coefficients are contained in Basttistini et al (2016). The reduced axial stiffness should be used when modeling the cross frame members in accurate grid or 3D FEA analysis. In lieu of requiring a refined analysis that directly determines the locked-in force effects due to the DLF detailing, the larger guide document on fit provides simple reduction factors that may be applied to the cross-frame forces (for TDLF only) and the girder flange lateral bending stresses obtained via a refined analysis that does not otherwise account for these effects.

For straight skewed bridges detailed for SDLF, little to no forcing is needed to fit the cross-frames and girders during the steel erection. That is, the required external "fit-up" forces are small. In straight skewed bridges detailed for TDLF, the cross-frames must be forced to fit to the girders during the erection of the steel, but the associated internal forces largely come back out when the final dead loads are applied and the system deflects to the TDL condition. As the skew approaches zero in a straight I-girder bridge, both the internal forces due to SDLF or TDLF detailing, as well as the fit-up forces required to erect the steel, become small and inconsequential.

The girders in curved bridges have radial forces 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 and girder flange lateral bending stresses, since the cross-frames are used to twist the girders back in the direction opposite to the direction they naturally roll under the dead loads. Further, curved girders can be much stiffer than straight girders and the girder vertical and torsional deflections are generally coupled. 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.

The additional internal cross-frame forces and flange lateral bending stresses due to SDLF effects tend to be relatively small in horizontally curved bridges, unless the maximum *L/R* is greater than or equal to approximately 0.2 (NCHRP, 2015).

For these curved bridges with more significant horizontal curvature, the local twisting of I-girders to make the connections may become more difficult. In these cases, NLF is recommended, unless the additive locked-in force effects associated with SDLF detailing are considered. It is possible to directly calculate the internal "locked-in forces" associated with SDLF detailing in such cases by performing a refined analysis that includes the lack-of-fit due to the SDLF detailing (NCHRP, 2015). In lieu of such an analysis, the larger guide document on fit provides an approximate approach for estimating the additional locked-in force effects.

Conclusion

In I-girder bridges, the relationship between the girders changes as the girders deflect under the dead load. These changes introduce internal forces and affect fit-up; when the changes are significant, it is important that the appropriate fit decision be made to facilitate the construction of the bridge and to achieve benefits in limiting girder dead load twist rotations, cross-frame dead load internal forces and girder flange lateral bending stresses. Making the right fit choice is a key consideration that can impact engineers, fabricators and erectors, and the best fit choice is one made by the engineer informed by all of the stakeholders.

References

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