Skewed and Curved Steel I-Girder Bridge Fit

NSBA Technical Subcommittee

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This document is dedicated to the late Fred R. Beckmann of the American Institute of Steel Construction, who diligently gave of himself to help others achieve the best solutions for the nation's steel bridges.

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Smarter.
Stronger.
Steel.

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FOREWORD

Tighter constraints on right-of-way, particularly in urban environments, have led to a significantly increased utilization of skewed and curved alignments in highway bridge construction. Due to the relative ease of configuring the structure to the roadway geometry, steel I-girder bridges are often a preferred option for these cases.

Skewed and curved I-girder bridges have been successfully fabricated and erected for many years and have performed well in service. However, challenging attributes of the framing arrangements combined with long-used detailing practices and common erection procedures can result in issues during construction at certain extremes. Some of the issues encountered have included:

- Girders and cross-frames that are difficult to assemble during the erection, requiring un-planned operations such as substantial force fitting of connections, field drilling and field welding;
- Erected girders with webs that are significantly out-of-plumb (although out-of-plumbness of girder webs is not necessarily problematic);
- Additive locked-in stresses in the cross-frames and girders, which may be significant in some cases;
- Bearing rotations that are larger than allowable design limits; and
- Deck joints and barrier rails that are out-of-alignment between the approach and the end of the bridge.

In certain instances, these issues, which often result from a lack of understanding of the behavior of these bridge types and/or poor communication between the various parties associated with the project, have resulted in construction delays, rework, cost overruns, disputes and litigation.

Skewed and curved I-girder bridges generally exhibit torsional displacements, or twisting, of the individual girders and of the overall bridge cross-section under load, including the loads during construction. The above issues can be avoided by developing a better understanding of the causes and effects of this twisting, and the ways in which framing arrangements, cross-frame detailing practices, and erection procedures influence the bridge behavior.

The following terms are used commonly to refer to the deflected or undeflected geometry under which the cross-frames in these bridges are detailed to attach to theoretically plumb girders. The most commonly referenced fit conditions are:

- No-Load Fit (NLF), also referred to as Fully-Cambered Fit, where the cross-frames are detailed to attach to the girders without any force-fitting in their initially fabricated, plumb, undeflected geometry under zero dead load;
- Steel Dead Load Fit (SDLF), also referred to as Erected Fit, where the cross-frames are detailed to attach to the girders in a plumb position in which the girders are deflected only vertically under the bridge steel dead load, and
- Total Dead Load Fit (TDLF), also referred to as Final Fit, where the cross-frames are detailed to fit to the girders in a plumb position in which the girders are deflected only vertically under the bridge total dead load.

The "fit" or "fit condition" is selected by considering the dead load condition (i.e., no load, steel dead load, or total dead load) at which it is desired for the girders to be approximately plumb. The choice of fit condition can influence the constructability and long-term bridge performance because it can affect the magnitude of the locked-in force effects in the cross-frames and the girders, and it can influence the forces required to assemble the steel together during the erection. This paper addresses the behavior of skewed and/or curved I-girder bridges, and the intricate interplay of the fit decision with this behavior.

Different skewed and curved I-girder bridges experience the above issues to different degrees. Bridges with less severe skew, larger radii and/or shorter spans are not as sensitive to the choice of the fit condition. For a given skew and/or horizontal curvature, bridges with longer spans potentially can experience more difficulties with respect to key responses during and at the completion of the construction, such as:

- Fit-up (i.e., assembly) of the steel during the erection,
- Achievement of the targeted constructed geometry under dead load, and
- Development of significant changes in the internal force states in the structure under dead load due to detailing and erection procedures.

The design engineer typically analyzes and designs a bridge as if it is fully constructed in the unstressed (No-Load) position, without any force-fitting, and then the gravity loads are simply "turned on." This is a simplifying assumption which does not account for the influence of the actual fit condition on the bridge response.

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. The intent of this provision is to ensure that the preferences of the owner and engineer of record regarding the fit condition are clearly conveyed to those involved in the fabrication and construction of the bridge.

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, in consultation with a fabricator and erector. The desired outcome, safe, easy and economical construction of skewed and curved steel I-girder bridges, is more likely to be achieved if all parties involved in the design and construction understand the issues and communicate early (and with a common language) to ensure that an appropriate fit decision is made for a particular bridge project.

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; and
4. Select the load condition in which the girders will be approximately plumb. The plumbness condition should not be specified by the engineer; girder plumbness is dictated by the fit condition.

The key question, then, is under what (load) condition should an I-girder bridge be detailed to fit? Certainly, the Total Dead Load condition is of great interest: to perform effectively in service, girders and cross-frames need to be in place, properly connected and properly functioning, with internal loads that do not exceed the capacity of the structure. 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; 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.

The behavior of straight skewed bridges is fundamentally different than the behavior of curved girder bridges. These differences in the fundamental behavior should be fully understood and carefully considered, since the selected fit condition will affect the constructability and performance of these different bridges types in different ways. Sections 2 and 3 of this document therefore discuss the fundamental behavioral characteristics of straight skewed and horizontally curved I-girder bridges, respectively, and highlight the important differences in these characteristics and how they might influence the selection of a particular fit condition.

In addition to pointing out the important fundamental differences in the behavioral characteristics of straight skewed and horizontally curved I-girder bridges, this document is also intended to assist the owner and the engineer, in consultation with fabrication and construction professionals, to make a more informed consensus decision in specifying the fit condition for a particular skewed and/or curved steel I-girder bridge based on the fundamental behavioral characteristics. Section 7 of this document provides tables of recommended and acceptable fit conditions for straight skewed and curved steel I-girder bridges (with or without skew) as a function of broad generalized characteristics of the bridge geometry. The tables also indicate which fit condition(s) should be avoided for a particular bridge type. The recommendations represent an industry consensus based on experience, recent research regarding steel I-girder bridge fit behavior (NCHRP 2012; NCHRP 2015), and state-of-the-art practices and knowledge related to skewed and curved steel I-girder bridge fit. It is further noted that this document should also be useful for a field engineer to better understand the observed behavior of these bridges during construction. The reader is referred to Section 9 for recommended best construction inspection practices to ensure that the erected geometry sufficiently meets the specified fit conditions.

In addition to the above summary recommendations, this document also includes detailed discussions of the three most common options for the fit condition: NLF, SDLF and TDLF. Section 4 includes a thorough explanation of the cross-frame detailing procedure that is used for each option, the outcomes that can be expected when each option is employed, and the effects of these outcomes on various bridge components. Important issues the engineer should consider in the design and analysis of straight skewed and horizontally curved I-girder bridges are discussed in Section 5. Section 6 summarizes the advantages and disadvantages of each fit option. Lastly, Section 8 briefly describes additional considerations related to the design of bearings at skewed supports, specific erection practices, fabrication of bolt holes and bolt tightening during erection, shop assembly practices, and some fit considerations for tub girders. After brief conclusions are presented in Section 10, commonly used terms are defined in Section 11 of the document to assist the reader in understanding the discussions.

1 INTRODUCTION

Skewed and/or curved I-girder bridges generally exhibit torsional displacements of the individual girders and of the overall bridge cross-section under load. As a result, the girder webs can be approximately plumb in only one load condition. For instance, if the structure is fabricated such that the girder webs are plumb in the ideal No-Load (NL) position, they cannot be plumb under the action of the structure's dead load. Furthermore, live loads produce additional deflections.

It is important to recognize that twisting of the girders in a skewed and/or curved I-girder bridge is not necessarily indicative of a structural problem or deficiency; it is a natural, predictable, and controllable response of these types of structures to the gravity loads. If this were not the case, essentially all of these bridges would be deficient under the design live loads (since they twist under live load).

Skewed and curved I-girder bridges have been successfully fabricated and erected and have performed well in service for many years. However, it is important to recognize and understand the effects of the girder and system twisting in these bridges so that an informed decision on an appropriate fit condition can be made as a function of the bridge geometry, thus reducing the potential for construction problems related to the steel erection.

In selecting a particular fit condition, it is important to keep in mind that the behavior of straight skewed bridges is fundamentally different than the behavior of curved bridges. Therefore, the following Sections 2 and 3 first discuss the fundamental behavior characteristics of straight skewed and horizontally curved I-girder bridges, respectively, and highlight the important differences in those characteristics and how they might influence the selection of a particular fit condition. A thorough explanation of the cross-frame detailing procedure used for each of the three most common options for the fit condition discussed in Sections 2 and 3 (i.e., NLF, SDLF and TDLF) follows in Section 4.

Section 5 next discusses important aspects the engineer should consider pertaining to the fit condition and the analysis and design of straight skewed and horizontally curved I-girder bridges. The advantages and disadvantages of each fit option are summarized subsequently in Section 6. Section 7 then provides tables of recommended and acceptable fit conditions for straight skewed and curved I-girder bridges (with or without skew) as a function of broad generalized characteristics of the bridge geometry, which are based on industry consensus and recent research regarding steel I-girder fit behavior (NCHRP 2012; NCHRP 2015). The tables also indicate which fit condition(s) should be avoided for a particular bridge type. Section 8 briefly describes additional considerations related to the design of bearings at skewed supports, specific erection practices, fabrication of bolt holes and bolt tightening during erection, shop assembly practices, and some fit considerations for tub girders. Section 9 discusses recommended best construction inspection practices for evaluation of the constructed geometry of these bridge types. Following brief conclusions that are presented in Section 10, commonly used terms are defined in Section 11 of the document to assist the reader in understanding the discussions.

2 BEHAVIOR OF STRAIGHT SKEWED I-GIRDER BRIDGES

In straight skewed I-girder bridges, the girders only deflect vertically under their self-weight as long as the cross-frames are not connected to the girders in a manner such that they are engaged and can transfer internal shears and moments (Figure 1).

If the cross-frames are detailed for SDLF or TDLF using these deflections, i.e., the deflections determined from a 1D line-girder analysis, the cross-frames will fit exactly to the girders in the above Steel Dead Load (SDL) or Total Dead Load (TDL) geometry (assuming all loads are properly accounted for in the analysis). Therefore, if SDLF detailing is used with the above SDL deflections, the cross-frame internal forces are theoretically zero under the SDL and the cross-frame connections to the girders can be completed with little to no force-fitting during the steel erection. Similarly, if TDLF detailing is used, the cross-frame internal dead load forces are theoretically zero under the TDL condition based on the line girder analysis deflections. However, the erector will need to apply additional force to the steel to make the connections during the steel erection (NCHRP 2015). The conclusion of theoretically zero cross-frame forces under TDL, for TDLF detailing, assumes that the deck forms and the bridge deck in its early condition during concrete placement, including any staged deck placement, do not provide any interconnection between the girders in resisting the TDL, and that the deck overhang loads predominantly affect only the fascia girders and the adjacent cross-frame lines (such that the deck overhang load effects can be calculated separately and independently from the above effects).

Once the cross-frames are connected to the girders, the interconnected girders deflect as a three-dimensional system under all subsequent loads. The cross-frames brace the girders, but they also serve as an additional transverse load path in the system. As a result, the girders deflect vertically and simultaneously twist under the dead loads (Figure 2).

Where the cross-frames are perpendicular to the girders, the twisting occurs primarily because of the differential vertical deflections between the girders at each of the intermediate cross-frames, since these cross-frames connect to different positions within the span of each of the girders. In straight skewed bridges with parallel skews and contiguous cross-frames aligned with the skewed bearing lines, which is permitted by AASHTO for skew angles less than or equal to 20 degrees from normal, the differential vertical deflections at the ends of the cross-

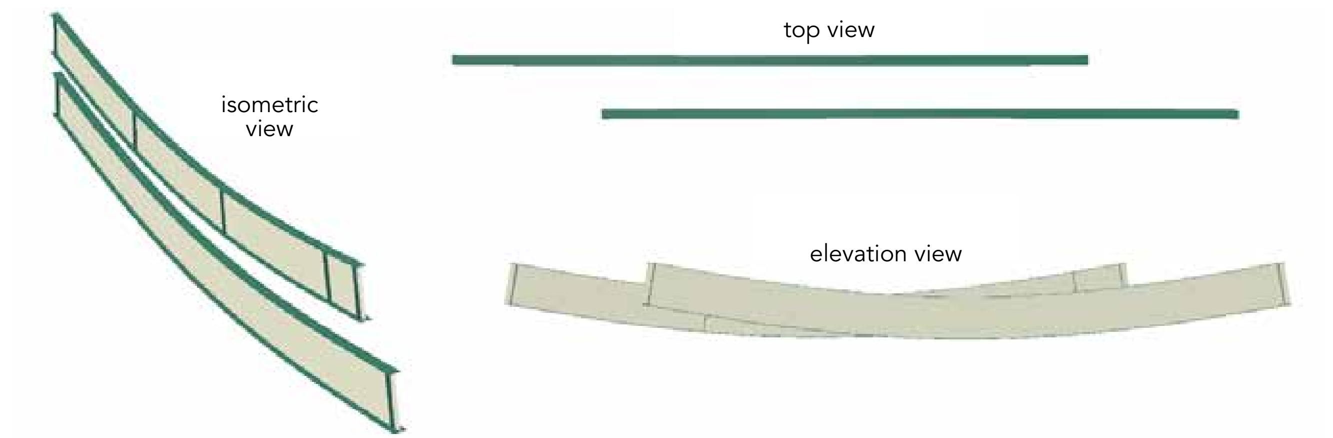

Fig. 1. Magnified Girder Vertical Deflections for Two Simple-Span I-Girders on Parallel Skewed Supports, Subjected to Steel Dead Load (SDL) Prior to Connecting the Cross-Frames

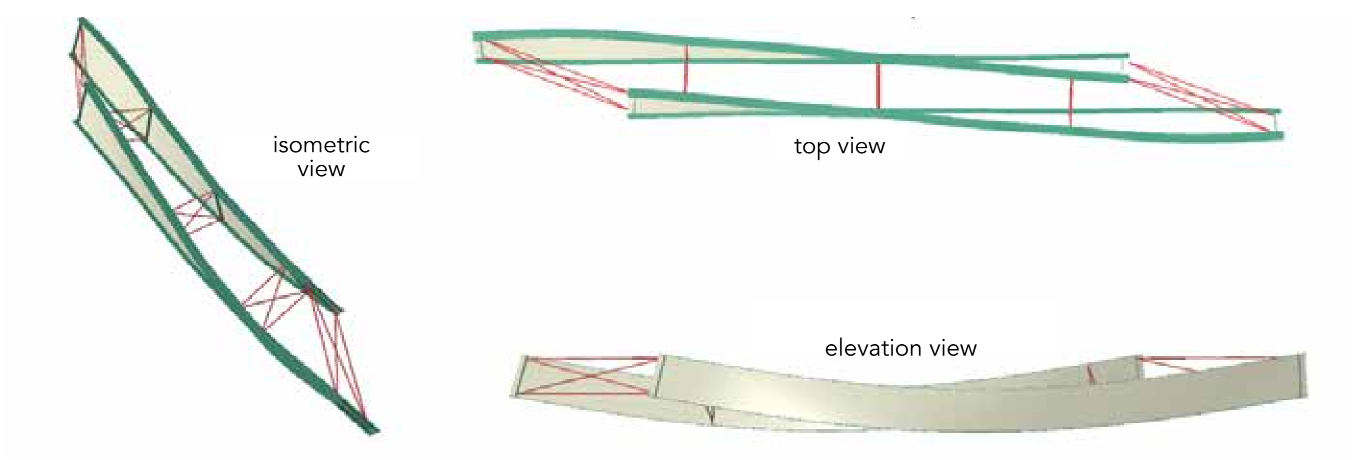

Fig. 2. Magnified Girder Vertical Deflections and Twist for Two Simple-Span I-Girders on Parallel Skewed Supports, Subjected to Vertical Load After Connecting the Cross-Frames.

frames are essentially zero. However, in this case, girder twisting is induced by the rotational continuity between the skewed cross-frames and the girders. Similarly, along skewed bearing lines, where the vertical deflections of the girders are zero, the girders have to twist to maintain rotational continuity between the bearing-line cross-frames and the girders. Basically, at any position along the bridge where the cross-frames are skewed relative to the girders, if the girders have non-zero major-axis rotations, the girders must twist to maintain rotational continuity with the cross-frames. If the cross-frames are detailed for SDLF or TDLF, the corresponding lack-of-fit in the fully-cambered NL geometry induces girder twist rotations that approximately compensate for these twist rotations in the SDL or TDL condition of the bridge.

If the cross-frames are detailed for SDLF using the vertical self-weight deflections computed considering the three-dimensional interaction of the girders with the cross-frames as an overall structural system, i.e., if the vertical deflections are calculated from an accurate 2D grid or 3D refined analysis, the connections to the girders typically still can be completed with little force-fitting (outside of any transverse stiffness or other framing arrangement effects described below in Section 4.4). In this case, the cross-frame internal forces are reduced substantially but will not be theoretically zero (NCHRP 2015).

It should be noted that the girder deflections in a partially erected structure are different from those at the completion of the steel erection. However, SDLF detailing is always based on the computed girder deflections due to the steel self-weight applied to the fully erected steel system. The computed SDL deflections and internal forces at the completion of the erection are essentially independent of the steel erection sequence assuming the following:

1. The bridge responds elastically under the dead loads and any erection loads;
2. The influence of connection tolerances is small and may be ignored (i.e., oversize or slotted holes are not used); and
3. The influence of any incidental restraint from friction at bearing locations is small and may be ignored.

These are the assumptions generally made by the design engineer when analyzing a bridge. (This does not mean that the erector can neglect the movements induced by play in the connections associated with connection tolerances.)

If the cross-frames are detailed for TDLF, the erector will need to apply force during the steel erection in order to complete the connections. This is because the TDL is not yet applied to the bridge. Therefore, the girders must be twisted out-of-plumb to overcome the fact that they are not yet subjected to the TDL deflections. However, in many cases with straight skewed bridges, the girders are relatively flexible in torsion and can be twisted out-of-plumb with minimal force during the cross-frame installation.

Once installed, the cross-frames are typically able to hold the girders in their intended (plumb) position with relative ease under the targeted dead load. In fact, straight girders naturally tend to remain straight under gravity loads if they are not connected to the cross-frames, global stability effects aside. As such, in a straight skewed bridge, the locked-in forces that result due to the lack-of-fit detailed between the cross-frames and the girders in the base NL geometry tend to be reduced substantially (i.e., they tend to be substantially offset) by the dead load effects. That is, the sum of the locked-in cross-frame forces from the lack-of-fit effects and the dead load effects in the targeted dead load condition (obtained from a refined analysis neglecting the SDLF or TDLF detailing effects) tends to be a small value. The locked-in forces tend to be largely opposite in sign (direction) to the internal dead load forces and stresses (NCHRP 2012; NCHRP 2015). Since the resulting cross-frame forces are small in the targeted dead load condition, and since the girders are approximately plumb in this condition, the girder flange lateral bending stresses are also small in the targeted dead load condition. This is a desirable dead load geometry and stress condition.

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 cross-frame framing arrangement satisfies the recommendations discussed further in Section 4.4.

NLF detailing is not typically used and should be avoided for straight skewed bridges. This is because, with NLF detailing, there is no compensation for the twist rotations that occur at skewed bearing lines. This increases the total rotation demands on the bearings under the dead and live loads and can cause potential alignment difficulties at deck joints and barrier rails at skewed end supports.

3 BEHAVIOR OF HORIZONTALLY CURVED I-GIRDER BRIDGES

The bridge cross-section in horizontally-curved I-girder bridges is subjected to significant internal torsional moments due to the fact that the resultant of the bridge vertical loads within the spans has an eccentricity relative to a straight chord between the supports. In a straight skewed bridge, the total internal torsion tends to be relatively small and the girder torques are induced predominantly by the compatibility of deformations between the girders and the cross-frames; that is, if the girders are not interconnected by the cross-frames, there is no tendency for them to twist under the primary vertical loads. However, the internal torsion in curved bridges exists independently of the interconnection of the girders by the cross-frames. If the curved I-girders are not connected to the overall bridge structural system by the cross-frames, they tend to exhibit large torsional deflections.

The predominant resistance to the above internal torsion in horizontally-curved I-girder bridges is developed by interconnecting the girders across the entire bridge width by the cross-frames. Vertical forces ("V-loads") are applied to the girders by the cross-frames. This produces a shift in the internal vertical forces toward the girders on the outside of the horizontal curve. Associated radial forces are applied from the cross-frames to the girders that prevent excessive individual girder torsional rotations by attaching the girders to the overall bridge cross-section. Because the girders and the overall bridge cross-section want to rotate torsionally (Figure 3), curved I-girders and curved I-girder bridge units often cannot be erected without providing some type of intermediate vertical support within the spans, typically via holding cranes or temporary shoring at critical stages of the erection.

In addition, horizontally curved I-girders generally exhibit significant coupling between their major-axis bending displacements and their torsional rotations. Major-axis bending of curved girders cannot occur without also inducing twisting of the girders, and twisting of curved girders cannot occur without inducing major-axis bending. This behavior can exacerbate fit-up problems in curved girder bridges since it is more difficult to adjust the twist of the girders to connect them with the cross-frames. In addition, both the completed bridge, as well as separate curved-bridge units during construction, exhibit these coupled vertical deflection and torsional rotation characteristics at an overall system level.

In horizontally curved bridges built with either SDLF or TLDF detailing, the cross-frames are fabricated such that they twist the girders an additional amount in the opposite direction that they and the bridge cross-section want to roll under the corresponding dead load. That is, the cross-frames generally restrain excessive torsional deflection of the girders in a curved bridge. SDLF and TDLF detailing increase these restraining effects. With NLF detailing, there will be a non-zero twist of the girders that is essentially equal to the overall twist rotation of the bridge cross-section at the cross-frame locations under SDL and TDL. In contrast, with SDLF or TDLF detailing, the lack-of-fit fabricated into the cross-frames twists the girders back an additional amount in the direction opposite from the twist rotations of the bridge cross-section such that the girders are approximately plumb, at the cross-frame locations, under SDL or TDL. As such, both SDLF and TLDF detailing tend to increase the cross-frame forces in curved girder bridges, particularly the forces in the cross-frame diagonals. That is, unlike straight skewed bridges, the locked-in cross-frame forces associated with SDLF and TDLF detailing tend to be additive with the general dead load effects in the cross-frames in horizontally curved bridges (NCHRP 2012; NCHRP 2015). SDLF and TDLF detailing increase the restraining effects on the girders in horizontally curved bridges. The additive cross-frame force effects in horizontally curved bridges can make the cross-frames more difficult to install compared to the use of NLF detailing. Fortunately, for SDLF detailing, the additional forces usually are not particularly large. As such, it is common that the cross-frame installation can be completed successfully. This fact has been demonstrated extensively in practice, since SDLF is the most common detailing practice used for curved bridges.

TDLF and SDLF detailing also twist the girders during erection substantially in the direction opposite from that which they want to roll under the dead load in straight skewed bridges. In the case of straight skewed bridges, the detailing relieves the TDL or SDL effects in the cross-frames. This is because the

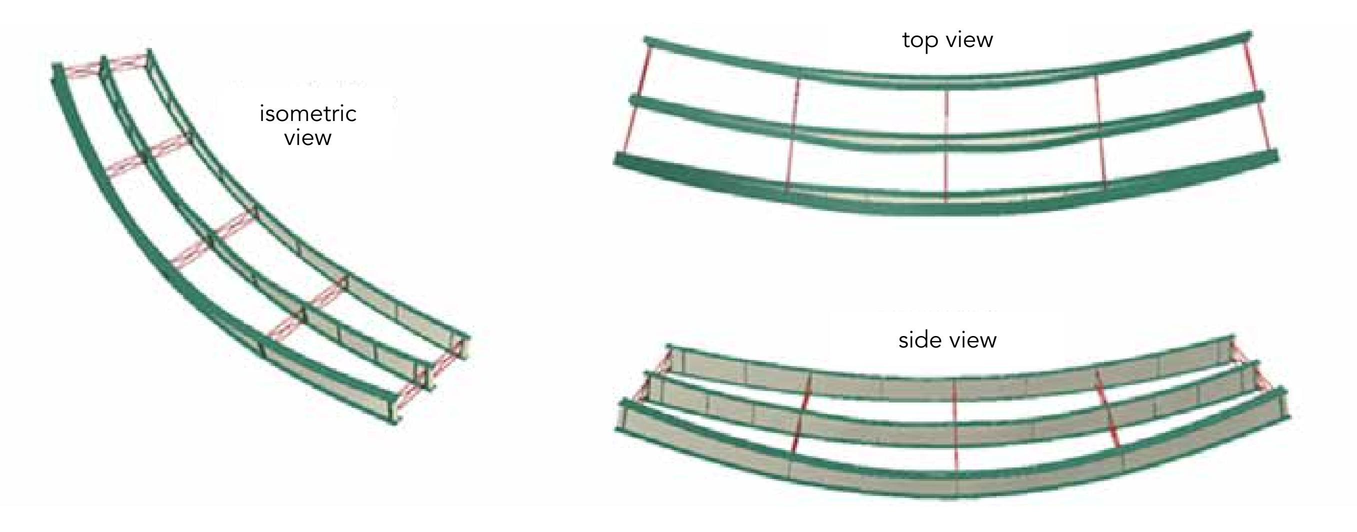

Fig. 3. Magnified Girder Vertical Deflections and Twist for a Four-Girder Horizontally Curved Simple Span Bridge with Non-Skewed Supports, Subjected to Vertical Load

TDL or SDL twist rotations in a straight skewed bridge are imposed on the girders via the compatibility of deformations with the cross-frames. Conversely, in curved radially-supported bridges, the intermediate cross-frames restrain or resist the tendency of the curved girders to twist and deflect excessively. In curved radially-supported bridges, the intermediate cross-frames tie the girders to the overall structural system, and force them to work together to resist torsion via differential major-axis bending across the bridge cross-section. Therefore, the additional pulling or twisting of the girders during erection in the opposite direction from that which they want to roll adds to the other DL cross-frame forces in curved radially-supported bridges, since the other DL forces and the additional forces associated with the TDLF or SDLF detailing are both restraining or resisting the tendency of the individual girders to twist and deflect excessively under the SDL and the TDL.

For the case of TDLF detailing of curved bridges, the additional forces required to twist the girders back in the opposite direction from which they and the bridge cross-section want to roll, and the resulting additive locked-in force effects, can be more substantial. This is because TDLF aims to overcome the rotations caused by the total dead loads (typically steel plus concrete deck dead load). Also, the TDL is not yet in place on the structure when the steel is being erected.

Due to the above issues, Article 6.7.2 of the AASHTO *LRFD Bridge Design Specifications* (8th Edition, 2017) states that 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 (where *L* is the span length between adjacent bearing lines along the centerline of the bridge and *R* is the radius of the centerline of the bridge cross-section—refer to Table 4 in Section 7). Although not recommended, TDLF detailing may be specified 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 either NLF or SDLF, unless the maximum *L/R* is greater than or equal to 0.2. In this case, either the bridge should be detailed for NLF, or the additive locked-in force effects associated with the SDLF detailing should be considered (refer to Section 5.3). The additive locked-in force effects tend to be particularly significant for bridges with a maximum *L/R* greater than or equal to approximately 0.2 that are detailed for SDLF (NCHRP 2015). Detailing these bridges for 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 can be erected in a "quasi" NL condition as a general practice and the cross-frames can be easily installed in this shored condition.

In addition, for curved radially supported bridges, the resulting girder out-of-plumbness under load will occur out in the spans and not at the supports and is not likely to be objectionable from an aesthetic or structural performance standpoint. These girder twist rotations generally do not indicate a structural problem for the girders and cross-frames as long as the global stability provisions in AASHTO LRFD 6.10.3.4.2 are properly satisfied. For horizontally curved bridges that also have significant support skew, the twist rotations at the supports can be (and need to be) addressed in the bearing design and in the deck joint alignment. SDLF detailing assists with reducing these rotations.

It should be noted that for straight-skewed bridges, SDLF and TDLF detailing do not have a significant effect on the girder elevations in the completed structure, as long as the detailing is based on vertical deflections determined from a refined analysis (NCHRP 2015). For curved bridges, SDLF and TDLF generally tend to increase the elevations of all the girders within the bridge spans (NCHRP 2012; NCHRP 2015). However, these effects have been shown to be small enough to be accommodated within typical practices for selecting girder haunch depths and setting of formwork elevations for placement of the deck concrete, with the exception of an extreme notable case where the critical span length was larger than 250 ft, the subtended angle between the bearing lines L_s/R was greater than 0.5, and the length-to-width ratio of the span L_s/w_g was relatively small (NCHRP 2015).

4 DEFINITION OF THE "FIT" OR "FIT CONDITION"

4.1 General

The "fit" or "fit condition" of an I-girder bridge refers to the deflected or undeflected girder geometry under which the cross-frames are detailed to connect to theoretically plumb girders. The fit condition is selected by considering the dead load condition (i.e., NL, SDL, or TDL) at which it is desired for the girders to be approximately plumb. The choice of fit condition can influence the constructability and long-term performance of the bridge because it can affect the magnitude of the locked-in force effects in the cross-frames and the girders, and it can influence the forces required to assemble the steel together during the erection.

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 in the deflected geometry between the members are small, the fit choice can be inconsequential, but when the changes are large, the proper fit choice is essential for achieving a successful bridge project.

In straight bridges with no skew, the vertical dead load deflections in adjacent girders are essentially equal across the width of the bridge at any given location along their length (aside from some twisting of the fascia girders between cross-frames that may occur due to eccentric vertical loads applied to the deck overhangs). In these bridges, the cross-frames simply deflect along with the girders. As a result, there are no special fit condition considerations for these bridges.

Skewed and/or curved I-girder bridges, however, respond differently. The fit of a skewed and/or curved I-girder bridge is influenced by the difference in girder deflections at the ends (i.e., sides) of the cross-frames. The differential deflections increase with larger skew, sharper curves, and larger span lengths. Indeed, a quick way to evaluate potential constructability issues is to note the magnitude of 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. Table 1 summarizes the three most common fit conditions considered in skewed and/or curved I-girder bridges. Engineers tend to be more familiar with names associated with the loading conditions; fabricators and detailers tend to be more familiar with terms associated with stages of construction; the names are used interchangeably in practice.

I-girder bridge fit is accomplished by the detailer setting the "drops" for the fabrication of the cross-frames and connection plates. The drops are defined as the difference in the vertical elevation between the tops of the girder webs at a cross-frame location under NL or the targeted dead load condition. The setting of drops discussed in the "Practice" column of Table 1 refers to the detailer establishing the relative position of each cross-frame to each girder. This terminology is discussed further in the explanations below.

Steel Dead Load Fit (SDLF) gives approximately plumb girder webs once the erection of the steel is completed. Total Dead Load Fit (TDLF) gives approximately plumb girder webs once the bridge is subjected to its TDL. For the purposes of evaluating the behavior of the bridge to choose an appropriate fit condition, the term "Total Dead Load" typically refers to the self-weight of the structural steel plus the self-weight of the concrete deck. In most (but not all) cases, composite dead loads such as the weight of barrier rails, future wearing surface loads, utilities, etc. are not considered as a part of the TDL in setting the drops for TDLF. No-Load Fit (NLF) corresponds to detailing of the cross-frames so that they fit with the girders in their NL undeflected geometry. In this case, the girder webs will not be plumb, except at non-skewed bearing lines, once the bridge is subjected to dead loads. In any case, it should be recognized that due to common construction tolerances and variations in factors such as early set-up of the concrete during staged deck placement, incidental stiffness of the deck forms and reinforcement, friction at supports, etc., the girders may not be truly plumb in the associated fit condition. For straight skewed bridges, both SDLF and TDLF are common and effective. For curved bridges, the use of SDLF is most common. Furthermore, practice and research studies have demonstrated that the use of TDLF on curved bridges can potentially render the bridge unconstructable. This is largely because curved girders cannot be twisted as readily as straight girders to facilitate erection.

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.

4.2 Displacement Contributions to the Cross-Frame Detailing

There are two important displacement contributions to the detailing of cross-frames for SDLF or TDLF:

1. The girder vertical SDL or TDL deflections provided on the Design plans, and
2. The associated major-axis bending rotations at the girder connection plates under the targeted dead load.

To accomplish SDLF or TDLF at intermediate cross-frames that are normal to the girder tangents, the detailer typically determines the girder geometry in the targeted fit condition by subtracting the vertical SDL or TDL deflections from the girder plumb fully-cambered NL geometry. (Note that the fully-cambered NL girder profiles are based on the roadway profile plus the total vertical cambers, which are the negative of the girder TDL deflections.) The girders are assumed to be plumb in their initial fully-cambered NL geometry as well as in their targeted SDL or TDL positions, i.e., only the girder vertical deflections are considered. The fabricated SDLF or TDLF cross-frame geometries are then calculated such that the cross-frames fit to the work points at the girder connection plates in these targeted plumb SDL or TDL positions. Alternatively, some detailers start from the TDL position and add the appropriate deflections to that position (e.g., no adjustment for TDLF, the TDL minus the SDL deflections for SDLF, and the TDL deflections for NLF) to determine the girder geometry in the targeted fit condition.

The resulting difference in elevations between the sides of the cross-frames (typically measured at the top of the girder webs) with the girders in their NL, SDL, and TDL positions are referred to as the drops. The drops generally will be different at each of the cross-frames along the span, as well as along a given line across the bridge. At intermediate cross-frames that are framed normal to the girders, the different drops at the cross-frame locations are the key distinguishing factor between cross-frames detailed for NLF, SDLF or TDLF (Figure 4).

Along skewed cross-frame lines (either intermediate lines or bearing lines, as applicable), the rotated positions of the girder connection plates on the plumb girder webs in the targeted dead load (or NL) geometry also must be considered by the detailer in determining the cross-frame geometries. Due to the girder major-axis bending rotations, the points on the connection plates move longitudinally when the girders deflect vertically. Correspondingly, the cross-frames rotate about their own axes, which are not normal to the girder web; as a result, the corners of skewed cross-frames move both longitudinally and transversely when the girders deflect vertically (Figure 5).

At skewed support lines, the girders do not deflect vertically, but the girders still experience major-axis bending rotations (rotation about an axis normal to the girder web) and layover (rotation about the longitudinal axis of the girder), as illustrated in Figure 5; hence, the cross-frames are detailed to fit to the rotated positions of the girder bearing stiffeners or connection plates on the plumb girder webs in the targeted dead load geometry. The bearing stiffener and connection plate rotated positions are determined starting with the rotated positions on the plumb fully-cambered NL girder geometry and then subtracting the major-axis bending rotations corresponding to the girder SDL or TDL vertical deflections. These rotations are determined indirectly from the SDL or TDL displacements. At the bearing lines, the girder bearing stiffeners and connection plates are customarily detailed so that they are vertical under the TDL (neglecting any non-verticality due to twisting of the girder about its longitudinal axis). This can be used as a starting point to establish the rotated position of these plates in the SDL or NL conditions, and is preferred by some detailers.

At skewed intermediate cross-frames, *both* the drops (i.e., the differences in the girder elevations) as well as the rotational orientation of the connection plates in the targeted dead load geometry must be considered by the detailer in determining the fabricated cross-frame geometries (i.e., the cross-frame member lengths and their angles of orientation within the plane of the fabricated cross-frames).

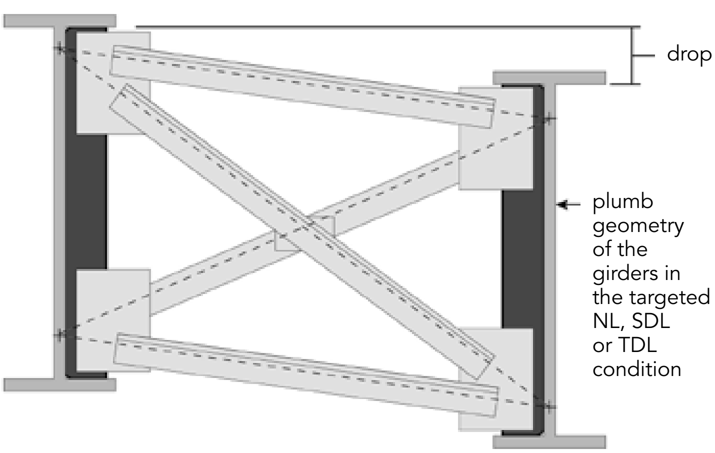

Fig. 4. Drop Between Girders at an Intermediate Cross-Frame Framed Normal to the Girder Tangents

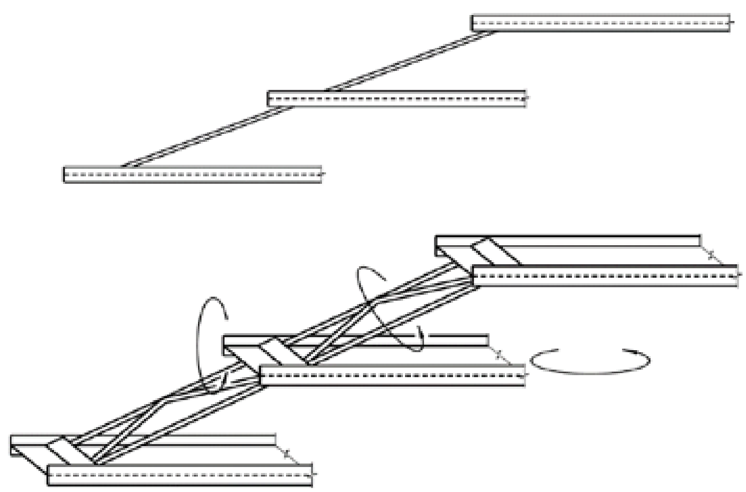

Fig. 5. Rotations of Girders and Cross-Frames & Layover of Girders at Skewed Cross-Frame Lines

The detailer does not require the girder twist rotations, i.e., the rotations about the longitudinal axis of the girders, which are associated with the three-dimensional interaction of the girders with the cross-frames in the structural system, in order to perform the above calculations. This is because the girders are assumed to be plumb in detailing for the selected fit condition. Therefore, the girder twist rotations need not be shown on the Design Plans.

4.3 Key Behavior Associated with the Cross-Frame Detailing

For SDLF or TDLF detailing, since the cross-frames are detailed to connect to an ideal plumb *deflected* position of the girders, they do not fit to the girders in the initial fully-cambered NL geometry. For purposes of illustration, Figure 6 shows a hypothetical cross-frame and girder configuration under NL (i.e., zero dead load). For this example, the cross-frame is assumed to be at a location where the girders eventually will be at the same elevation in the TDL condition, and it is assumed that the cross-frames are detailed for TDLF. The sketch corresponds to a case where the cross-frame is normal to the girder tangent lines. Since the girders are assumed to be at the same elevation under the TDL in this example (i.e., the deck cross slope is ignored), the cross-frame chords are horizontal in the sketch. The cross-frame is assumed to be attached to the girder on the left. Since the cross-frame is detailed to fit between the girders only after the targeted dead load is applied to the bridge (the TDL in this example), the cross-frame does not "fit up" with the girder on the right. This displacement incompatibility on the right-hand side of the cross-frame is referred to in structural mechanics as a "lack-of-fit."

Since the NL geometry is the reference from which all strains in the structural system are measured, this means that some straining must be induced in the structure to resolve the above incompatibility. For a simple two-girder case, such as illustrated here, typically the cross-frame is relatively rigid compared to the torsional stiffness of the girders. Therefore, when the girders and cross-frames are forced to fit together, the initial lack-of-fit results in a twisting of the girders. This is shown in Figure 7.

It is important to note that, in general, the cross-frames must be twisted from their planar fabricated geometry when the erector installs them during the erection of the steel. This is because the work points on the girders at the connection plates, in the idealized plumb girder positions of the targeted deflected geometry (or undeflected geometry for NLF detailing), are generally not all in one plane. The above process implicitly assumes that the cross-frames can be easily twisted to attach them to the connection plates, which is a reasonable assumption in the majority of cases (except perhaps for cross-frames to be installed between deep closely-spaced girders).

The twisting of the girders due to the above lack-of-fit is generally in the opposite direction from which the girders want to twist under the targeted dead load. Therefore, once these rotations are combined with the rotations caused by the targeted dead load, the girders deflect into an approximately plumb position within the targeted dead load condition (Figure 8). Figure 8 again assumes that the cross-frames have been detailed for TDLF so that the girders are at the same elevation under the TDL (the roadway profile and deck cross slope are ignored to simplify the sketch).

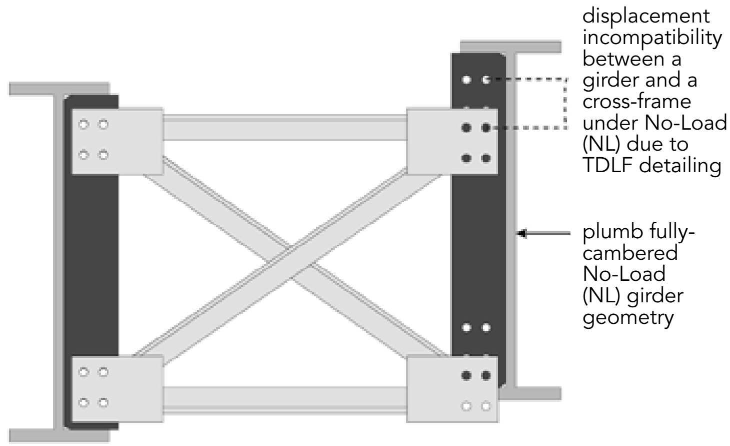

Fig. 6. Displacement Incompatibility due to TDLF Detailing at a Cross-Frame Framed Normal to the Girder Tangents

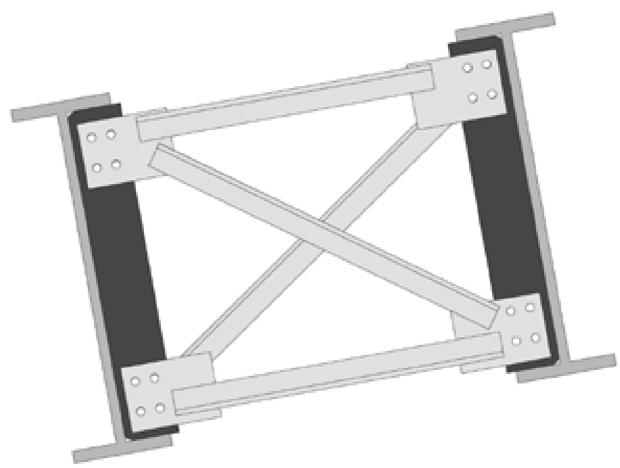

Fig. 7. Girder Twist Rotations due to the Resolution of the Lack-of-Fit Illustrated in Fig. 6

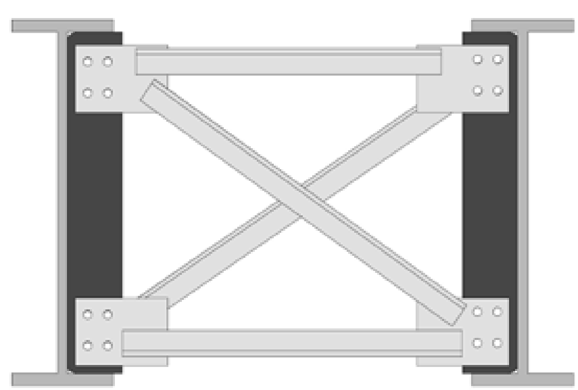

Fig. 8. Girder and Cross-Frame Geometry in the TDL Condition corresponding to the Combined TDL and the Targeted TDLF Detailing Effects

The internal forces associated with the resolution of the displacement incompatibility shown in Figure 6 are referred to as "locked-in forces." As discussed subsequently, in some cases, the locked-in forces are opposite in sign to the internal forces caused by the targeted dead load. In fact, in many of these cases, the locked-in forces can result in a *substantial reduction* in the net internal cross-frame forces within the targeted dead load condition. In other cases, the locked-in forces tend to be additive with the internal force effects due to the dead load, and therefore, they can result in a net increase in the internal cross-frame forces. This increase can be significant in some cases.

Targeting the girder webs to be plumb under the TDL might at first seem to be the obvious choice. However, the TDL bridge deflections can be substantially larger than the SDL deflections in many bridges. Since the TDL is not fully applied to the bridge at the time of the erection of the steel, the use of TDLF detailing may require the erector to apply relatively large forces during the steel erection (via cranes, jacks, come-alongs, etc.), in some cases, to twist the girders out-of-plumb so that the connections of the steel components can be completed. This issue can be particularly problematic in bridges involving combinations of longer spans, sharper skews and/or tighter horizontal curves.

4.4 Stiffness and Geometry Effects

The framing arrangement (or layout) of the cross-frames within the bridge plan also can be an important factor. Cross-frame arrangements that inadvertently create stiff transverse load paths in certain portions of the structure (Krupicka and Poellot, 1993), combined with other attributes of the bridge geometry such as large span length to girder depth ratios, simply-supported spans, or poor span balance in continuous-spans, can lead to difficulties in assembling the bridge. Basically, substantial differences in stiffness of different portions of a large bridge structure can be problematic.

Stiff transverse load paths can produce dramatically increased cross-frame forces and can result in potential fit-up difficulties during the steel erection. In bridges where the bearing lines are skewed more than 20°, it is often advantageous to place the intermediate cross-frames in discontinuous lines perpendicular to the girders, 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, particularly in the vicinity of the supports. Removal of highly stressed cross-frames, particularly in the vicinity of the obtuse corners of a span, interrupts and reduces the stiffness of the corresponding transverse load path by forcing load transfer via girder flange lateral bending. The above practices are often beneficial as long as the unbraced lengths between the cross-frame locations satisfy the flange resistance requirements of the design specifications. These 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. Where the flange sizes are increased due to the additional flange lateral bending, this increase often is not significant. In fact, the increased cost resulting from the larger flange sizes is typically offset by the reduced material and fabrication costs of providing fewer cross-frames and smaller cross-frame members and connections.

Where cross-frames are provided along bearing lines that are skewed more than 20°, AASHTO LRFD C6.7.4.2 suggests that the first intermediate cross-frames placed normal to the girders adjacent to the skewed support ideally should be offset by a minimum of the larger of $4b_f$ and $0.4L_{b.adj}$, 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). This practice helps to alleviate the introduction of a stiff load path that will attract and transfer large transverse forces to the skewed supports, particularly at the obtuse corners of a skewed span. In some cases, the limit of $0.4L_{b.adj}$ may be difficult to achieve, in which case the offset should be made as large as practicable but not less than $4b_f$. At the acute corners of severely skewed bridge spans, the above requirements may result in an excessive unbraced length on the fascia girder. In this case, a cross-frame with top and bottom chords but without diagonal members can be framed from the first interior girder to the fascia girder at a small offset from the support, perpendicular to the girders, to avoid introducing a large transverse stiffness while also providing adequate lateral support to the fascia girder.

Where practicable, the smallest unbraced lengths between the cross-frame locations within the skewed bridge spans should be greater than or equal to the larger of $4b_f$ or $0.4L_{b.adj}$, where b_f and $L_{b.adj}$ are as defined above but corresponding to the intermediate cross-frames and unbraced lengths within the span. The use of unbraced lengths smaller than $4b_f$ tends to result in the associated cross-frames working more like a contiguous cross-frame line rather than a discontinuous one. NCHRP (2015) recommends framing of the cross-frames within straight skewed spans using arrangements such as those shown in Figures 9 through 11 to both reduce the number of cross-frames required within the bridge as well as to reduce the overall transverse stiffness effects. In Figure 9, the cross-frames adjacent to the bearing lines are all placed at the same offset distance relative to the skewed bearing lines, satisfying the above offset recommendations. The other intermediate cross-frames are placed at a constant spacing along the span length to satisfy the flange resistance requirements of the design specification. In addition, every other cross-frame is intentionally omitted within the bays between the interior girders of the bridge plan. This relaxes the large transverse stiffness that would otherwise be developed in the short diagonal direction between the obtuse corners of the span.

Figure 10 shows a similar concept on a straight bridge with an extreme non-parallel skew. The essential consideration, when intentionally omitting cross-frames between the interior girders, is that a cross-frame must be provided on at least one side of a girder at each location where a braced point is desired. In some situations, additional cross-frames may be retained to provide additional lateral stiffness for bracing or other purposes; however, the alternating removal of the internal cross-frames is sufficient and is the preferred option in most cases.

Figure 11 shows a continuous-span straight skewed I-girder bridge with different skew angles at the bearing lines. Within the end spans of this bridge, the intermediate cross-frames adjacent to the bearing lines are all placed at the same offset distance relative to the skewed bearing lines, satisfying the above offset recommendations, except that a number of these cross-frames are intentionally omitted. This is necessary to satisfy the offset recommendations, given the geometry of this bridge. Note that similar to the above examples, additional cross-frames are intentionally omitted in the end spans, progressing along the length of the span within the bays between the interior girders. Each girder still has at least one side braced by a cross-frame at each braced point. Furthermore, intermediate cross-frames still remain within each cross-frame line across the width of the bridge to interconnect the girders and help control the differential deflections between the girders.

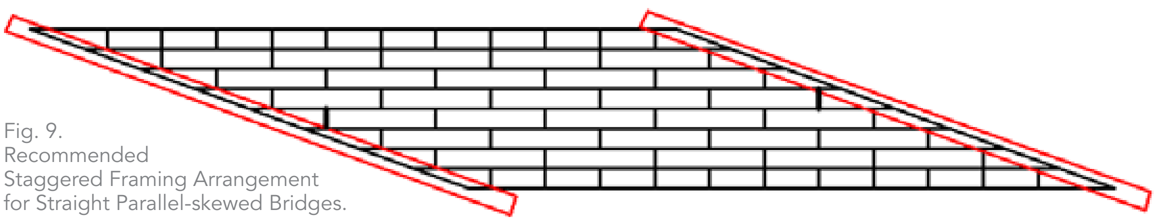

Fig. 9.
Recommended
Staggered Framing Arrangement
for Straight Parallel-skewed Bridges.

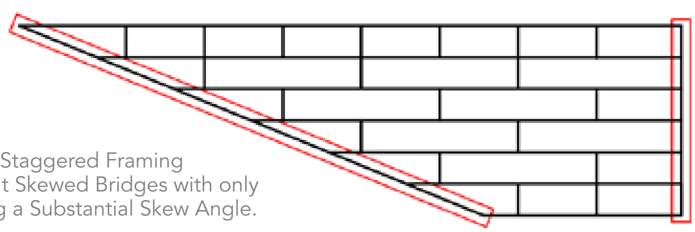

Fig. 10. Recommended Staggered Framing Arrangement for Straight Skewed Bridges with only One Bearing Line having a Substantial Skew Angle.

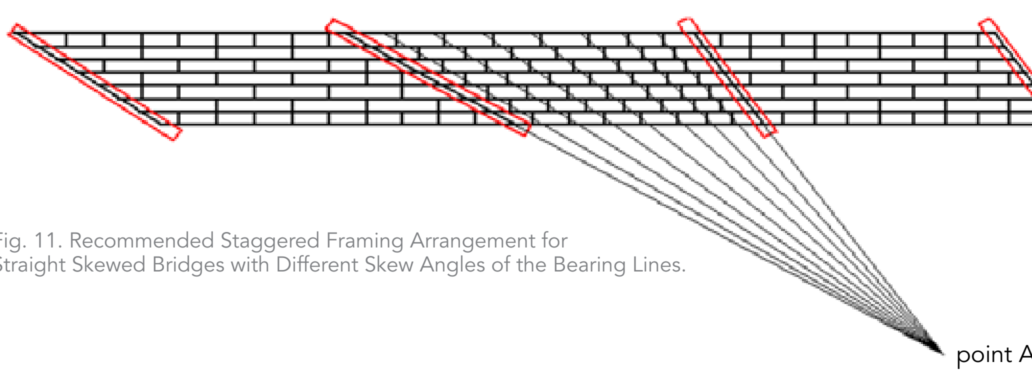

Fig. 11. Recommended Staggered Framing Arrangement for Straight Skewed Bridges with Different Skew Angles of the Bearing Lines.

Within the center span of this bridge, where the bearing lines are non-parallel but both have significant skew, the cross-frames are arranged in a "fanned" pattern from one bearing line to the next. The lighter weight lines in this sketch, which pass through work points at the mid-length of the cross-frames in the center span, all intersect at Point A. This arrangement can be shown to be one of the best options to mitigate the transverse stiffness load paths in this type of span. Figure 12 shows a simple variation on the concept used in the center span of Figure 11, applied to a straight bridge with parallel skew. In this figure, the cross-frames adjacent to the bearing lines are all placed at the same offset distance from the skewed bearing lines, satisfying the above offset recommendations. The other intermediate cross-frames are placed at a constant spacing along the span length in all the bays between the girders. The flange resistance requirements of the design specifications are satisfied by framing one cross-frame into each girder location where a braced point is desired. Given the particular skew angle in this bridge, the stagger distances between the intermediate cross-frame locations within the span are larger than both $4b_f$ and $0.4L_{b.adj}$. The lines through the work points at the mid-length of the cross-frames are all parallel to the bearing lines in this bridge.

Another framing option that alleviates transverse stiffness effects, and significantly reduces the number of cross-frames containing diagonal members, is the use of lean-on bracing (Helwig and Yura 2012; Herman, et al. 2015). NCHRP (2015) studied both lean-on bracing and the framing arrangements discussed above and found that both types of framing arrangements provided comparable performance. The above recommended use of cross-frames without diagonals at the acute corners of sharply skewed spans is a basic variation on the lean-on bracing concept.

At skewed interior piers in continuous-span bridges, FHWA/NHI (2011) and NCHRP (2015) found that transverse stiffness effects are alleviated most effectively by placing cross-frames along the skewed bearing line and locating intermediate cross-frames normal to the girders at greater than or equal to the minimum offset from the bearing lines discussed above. The bearing line cross-frames in Figures 11 and 12 are framed in this manner. Framing of an intermediate cross-frame perpendicular to the girders and into or near a bearing location along a skewed support line is strongly discouraged unless the cross-frame diagonals are omitted as discussed previously. NCHRP (2015) found that alternate framing schemes in which the skewed bearing line cross-frames are omitted and intermediate cross-frames are framed perpendicular to the girders and into or near the bearing locations typically results in unnecessary transverse restraint and correspondingly large cross-frame forces.

For curved and skewed spans, omitting intermediate cross-frames in the vicinity of skewed bearing lines, as shown in Figure 13, can help to alleviate uplift at critical bearing locations at and near an obtuse corner of a span; however, this is typically at the expense of larger cross-frame forces and larger bridge deflections compared to the use of contiguous intermediate cross-frame lines with the recommended offset provided at the skewed bearing lines. Contiguous cross-frame lines are necessary within the span of curved I-girder bridges to develop the width of the bridge structural system for resistance of the overall torsional effects. As such, the use of discontinuous cross-frame lines near a skewed bearing line in these bridge types involves competing considerations. Cross-frames can be omitted to alleviate uplift considerations at certain bearings, and potentially to relieve excessive cross-frame forces due to transverse stiffness effects in certain cases—for instance, if the horizontal curvature is relatively small and the skew is significant. However, removal of too many cross-frames may result in a larger than desired increase in the cross-frame forces and bridge system deflections due to the horizontal curvature effects when the bridge is significantly curved.

In horizontally curved I-girder bridges, it is important to select a spacing of the cross-frames within the curved spans that limits the magnitude of the flange lateral bending stresses due to the horizontal curvature of the girders between the cross-frame locations. This also limits the magnitude of the cross-frame forces that need to be developed to stabilize the curved unbraced lengths of the girders. AASHTO LRFD Eq. C6.7.4.2-1 is a useful simple calculation that achieves this goal.

Elimination of skewed interior supports in curved continuous long-span bridges is always desirable, where practicable; an integral pier cap in conjunction with a single-shaft pier is one possible option to avoid a skewed interior support while maintaining adequate vertical clearance. In addition, extending the end spans to eliminate skewed end supports is also a desirable option where practicable.

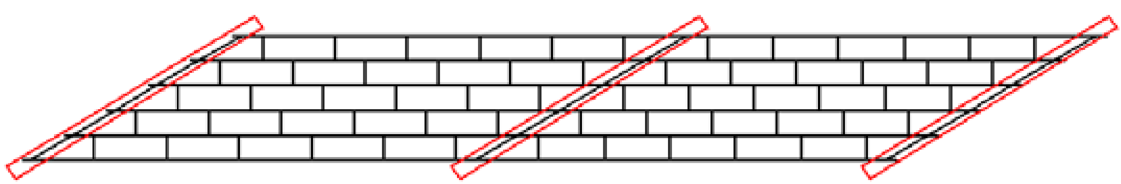

Fig. 12. Recommended Staggered Framing Arrangement for Straight Skewed Bridges with Parallel Skew Angles of the Bearing Lines

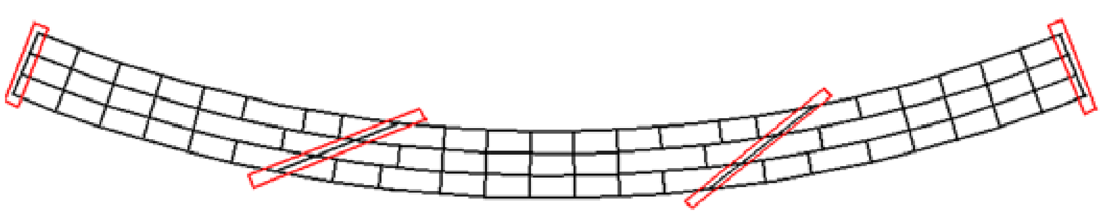

Fig. 13. Curved and Skewed Bridge Framing Plan showing the use of Staggered or Discontinuous Intermediate Diaphragm or Cross-Frame Lines in the vicinity of the Skewed Bearing Lines

5 DESIGN AND ANALYSIS CONSIDERATIONS

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.

In the following, these two force effects are discussed separately in the context of straight skewed and horizontally curved bridges.

5.1 Straight Skewed Bridges

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—see Table 3 in Section 7 and Equation 2 below), 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, NCHRP 2015 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. These reduction factors are discussed in Section 5.3.

When a line girder analysis is employed for the design of a straight-skewed I-girder bridge, the line girder analysis assumption that the cross-frames have zero force actually is approximately correct in the SDL condition for SDLF, or in the TDL condition for TDLF. However, it should be emphasized that line girder analysis does not provide any estimate of the non-zero cross-frame forces caused by other effects such as live loads, wind loads, and/or stability bracing effects. Also, it should be emphasized that the cross-frame forces approach zero only under the corresponding dead load condition (i.e., under SDL for SDLF and under TDL for TDLF).

Since the I-girder flange SDL/TDL lateral bending stresses are directly related to the cross-frame internal SDL/TDL forces, the above comments also apply to the girder flange lateral bending stresses. Also, it should be noted that the above comments do not apply to the internal cross-frame forces and girder flange lateral bending stresses due to eccentric overhang bracket loads on fascia girders; the effects of these internal forces should be calculated separately and added to the above overall bridge dead load 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. Stated more directly, since the cross-frames are detailed to fit to the elevations at which the girders are deflected under the full SDL of the bridge, the cross-frames fit to the girders without any significant force-fitting, if the girders are deflected under their self-weight during the steel erection. Later, when final dead loads are applied, the girders deflect and the cross-frames resist the differential deflections. As a result, the girders experience torsion and the cross-frames are subjected to internal dead load forces during deck placement and other subsequent loading of the composite bridge system. 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 TDLF 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. As the skew increases and the differential deflections increase in a straight-skewed bridge, all of the above effects become more important.

5.2 Horizontally Curved Bridges

Horizontally curved I-girder bridges also have internal forces that are induced due to SDLF/TDLF detailing and require externally applied fit-up forces to erect the steel. However, there are important differences in the characteristics of both of these types of forces in curved bridges versus straight skewed bridges. The girders in curved bridges 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 they naturally roll under the dead loads; this action effectively increases the restraint provided to the girders from the cross-frames.

The fundamental difference in the behavior with respect to straight skewed bridges is that, in straight skewed bridges, internal dead load cross-frame forces are not required for the equilibrium of the girders. Furthermore, curved girders are generally much stiffer than straight girders and the girder vertical deflections and torsional rotations are generally coupled; therefore curved bridges cannot be detailed for TDLF with the simple expectation that the girders and cross-frames can be forced together during the steel erection. In fact, there is potentially no practical way to erect some curved bridges detailed using TDLF.

Curved I-girder bridges have been detailed successfully for SDLF in common practice. As discussed above, this results in some additional internal forces due to the SDLF fit-up effects; however, the additional internal cross-frame forces due to SDLF effects are relatively small in bridges for which SDLF detailing is recommended in Table 4 of Section 7; i.e., curved bridges with a maximum *L/R* less than approximately 0.2. Section 5.3 provides guidance for when the force effects from SDLF detailing may be neglected, and provides simple scale factors that can be applied to the refined analysis results to approximate these effects when they should be considered. As indicated by Table 4 of Section 7, for bridges with significant horizontal curvature (i.e., with a maximum *L/R* greater than or equal to approximately 0.2), NLF is recommended to limit these effects, unless the additive locked-in force effects associated with SDLF detailing are explicitly considered (the reader is referred to Section 5.3 for additional discussion of these recommendations). These types of bridges are more likely to require significant shoring and support during the erection as a matter of course—as such, the bridge can be erected in a "quasi" no-load condition as the general practice and the cross-frames can be easily installed in this shored condition.

NCHRP (2015) indicates that the girder deflections calculated from an accurate refined analysis, without the consideration of the SDLF or TDLF effects, are sufficient in all cases for the straight and curved bridge characteristics where these detailing methods are recommended or allowed in Tables 3 and 4 of Section 7. The engineer need not consider the influence of the DLF detailing on the girder vertical deflections when setting the girder cambers and/or determining the cross-frame drops and the associated girder connection plate rotational orientations. In addition, NCHRP (2015) finds that the deviation from the targeted girder elevations and the girder plumb condition is small enough to be neglected in all cases that satisfy the recommendations in Tables 3 and 4 when the girder deflections are calculated using an accurate refined analysis. Furthermore, the girder layovers in the TDL condition can be estimated as the concrete dead load layovers from a refined analysis, for bridges detailed for SDLF, and the girder layovers in the SDL condition can be estimated as the negative of the concrete dead load layovers from a refined analysis, for bridges detailed for TDLF.

5.3 Calculation of Internal Force Effects due to SDLF and TDLF Detailing

Although the use of refined analysis methods is not required for curved and/or skewed I-girder bridges, these methods, when utilized, do allow for direct consideration of DL cross-frame forces and girder flange lateral bending stresses. In straight skewed I-girder bridges, these DL force effects are partially offset by the corresponding locked-in force effects at the completion of the steel erection (NCHRP 2012; NCHRP 2015). It is important to recognize that the DL force effects, when determined from a refined analysis 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.

It is possible to directly calculate the internal "locked-in forces" associated with SDLF or TDLF detailing within either an accurate 2D grid or 3D Finite Element Analysis. The handling of these effects is very similar to the calculation of the effects of temperature change in 3D FEA. 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 DLF detailing.

Section 3.9 and the associated appendices of NCHRP (2015) provide a detailed explanation of the above procedures, complete with benchmark example 2D-grid and 3D FEA calculations for a basic straight skewed bridge as well as a horizontally curved radially-supported bridge. Section 3.4.3 of NCHRP (2015) 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.

The corresponding detailed effects of the basic lack-of-fit on the internal forces and stresses in I-girder bridge structures are relatively complex. This complexity is best addressed by including the lack-of-fit effects directly in the structural analysis. Nevertheless, at the present time (2016), 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 conduct a significant amount of calculations external to the software, then input information such as, for example, pseudo temperature increases or decreases 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 simple sanity checking of the results from these types of analysis calculations when they are performed, the basic equations recommended in Table 2 may be employed to estimate the locked-in force effects associated with SDLF and TDLF detailing in lieu of including lack-of-fit effects directly in the structural analysis. This table is based on the extensive studies conducted in NCHRP (2015).

The first column of Table 2 lists the primary responses that need to be calculated for the design of the structural components in a curved and/or skewed I-girder bridge. The second through fourth columns list recommended calculations of the factored DL responses including the consideration of the SDLF and/or TDLF detailing effects as appropriate for curved radially-supported, straight skewed, and curved and skewed I-girder bridges. The term γ_p in Table 2 is the maximum load factor for *DC* specified in AASHTO LRFD Table 3.4.1-2, or the maximum load factor specified in AASHTO LRFD 3.4.2.1 for *DC* and any construction loads that are applied to the fully erected steelwork, as applicable.

In curved I-girder bridges, the locked-in force effects from SDLF and TDLF detailing tend to be additive with the corresponding DL effects. As discussed in Section 3, 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 2 does not address estimates for curved bridges detailed for TDLF. In addition, the procedures do not address the effects due to the bracket loads supporting the eccentric deck overhangs during deck construction. These effects may be estimated separately as described in AASHTO LRFD C6.10.3.4.1 and combined as appropriate with the other dead load effects discussed on the next page.

Table 2 **Recommended Estimates of Factored Dead Load Responses for Curved and/or Skewed Bridges in their Final Constructed Condition**

Responses	1. Curved Radially-Supported	2. Straight Skewed	3. Curved and Skewed
CF Forces	For bridges with a maximum $L/R \geq 0.2$ [a]: $\gamma_p \times$ (2.0 SDL + ADL[b]) for SDLF [c], except $\gamma_p \times$ (SDL + ADL) for chords of X-Type CFs	$\gamma_p \times$ TDL for SDLF, $(\gamma_p - 0.4) \times$ TDL for TDLF	Same as (1)
Flange Lateral Bending	For bridges with a maximum $L/R \geq 0.2$ [a]: $\gamma_p \times$ (1.2 SDL + ADL[b]) for SDLF [c]	$(\gamma_p - 0.5) \times$ SDL + $\gamma_p \times$ ADL[b] for SDLF $(\gamma_p - 0.4) \times$ TDL for TDLF	Same as (1)
Major-axis Bending	$\gamma_p \times$ TDL for SDLF [c]	$\gamma_p \times$ TDL for SDLF [d] $\gamma_p \times$ TDL for TDLF [e]	Same as (1)
Vertical Reactions	$\gamma_p \times$ TDL for SDLF [c] For simply supported bridges, DLF tends to increase the smallest reactions at the girders on the inside of the curve[e]	$\gamma_p \times$ TDL for SDLF [d,g] $\gamma_p \times$ TDL for TDLF [e,g] 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 DLF detailing based on RA cambers (compared to the use of LGA cambers)	For simply-supported bridges [f,h]: Worst-case maximum reactions [i]: • $\gamma_p \times$ (1.2 SDL + ADL) for SDLF [c], when the length of girder on the inside of the curve is increased by the skew • $\gamma_p \times$ (1.6 SDL + ADL) for SDLF [c], when the length of girder on the outside of the curve is increased by the skew

a The locked-in force effects may be neglected in bridges with $L/R < 0.2$.

b ADL = Additional Dead Load

c TDLF detailing is strongly discouraged for curved bridges with $L/R > 0.03$ ±, where L is the span length along the centerline of the bridge.

d Contingent on the use of discontinuous CF lines with $L_b \geq \max(4b_f, 0.4L_{b.adj})$ for all unbraced lengths within the span, where b_f is the largest girder flange width within on either side of a given CF, and $L_{b.adj}$ is the smallest adjacent unbraced length.

e Contingent on $I_S \leq 1.0$ ± and $L_b \geq \max(4b_f, 0.4L_{b.adj})$.

f The influence of DLF detailing on the reactions for curved continuous-span bridges is relatively complex; if potential uplift and/or increases in the reactions are a concern, a Dead Load Fit Refined Analysis (DLF RA) is recommended.

g 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 DL condition and NLF RA for additional dead and/or live loads.

h In curved and skewed I-girder bridges, the CF lines need to be contiguous out 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.

i If potential uplift at obtuse corners of the bridge plan is a concern, a DLF RA should be considered.

For curved I-girder bridges, with or without skew and with a maximum L/R greater than or equal to 0.2 that are detailed for SDLF, the additional locked-in force effects may be accounted for approximately by multiplying the unfactored SDL cross-frame forces by the factor 2.0 and the unfactored SDL flange lateral bending stresses by the factor 1.2 prior to applying the specified AASHTO LRFD DL factor γ_p. For X-type cross-frames, SDLF detailing has a substantial effect only on the cross-frame diagonal forces; therefore, the above factor of 2.0 need only be applied to the diagonal forces for these types of cross-frames. The smaller increase in the flange lateral bending stresses is due to the attribute that the ratio of the locked-in effects from SDLF detailing to the effects from the horizontal curvature generally tend to be smaller for the flange lateral bending stresses than for the cross-frame forces. For a bridge where the factored SDL cross-frame forces are one-half of the factored TDL forces, and the factored TDL forces are one-half of the total factored forces for design, the total factored cross-frame forces are increased by a factor of 1.25. For bridges with smaller L/R that are detailed for SDLF, the horizontal curvature effects are smaller, and hence the scaled SDL cross-frame forces and girder flange lateral bending stresses are smaller.

Table 2 shows that the girder major-axis bending stresses and vertical reactions in curved radially-supported I-girder bridges may be estimated sufficiently from a refined analysis that does not include the consideration of the initial lack-of-fit from the SDLF detailing of the cross-frames. One caveat associated with this recommendation, shown as a footnote to the table, is that the influence of DLF detailing on the reactions for curved continuous-span bridges is relatively complex. In cases where potential uplift and/or increase in the reactions are a concern in these types of bridges, it is recommended that a refined analysis that includes the consideration of the initial lack-of-fit displacements should be considered. This type of analysis is referred to as a Dead Load Fit Refined Analysis (DLF RA) in the table.

The third column of Table 2 lists recommended calculations of the factored DL responses for straight skewed I-girder bridges, including the consideration of the SDLF and/or TDLF detailing effects as appropriate. For straight skewed I-girder bridges detailed for SDLF, and where the recommendations of Section 4.4 to lessen the transverse stiffness effects are not applied, direct calculation of the influence of DLF detailing on the girder vertical reactions and major-axis bending stresses should be considered. For straight skewed I-girder bridges detailed for TDLF, the recommendations of Section 4.4 should be applied *and* the skew index, I_s, should be less than 1.0 ± in order to avoid potential significant impacts from transverse stiffness effects on the girder reactions and major-axis bending stresses.

For straight skewed I-girder bridges that are detailed for TDLF, the TDL cross-frame forces and flange lateral bending stresses, when determined from a refined analysis not including the influence of DLF detailing, may be reduced to account for the corresponding locked-in forces introduced into the structural system during the steel erection. In this case, a net reduced load factor of (γ_p – 0.4) may be applied to the unfactored TDL cross-frame forces and flange lateral bending stresses, where γ_p is the specified AASHTO LRFD factor on DL and 0.4 is an estimated lower-bound estimate of the internal locked-in force effect (AASHTO LRFD multiplies locked-in force effects by a load factor of 1.0). It should be noted that larger beneficial locked-in force effects can be calculated in many situations by performing a direct DLF RA. In straight skewed bridges detailed for TDLF, the engineer should also check the cross-frame forces and the flange lateral bending stresses for the fit-up force effects during the steel erection. These effects may be estimated as the negative of the corresponding unfactored concrete dead load force effects, which should then be multiplied by γ_p (NCHRP 2015).

NCHRP (2015) recommends that the AASHTO LRFD load factor, γ_p, should be applied directly to the total DC cross-frame forces for straight skewed bridges detailed for SDLF in lieu of performing a DLF RA. As discussed previously, significant cross-frame force reductions are achievable in straight skewed bridges detailed for SDLF; however, in the most extreme cases studied by NCHRP (2015), incidental and elastic deformation effects in the structural system lead to negligible corresponding locked-in force effects in the cross-frames for SDLF. NCHRP (2015) found that the SDLF locked-in force effects on the girder flange lateral bending stresses may be estimated conservatively as 0.5 of the f_ℓ values determined from a refined analysis not considering the initial lack-of-fit (i.e., a NLF RA). Therefore, Table 2 recommends a net reduced load factor of (γ_p – 0.5) on the SDL flange lateral bending stresses for these bridges. The overall influence of this beneficial effect is relatively small, since the SDL stresses are often a fraction of the overall required design stresses, plus these stresses are multiplied by ⅓ in the application of the AASHTO LRFD one-third rule equations for the strength design. Therefore, a simpler conservative approximation would be to use the same approach as recommended for the cross-frames for SDLF of straight skewed bridges, i.e., simply factor the SDL f_ℓ values obtained from a NLF RA by γ_p, neglecting the beneficial locked-in force effects from the SDLF detailing. It should be emphasized that the best estimate of the internal force reductions, when either SDLF or TDLF is employed, is obtained by calculation of the locked-in force effects directly within the structural analysis.

The fourth column of Table 2 lists recommended calculations of the factored DL responses for curved and skewed I-girder bridges. NCHRP (2015) found that the cross-frame forces and the girder flange lateral bending and major-axis bending stresses can be estimated conservatively for curved and skewed bridges by applying the same recommendations discussed above for curved radially-supported bridges. Unfortunately, the accurate estimation of the girder reactions is rather difficult in curved and skewed I-girder bridges. Therefore, if potential uplift and/or increases in the reactions are a concern in these types of bridges, it is recommended that a DLF RA be considered.

All of the above recommendations are based on the use of the girder deflections determined from an accurate refined analysis for setting the girder cambers, and the associated cross-frame drops and corresponding connection plate rotational orientations for SDLF or TLDF detailing. For straight skewed I-girder bridges designed using Line Girder Analysis (LGA), the LGA cambers may be used for detailing of the cross-frames. However, various limitations associated with doing so should be recognized. Section 3.4.2.3 of NCHRP (2015) details these considerations. In short, the use of LGA girder deflections for SDLF or TDLF detailing of the cross-frames in straight skewed bridges theoretically imposes (or allows) the girders to respond under the targeted DL condition (SDL for SDLF or TDL for TDLF) precisely in the manner assumed within the LGA. This means that, theoretically, the girders all deflect independently of one another, only in the vertical direction, and the cross-frame forces and girder flange lateral bending stresses are effectively zero. As discussed in detail in Section 3.4.2.2 of NCHRP (2015), various incidental effects can result in these theoretical or ideal conditions not being exactly achieved. Nevertheless, the cross-frame force and flange lateral bending stress reductions associated with the use of LGA cambers tend to be substantial. NCHRP (2015) provides a lower-bound estimate of the beneficial locked-in force effects as 0.65 of the corresponding responses obtained from a NLF RA. That is, one can expect the corresponding forces and stresses to be reduced to values less than or equal to 35% of the calculated NLF RA responses.

Of course, if LGA is used for the design of a straight skewed I-girder bridge, the structural analysis does not provide any information regarding the corresponding cross-frame forces and girder flange lateral bending stresses. Fortunately, if the recommended practices discussed in Section 4.4 are employed, the cross-frame forces and flange lateral bending stresses tend to be relatively small. In cases where these practices are not used, the cross-frame forces and flange lateral bending stresses in a sharply skewed bridge can be relatively large.

It is important to note that the above theoretical results associated with SDLF or TDLF based on LGA girder deflections occur ONLY in the targeted DL condition. The results for any other loading, aside from the approximations associated with live load distribution factors, completely miss the fact that the girders, the cross-frames and the composite bridge deck respond as a three-dimensional system.

6 SUMMARY ADVANTAGES AND DISADVANTAGES OF VARIOUS FIT CONDITIONS

The advantages of NLF detailing are as follows:

- NLF detailing is completely consistent with the analysis assumptions commonly made in bridge design; that is, it is commonly (and implicitly) assumed in the dead load analysis that the bridge is fully erected in the unstressed (NL) position and then the gravity load is simply "turned on." Thus, the stress state and final geometry of the bridge is as close as possible to that intended by the engineer when NLF is used.
- In bridges constructed with some amount of temporary shoring or hold cranes (in the case of longer spans, for example), NLF detailing more closely approximates the actual geometry during erection, resulting in easier fit-up and reductions in additive locked-in force effects.

The disadvantages of NLF detailing are as follows:

- As noted previously, for horizontally curved bridges, the girders and bridge units generally need to be supported to some extent under critical erection conditions regardless of the type of fit. However, NLF detailing does not necessarily imply the need to use temporary shoring, nor does the use of SDLF or TDLF detailing imply that temporary shoring cannot be used. As discussed in the Design and Analysis section of this document, the choice of detailing method affects the nature and magnitude of the bridge's internal dead load forces and of the "fit-up" forces that the erector may need to apply to assemble the structural steel. The nature and magnitude of these forces are also influenced by the use of temporary shoring. Bridges erected without temporary shoring can be detailed for NLF and successfully erected if the fit-up forces are manageable. Likewise, bridges which are to be erected using some form of temporary shoring can be detailed for SDLF or TDLF and successfully erected if the fit-up forces are manageable.
- The girders will deflect out-of-plumb under the dead loads. (However, in curved radially supported bridges, this out-of-plumbness occurs in the spans and not at the supports and is not likely to be objectionable from an aesthetic viewpoint, nor is it likely to be a significant issue from a structural viewpoint as long as the global lateral stability of the bridge is ensured).
- For straight skewed bridges, NLF detailing results in the largest possible cross-frame forces (and corresponding girder flange lateral bending stresses) of all the potential fit options since there are no beneficial compensating or offsetting locked-in forces in the structure. However, in current practice, these are the cross-frame forces and girder flange lateral bending stresses that are commonly calculated for these types of bridges when an accurate 2D grid or 3D refined analysis is employed.
- At highly skewed end supports, the deck and barriers may be significantly out-of-alignment with the approach; that is, the alignment at the deck joints may be compromised.
- The girder twist rotations due to the total dead loads at skewed end supports should be considered in the design of the bearings, in addition to the other rotational demands on the bearings, since there is no compensation for or offsetting of these rotations by the detailing of the cross-frames when NLF detailing is used. Section 8.1 provides additional discussion of the bearing rotations at skewed supports.

The advantages of SDLF detailing are as follows:

- The girders will be approximately plumb at the end of erection, when the erector leaves the site.
- The girders typically require little or no temporary support in straight skewed bridges in order to install the cross-frames.
- Cross-frames typically can be installed with little force-fitting, particularly if the girders can be allowed to deflect under their self-weight. This reduces the erection time.
- The out-of-plumbness of the girders under the total dead loads is less than that corresponding to NLF detailing.
- In straight skewed bridges, the SDL cross-frame forces determined from an accurate grid or 3D FE analysis (and the corresponding girder flange lateral bending stresses) are often reduced substantially by the SDLF detailing effects, although as discussed further in Section 5.3, a DLF RA is recommended in order to compute the cross-frame force reductions.
- In horizontally curved bridges, the additional internal cross-frame forces due to SDLF effects tend to be relatively small, and as such, these forces can be neglected in most cases (i.e., in bridges for which SDLF detailing is recommended in Table 4 of Section 7; i.e., curved bridges with a maximum *L/R* less than approximately 0.2) without adverse impacts.

The disadvantages of SDLF detailing are as follows:

- The girders will be out-of-plumb under the total dead loads (however, as stated previously in Section 1, this out-of-plumbness is not indicative of a structural problem or deficiency).

The advantages of TDLF detailing are as follows:

- Provides approximately plumb girders under the total dead loads.
- At skewed bearing lines, the lateral position of the deck and barriers with respect to the approach and the alignment of the deck joints are more likely to be correct under the total dead loads. The girders are also more likely to rest squarely on the bearings under the total dead loads.
- In straight skewed bridges, a large fraction of the TDL cross-frame forces (as well as the corresponding girder flange lateral bending stresses) determined from the structural analysis can be subtracted from the TDL results from an accurate grid or 3D FEA analysis, with the exception of localized effects from eccentric overhang bracket loads (see Section 5.3 for procedures to estimate the reduced forces and stresses). The TDL internal cross-frame forces and girder flange lateral bending stresses are largely offset by the TDLF detailing effects.

The disadvantages of TDLF detailing are as follows:

- The girders will be out-of-plumb when the erector leaves the site since the deck weight and any other composite dead loads will not yet have been applied. However, this out-of-plumbness (or girder layover, Δ, in inches) at skewed supports can be estimated with reasonable accuracy using the negative of the girder major-axis bending rotations, ϕ_x, at the supports caused by the deck weight and any other composite dead loads considered as part of the TDL in the following equation:

  $$\Delta = \phi_x d (\tan \theta) \quad (1)$$

  where d is the girder depth and θ is the skew angle of the support measured with respect to a line drawn normal to the girder tangent (equal to zero for no skew). This equation may be used as an estimate for inspection of the geometry at the end of the steel erection when TDLF detailing is employed. Note that Eq. 1 can also be used to estimate the amount of girder layover at skewed supports under SDL and TDL when NLF detailing is employed or under TDL when SDLF detailing is employed. The reader is referred to Section 9 for recommended inspection practices to ensure that the erected geometry sufficiently meets the specified fit conditions. The best time to assess the position of the web is at the completion of the steel erection, prior to deck placement, when the steel erector still has a chance to make adjustments to achieve the targeted geometries.
- The girders are not likely to twist as much as theoretically predicted in some cases when the deck weight is applied (due to incidental restraint from deck forming and deck pans, unintended early setup of the concrete, etc.). As such, the girders may not reach their ideal vertical position.
- Since the girders are twisted an additional amount in the opposite direction from that which they want to roll under the dead loads, compared to the result for SDLF detailing, larger forces generally are required during the cross-frame installation. This is particularly true for horizontally curved bridges.
- In horizontally curved bridges, the additive locked-in force effects are likely to be significant in the majority of cases. Practically speaking, these effects are not readily calculable for consideration in design at the present time, although NCHRP (2015) provides specific guidelines and software tools for calculating these effects. Regardless, TDLF detailing is strongly discouraged for curved bridges, with or without skewed supports, and with a maximum L/R greater than 0.03.

7 RECOMMENDED FIT

Tables 3 and 4 provide general fit recommendations. The goals of these recommendations are:

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.

These recommendations reflect historic experience blended with improved understanding of the fit behavior of I-girder bridges from recent research.

The generalized terms used in the tables are as follows:

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

$$I_s = \frac{w_g \tan\theta}{L} \quad (2)$$

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 2 has been observed 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 I_S 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. Therefore, in highly curved bridges, the associated effects are more involved than just the consideration of I_S.

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

Table 3 **Recommended Fit Conditions for Straight I-Girder Bridges (including Curved I-Girder Bridges with L/R in all spans ≤ 0.03)[1]**

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

Table 4 **Recommended Fit Conditions for Horizontally Curved I-Girder Bridges ($(L/R)_{MAX} > 0.03$)[1]**

Radial or Skewed Supports			
	Recommended	Acceptable	Avoid
$(L/R)_{MAX} \geq 0.2$	NLF [2,3]	SDLF [4]	TDLF
All other cases	SDLF	NLF	TDLF

Note 1: For the various recommended fit conditions presented in Tables 3 and 4, the span length and skew index limits should be considered approximate guidelines and should be evaluated in the full context of the geometric and structural complexity of the given bridge.

Note 2: 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. NLF matches the normal analysis methods used in the design and will provide a better match between predicted forces and displacements than SDLF when the steel dead load displacements become large.

Note 3: The recommendation to use NLF detailing does not necessarily imply the need to use temporary shoring, nor does the use of SDLF or TDLF detailing imply that temporary shoring cannot be used. As discussed in Section 5 of this document, the choice of detailing method affects the nature and magnitude of the bridge's internal dead load forces as well as the "fit-up" forces which the erector may need to apply to assemble the structural steel. The nature and magnitude of these forces are also influenced by the use of temporary shoring. Bridges erected without temporary shoring can be detailed for NLF and successfully erected if the fit-up forces are manageable. Likewise, bridges which are to be erected using some form of temporary shoring can be detailed for SDLF or TDLF and successfully erected if the fit-up forces are manageable.

Note 4: SDLF detailing is considered acceptable in these cases if the additive locked-in force effects are considered (refer to Section 5.3).

layover will be present. This final layover is not known to cause any particular girder behavior problems as long as the overall bridge system is globally stable. However, 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 which is straight with no skew in any of the supports, (i.e., a "square" bridge), the effects of the fit condition become small and essentially inconsequential and the results of the different cross-frame detailing methods are all the same.

In horizontally curved bridges, the additional internal cross-frame forces due to SDLF effects tend to be relatively small, unless the maximum *L/R* is greater than or equal to approximately 0.2. For these curved bridges with more significant horizontal curvature, the local twisting of the 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.

The recommendations in Tables 3 and 4 assume that the proper steps have been taken to ensure global stability of the bridge system during construction, as detailed in AASHTO LRFD 6.10.3.4.2.

8 SPECIAL CONSIDERATIONS

8.1 Bearing Rotations at Skewed Supports

At skewed bearing lines, the girder layover can contribute substantially to the bearing rotation demands. AASHTO LRFD 2.5.2.6.1 requires that the computed bearing rotations in skewed bridges be accumulated over the assumed construction sequence. The accumulated factored bearing rotations due to the dead loads at any construction stage (as affected by SDLF or TDLF detailing effects, when these types of detailing are used) are not to exceed the rotation capacities of the bearings.

Girder layover occurs at skewed bearing lines due to the dead and live load effects as discussed in Section 2. However, when SDLF or TDLF detailing is used, "relieving" layovers (i.e., in the direction opposite to the layover caused by dead loads) are induced at skewed bearing lines. These relieving layovers can partially or fully offset the effects of dead load layovers; however, before the various dead loads are in place, the girders can have layovers that are opposite in direction to that caused by the dead loads.

In addition, the vertical load demand on the bearings is different at each stage of construction (structural steel alone, structural steel plus deck, etc.) as well as under in-service conditions (bridge open to traffic, subject to live load, thermal expansion/contraction, wind loads, etc.). Therefore, engineers should consider the bearing load along with the rotation demands that occur at each stage of construction and service (i.e., under NL conditions, SDL conditions, and TDL conditions) when designing the bearings.

The engineer should keep in mind that the rotation demands on the bearings during construction are temporary. The bearings can be designed to accommodate these demands, or if these temporary rotations are a cause for concern, the girders can be "blocked" (i.e., supported on temporary blocking) to protect the bearings during the steel erection. If the rotational demands on the bearings are excessive under final conditions, one way to mitigate these effects and reduce the long term rotational demand on the bearings is to use beveled sole plates, with the sole plate bevels determined so as to compensate for the girder layover and provide a level surface at the top of the bearing.

In addition, it should be noted that the girder layovers at interior piers of continuous spans are generally much smaller than at the end supports, and thus the bearing rotation demands at the interior bearing lines on continuous-span bridges are generally much smaller.

Listed below are some specific considerations related to bearing rotational demands, associated with the various fit conditions:

- For TDLF detailing, where the bearings can be protected by blocking during the steel erection, the maximum rotation demand from the girder twisting occurs at the completion of the steel erection, when the blocks commonly are removed prior to the concrete deck placement; the magnitude of this rotation is equal to the girder twist rotation caused by the TDL minus the girder twist rotation due to the SDL. Where the bearings are not protected by blocking during the steel erection, the maximum girder layover during the erection is due to the TDLF detailing effects and it can be estimated directly as the negative of the girder rotations caused by the TDL. These rotations can cause uneven seating or lift-off at the bearings. However, these rotations are temporary and will be removed when the TDL is applied and the girders rotate to an approximately plumb position. For TDLF detailing, the maximum rotations in the completed bridge occur under the live loads. However, the girders are approximately plumb at the skewed bearing lines under the nominal TDL and therefore, the dead load contribution to the twist rotation about the axis of the girders is essentially zero. This is contrary to the assumption often made in design practice that the bearings are level and plumb under NL and "fully rotated" under the TDL and live load.
- For SDLF detailing, there is essentially zero net layover at the bearings at the completion of the steel erection. Layovers can occur prior to completion of the steel erection, and uneven seating or lift-off may be observed at the bearings during the erection at highly skewed end supports (since the vertical loads may not be large enough to maintain contact between the sole plates and the bearings). However, these are temporary conditions that will be relieved as the erection proceeds and the girders rotate to an approximately plumb position. As such, these rotations usually should not be a cause for concern. If there is concern, the bearings can be protected against these rotations by blocking. The girder layovers due to SDLF detailing effects are opposite to the girder rotations caused by the SDL.
- For SDLF detailing, the maximum final rotation demand from the girder twisting occurs due to the effects of the additional dead load applied after the structural steel is fully erected (i.e., the additional dead load associated with the changes from the SDL to the TDL condition) plus the subsequent live load effects; however, this rotation is smaller than if the bridge is detailed for NLF. The girders are approximately plumb at the skewed bearing lines at the completion of the steel erection, and they rotate out-of-plumb under the subsequent dead and live loads.
- For NLF detailing, the girder twist rotations at the skewed bearing lines are small during the construction as long as the girders are adequately supported in their NL position, since there are no compensating effects from the detailing of the cross-frames. The girder layovers from SDL and TDL contribute additively to the final rotation demands on the bearings. This is consistent with typical design approaches that ignore the temporary conditions and focus on the final load and rotation demands on the bearings. However, it is important to note that at highly skewed bearing locations, the use of NLF detailing and/or the neglect of SDLF or TDLF detailing effects can result in substantial dead load layover (i.e., a substantial rotation demand) for bearing design. This is one reason why Table 3 recommends that NLF should be avoided for sharply skewed bridges.
- In all of the above cases, AASHTO LRFD requires that various factored load combinations be considered in determining the rotation demands for the design of the bearings. Although the SDLF and TDLF detailing effects are technically "locked-in" force effects, these effects are closely tied to the corresponding dead loads. Therefore, it is recommended that the LRFD dead load factors should be used for these effects, not the load factors for the *EL* load case. The factored twist rotations associated with the SDLF or TDLF detailing effects are to be superimposed with the appropriate factored dead and live load effects to obtain the total factored twist rotation demands on the bearings.

The girder twist (layover) rotations at skewed bearing lines due to the SDL or the TDL effects alone (unfactored or factored) may be estimated as

$$\phi_z = \phi_x \tan \theta \quad (3)$$

where ϕ_x is the girder major-axis bending rotation due to the desired dead load effect, and θ is the skew angle of the support measured with respect to a line drawn normal to the girder tangent (equal to zero for no skew). This equation is applicable as a reasonable approximation for both straight skewed and curved and skewed bridges.

The total rotational demands on the bearings at a skewed bearing line should consider both the twist and the major-axis bending rotations from the girders (i.e., the dead and live load rotations about the longitudinal axis of the girders as well as the dead and live load rotations about the transverse axis of the girders). It is important to recognize that the initial camber of the girders generally offsets the girder major-axis rotations at the bearings due to the TDL, much like the TDLF effects offset the girder twist rotations due to the TDL.

For some types and configurations of bearings (e.g., round elastomeric bearings), it may be appropriate to consider the vector sum of the two orthogonal rotational demands to determine the total rotational demand on the bearings, that is:

$$\text{Total Bearing Rotation Demand} = \sqrt{\Phi_x^2 + \Phi_z^2} \quad (4)$$

where Φ_x and Φ_z are the maximum factored major-axis and twist rotation demands, respectively, for the LRFD load combination being considered.

One should keep in mind that, for skewed and/or curved bridges, the bearing vertical reactions for each girder at any given support will likely be different. In some cases (i.e., severe skew or severe curvature), one or more bearings at a given support may experience uplift under certain loading conditions. An accurate 2D grid or 3D finite element analysis may be appropriate or necessary to properly quantify the bearing reactions for some curved and/or skewed bridges.

In summary, it is important that engineers fully consider the vertical load, horizontal load, and rotational demands on bearings at critical stages of construction and under final, in-service conditions. The choice of fit condition (NLF, SDLF, or TDLF) affects the girder twist (layover) rotation demands, and the girder cambers affect the bearing major-axis rotation demands. In addition, engineers should consider options to mitigate or reduce the rotational demands on bearings, including the use of beveled sole plates (potentially beveled both longitudinal and transversely), and specifying that girders be blocked to protect their bearings during the steel erection. The use of TDLF and SDLF reduces girder layover rotations at skewed bearing lines. Engineers should include this consideration when choosing the method of detailing, but this is only one of a number of pros and cons that must be considered in making a fit decision. Fit-up during erection, when that may be an issue, is typically the overriding consideration.

8.2 Erection Considerations

For curved bridges, the erection should be from the outside to the inside of the curve where practicable. Under these circumstances, the girder on the outside of the curve is erected first, and held in place with either a hold crane or temporary support structure, until the adjacent girder towards the inside of the curve is erected. Once these girders are connected via cross-frames, the hold crane or temporary support potentially may be released, at which point the girders will displace vertically and rotate. The vertical displacement on the girder at the inside of the curve in this temporary condition is often less than the final displacement of the girder. Additionally, the out-of-plane rotation that occurs often will be in a manner in which the top flange moves away from the center of the curve more than the bottom flange, thus allowing easier fit up of the next girder and the cross-frames that are being attached.

In addition, in curved and skewed bridges with at least one radially oriented bearing line, it is typically easier to erect first from a radial support, proceeding toward a skewed support, i.e., erecting the framing where the geometry conditions are simpler first.

Additional recommendations to facilitate the erection of curved and/or skewed I-girder bridges, and guidelines for assessment of erection conditions, are provided in NCHRP (2015).

8.3 Bolt Holes and Bolt Tightening

Unless otherwise permitted in the contract documents, oversize or slotted holes are not permitted for bolted cross-frame connections in horizontally curved bridges (AASHTO LRFD 6.13.1). This requirement is specified to ensure sufficient control of the geometry during the bridge construction. The perceived advantage of using oversize or slotted holes to aid in the fit-up can prove to be disadvantageous in terms of the overall loss of the geometry control in these types of bridges.

Vertical slotted holes have sometimes been used in the cross-frame connections of straight skewed bridges in an attempt to minimize the girder twisting and reduce the cross-frame forces. The use of vertically slotted holes nullifies the results of any analysis that assumes that the cross-frames are effective in resisting dead loads applied prior to tightening of the cross-frame bolts. If the bolts are left loose in these holes during the placement of the deck, there is a corresponding loss of geometry control and the girders will likely deflect differently than predicted. The erector will also have to return to the site to tighten the bolts after the deck is cast, a potentially cumbersome, time-consuming and costly operation. If the bolts are tightened prior to the deck placement, the slots must be of the proper size and location to allow the SDL deflections to occur freely (assuming that it is desired that no forces should be induced in the cross-frames). The resistance of the bolts in the slotted holes is reduced for all loads that are applied after the bolts are tightened. Thus, the use of vertical slotted holes is not recommended.

It is common that not all bolts are installed in the connections, and those that are installed typically are not fully tightened as the erection progresses. Final installation and tensioning of all the bolts typically occurs after the steel is substantially or fully completed. Recommendations are specified in Article 2.2.7 of AASHTO/NSBA (2014a) regarding the minimum number of standard-size holes that should be filled with erection bolts, pins and/or bolts in at least a snug-tight condition in connections of horizontally curved bridges during the erection. These recommendations should be followed to help maintain the geometry of the erected steel. All bolts in both skewed and curved bridges should be fully tightened and inspected prior to the deck placement to preserve the bridge geometry during this operation and to avoid the need for the erector to go underneath the bridge to tighten the bolts after the completion of the deck.

8.4 Shop Assembly

Full shop assembly of the entire bridge or any significant portion of the bridge is not customary and is typically not needed, except possibly for highly complex framing (e.g. SPUI structures) detailed for NLF. Such a requirement adds unnecessary cost to projects that utilize less complex and more conventional framing. Full shop assembly cannot be done if the bridge has been detailed for TDLF, as the TDL condition cannot be replicated in the fabrication shop.

8.5 Tub Girders

Steel tub girders with properly designed top flange lateral bracing effectively behave as closed sections, and as such, they are torsionally quite stiff. Straight or slightly curved tub girders without external intermediate diaphragms generally exhibit little twist under non-composite loading. Tub girders with longer spans and more significant curvature are potentially subject to more significant twisting of the individual girders, but this is often controlled and minimized by providing external intermediate cross-frames. Helwig et al. (2007) provide a simple preliminary analytical procedure to help determine if external intermediate cross-frames are needed to help control twist deformations in curved tub girders.

Tub girders are typically designed and detailed to be normal to the deck (cross-slope of the roadway) with all of the webs having equal depth (Figure 14). Thus, the concepts of NLF, SDLF, and TDLF—with their reference to identifying a fit condition that results in the girders being plumb under a given loading condition—do not apply. Also, since tub girders are inherently torsionally stiff, it is difficult to twist them in the field to achieve fit-up of external cross-frames. As a result, tub girder external cross-frames are typically detailed and fabricated to fit to the girder geometry under NL or SDL conditions depending on the intended erection sequence. In addition, depending on the magnitude of their twist deformations under loading, tub girders may need to be detailed and fabricated with a built-in "reverse" twist so that when they twist under dead load, they deflect to a position normal to the roadway cross-slope. The camber of the two webs in skewed and/or curved bridges can be significantly different.

A detailed discussion of tub girders is beyond the scope of this document; instead it is recommended that the detailing of tub girders to facilitate proper fit-up and control of the constructed geometry be addressed on a case-by-case basis, in consultation with experienced tub girder designers, detailers, fabricators, and erectors.

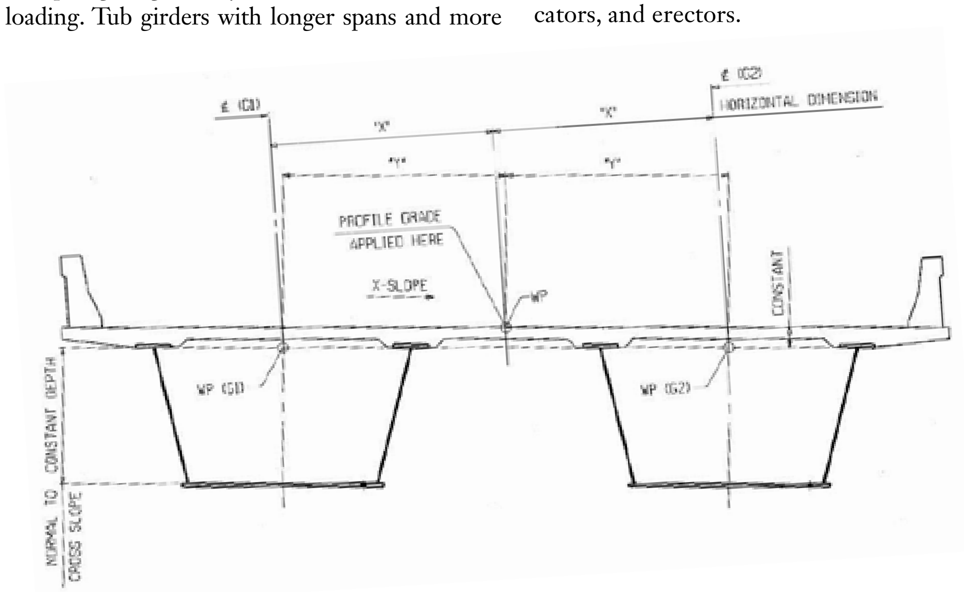

Fig. 14. Orientation of Steel Tub Girders Normal to the Deck (adapted from AASHTO/NSBA, 2006)

9 RECOMMENDED BEST PRACTICES FOR CONSTRUCTION INSPECTION

9.1 Introduction

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. The following discussion is taken is taken in large part from NCHRP (2015).

9.2 Common Items/Issues

A few items/issues which are common to any curved and/or skewed steel I-girder bridge, regardless of geometric configuration or specified detailing method, are discussed below.

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* (AASHTO/NSBA 2014a).

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 small up to certain practical limits (Domalik et al. 2005a; Domalik et al. 2005b; Howell and Earls 2007; NCHRP 2012). For curved girder bridges (with either radial or skewed supports), inspectors should not be overly concerned about the strength of or internal stresses in girders which are out-of-plumb less than two degrees (7⁄16 inch of layover per foot of girder height) in positive moment regions in the span. For straight skewed bridges, inspectors should also not be overly concerned about the strength of or internal stresses in girders which are out-of-plumb near end supports, regardless of the degree of out of plumbness.

However, at skewed end supports of straight or curved girder bridges, out-of-plumbness which deviates from predicted values by more than 0.6 degrees (1⁄8 inch of layover per foot of girder height) may lead to problems with bearing performance, and more significant deviations from predicted layover may lead to problems with alignment of joints, barriers, etc. Furthermore, at radial supports of straight or curved girder bridges, out-of-plumbness of more than 0.6 deg. (1⁄8 inch of layover per foot of girder height) is an indication of incorrect detailing, fabrication, or construction; girders should be plumb at radial supports under all loading conditions. The value 0.6 deg. (1⁄8 inch of layover per foot of girder height) is the tolerance listed in S10.1, which was developed as an industry-consensus document. While there is typically a 0.005 radian (approximately 0.3 deg.) construction tolerance value included in most elastomeric bearing designs, elastomeric bearings are typically fairly forgiving and should be able to tolerate higher rotations if necessary.

Girders in straight skewed bridges which exhibit their expected layover at end supports should be expected to be reasonably plumb at continuous supports and at maximum positive moment locations.

If a given bridge exhibits layovers which exceed the above limits, it is recommended that the inspector contact the engineer for a closer evaluation of the situation.

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 engineer 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 in later sections. 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, this 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 total dead load (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 limited and generally costly. Inspectors should carefully evaluate the position of the webs at supports at the end of steel erection, prior to deck placement.

9.3 Issues/Items Related to Straight Skewed Bridges

Straight skewed steel I-girder bridges will 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 the webs 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 layover 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, 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/engineers 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 (see Eq. 1). 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.

9.4 Issues/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 the webs 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.

Total Dead Load Fit (TDLF, also known as Final Fit) is strongly discouraged and should not be used for curved radially supported steel I-girder bridges 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.

9.5 Issues/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 the webs 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 and skewed steel I-girder bridge and generally does not represent a problem.

Total Dead Load Fit (TDLF, also known as Final Fit) is strongly discouraged and should not be used for curved and skewed steel I-girder bridges 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.

10 CONCLUSIONS

In curved and skewed I-girder bridges, the relationship between the girders changes as gravity loads are applied and the girders deflect. These changes introduce internal loads and affect the fit-up of the steel during erection; if the changes are significant, special considerations are needed to manage the internal loads and the constructed geometry, and to ensure that the bridge can be built.

Curved and skewed steel I-girder bridges are successfully fabricated and erected nearly every week. Making the right fit choice is one key consideration that can impact the ability of engineers, fabricators and erectors to ensure the completion of a successful project. The best fit choice is an informed one understood by all of the stakeholders.

11 DEFINITIONS

Contiguous Cross-Frames— Intermediate cross-frames arranged in a continuous line across the entire bridge cross-section.

Cross-Frame— A transverse truss framework connecting adjacent I-girders used to transfer and distribute vertical and lateral loads and to provide stability to the girder compression flanges. In this document, only the term cross-frame is used; the term cross-frame is considered to be synonymous with the term diaphragm herein.

Diaphragm— A vertically oriented solid transverse member connecting adjacent I-girders to transfer and distribute vertical and lateral loads and to provide stability to the compression flanges, sometimes used to refer to both solid-web transverse members as well as cross-frames. In this document, the term cross-frame is most often used; the term cross-frame is considered to be synonymous with the term diaphragm herein.

Discontinuous Cross-Frames— Intermediate cross-frames arranged in a discontinuous line across the bridge cross-section.

Drop— The difference in the vertical elevation between the top of the girder webs at a cross-frame location under the No-Load (NL) or a targeted dead load condition. For SDLF or TDLF, the drops are calculated by the detailer by subtracting the vertical dead load deflections provided on the Design Plans from the fully-cambered No-Load (NL) geometry, with consideration of the roadway profile and deck cross slope. Alternatively, some detailers may start from the TDL position and add the appropriate deflections to that position (e.g., the TDL minus the SDL deflections for SDLF, or the TDL deflections for NLF) in order to determine the girder geometry in the targeted fit condition. The goal is for the cross-frames to fit to the girders in these idealized deflected positions (or undeflected positions for NLF), thus achieving the desired fit condition. It is important to note that, generally, there are two major contributors to the detailing of the cross-frame geometry. The drops are one contributor. The other contributor, particularly at skewed cross-frame lines, is the girder connection plate rotated positions in the targeted geometry.

Fit Condition—The deflected girder geometry in which the cross-frames or diaphragms are detailed to connect to the girders.

Fit-Up Forces— External forces that may need to be applied by the erector to connect the steel together during the erection.

Girder Major-Axis Bending Rotation, ϕ_x— A rotation of a girder about its own major axis, i.e., the axis perpendicular to the girder web, causing displacements that are parallel to the plane of the web.

Girder Twist Rotation, ϕ_z— A rotation of a girder about its own longitudinal axis resulting from twisting, causing displacements out of the plane of the web.

Locked-in Forces— The internal forces induced into the structural system when Steel Dead Load Fit (SDLF) or Total Dead Load Fit (TDLF) detailing is employed. These internal forces are caused by the lack-of-fit detailed between the cross-frames and the girders in the base fully-cambered No-Load (NL) geometry. These internal forces would remain if the structure's dead loads were theoretically removed. The locked-in forces in the cross-frames of straight skewed bridges are largely opposite in sign to the corresponding targeted dead load effects. The locked-in forces in the cross-frames of curved radially supported bridges are largely additive to the dead load effects. When the locked-in forces are opposite in sign to the dead load forces, they offset them, resulting in reduced total internal dead load forces (approximately zero in the targeted dead load condition for straight skewed bridges).

No-Load Fit (NLF) Detailing— A method of detailing in which the cross-frames or diaphragms are detailed such that their connection work points fit with the corresponding work points on the girders without any force-fitting, with the girders assumed erected in their fully-cambered (plumb) geometry under zero load. NLF detailing is also synonymously referred to as fully-cambered fit detailing.

Transverse Stiffness— An undesirable stiff transverse load path in the structural system near skewed supports that can result in excessively large cross-frame forces at these locations, and somewhat difficult cross-frame installation along (and adjacent to) the skewed support line. Transverse stiffness effects can be attenuated when cross-frames are provided along a skewed support by offsetting the first intermediate cross-frame placed perpendicular to the girders adjacent to that support, where practicable, by the minimum recommended distance indicated in AASHTO LRFD C6.7.4.2, and by providing discontinuous cross-frame lines in the vicinity of skewed interior supports.

Skew Angle, θ – The angle of skew measured with respect to the normal to a girder tangent. A zero skew angle corresponds to no skew according to the definition of θ herein.

Steel Dead Load Fit (SDLF) Detailing— A method of detailing in which the cross-frames or diaphragms are detailed such that their connection work points fit with the corresponding work points on the girders with the steel dead load vertical deflections and the associated girder major-axis rotations at the connection plates subtracted from the fully-cambered geometry of the girders, and with the girder webs assumed in an ideal plumb position under the Steel Dead Load (SDL) at the completion of the steel erection. SDLF detailing is also synonymously referred to as erected-fit detailing.

Total Dead Load Fit (TDLF) Detailing— A method of detailing in which the cross-frames or diaphragms are detailed such that their connection work points fit with the corresponding work points on the girders with the total dead load vertical deflections and the associated girder major-axis rotations at the connection plates subtracted from the fully-cambered geometry of the girders, and with the girder webs assumed in an ideal plumb position under the Total Dead Load (TDL). TDLF detailing is also synonymously referred to as final-fit detailing.

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