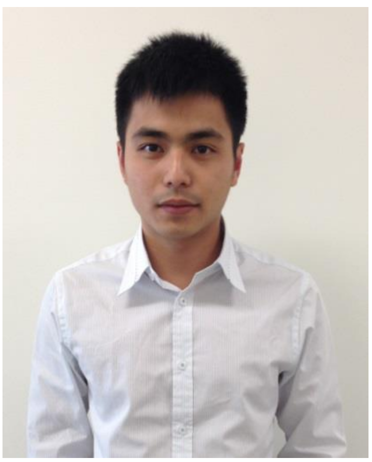
# IMPACT OF CAMBER CALCULATION, CAMBER AND DECK THICKNESS TOLERANCE, AND FRAMING ARRANGEMENT ON FIT RESPONSES IN STRAIGHT SKEWED I-GIRDER BRIDGES



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## BIOGRAPHY

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## SUMMARY

Cross-frames in straight skewed I-girder bridges are often detailed such that they fit to the girders in an idealized deflected position under a targeted dead load condition. This practice, typically referred to as Steel Dead Load Fit (SDLF) or Total Dead Load Fit (TDLF), ideally gives plumb girder webs, zero cross-frame forces, and zero girder flange lateral bending stresses under the targeted dead load condition.

This paper addresses the influence of the method of calculating the dead load cambers, which are an essential variable used in setting the fit in the above bridge types. The results for dead load cambers based on a line girder analysis are compared to those based on an accurate 2D-grid or a 3D FEA analysis. In addition, the impact of camber and deck thickness tolerances, and the influence of different cross-frame framing arrangements on the fit responses are discussed.

# IMPACT OF CAMBER CALCULATION, CAMBER AND DECK THICKNESS TOLERANCE, AND FRAMING ARRANGEMENT ON FIT RESPONSES IN STRAIGHT SKEWED I-GIRDER BRIDGES

## 1. Introduction

Dead load fit is the practice of detailing the cross-frames such that they connect to an idealized deflected position of the girders under a targeted dead load condition in a steel I-girder bridge. This practice compensates for, or offsets, the twist rotations and the corresponding layover deflections that occur in the girders under the targeted dead load. This reduces the dead load rotations that the bridge bearings need to accommodate, particularly at highly-skewed end abutments, and it can help in the alignment of the corresponding deck joints by reducing the lateral movement at the joints under the dead loads.

The cross-frames in straight-skewed I-girder bridges are often detailed for either steel dead load fit (SDLF) or total dead load fit (TDLF). That is, the cross-frames are detailed to fit (connect) to ideal plumb girder geometries with the steel dead load or total dead load camber profiles subtracted from the fabricated girder no-load elevations respectively. Therefore, it would be expected that the calculated camber profiles, as well as camber profile tolerances, may be important to achieving the desired results from these fit practices.

It is common for girder camber profiles to be calculated from a 1D Line Girder Analysis (LGA) for some bridges, 2D-grid analysis for others, and in some cases from a 3D Finite Element Analysis (FEA). For a highly skewed I-girder bridge, the differences in the cambers obtained from LGA versus the other two methods can be substantial. A thinking engineer may rightfully question whether these camber differences can have a significant influence on the intended fit behavior. This paper addresses the influence of these differences and explains the mechanics behind the findings. In addition, the impact of camber and deck thickness tolerances, and the influence of different cross-frame framing arrangements on the fit responses are discussed. A representative straight bridge with an extreme skew is used for these purposes.

Section 2 of the paper first defines the three most common types of fit. Several important 3D FEA Modeling considerations are addressed in Section 3. 3D FEA simulations are used as a benchmark of the system behavior in this paper. Section 4 then discusses the influence of the camber calculations on the dead load fit responses, Section 5 investigates the sensitivities to camber and deck thickness tolerances, and Section 6 discusses the influence of cross-frame framing arrangements. Section 7 provides conclusions.

## 2. Dead Load Fit Detailing

The "fit condition" refers to the geometry at which the cross-frames are detailed to attach to the girders in an I-girder bridge. There are many feasible ways to fit such a bridge. The AASHTO (2010) LRFD Article C6.7.2 discusses the following three most common fit conditions:

- No Load Fit (NLF): The cross-frames are detailed to fit to the girders in their cambered, plumb, no-load (NL) geometry. To achieve NLF, the cross-frame drops (i.e., the difference in elevation between the ends of the cross-frames) are set to the girder fully-cambered, NL profiles. The girders are commonly fabricated as plumb under no load. Therefore, for NLF, they are theoretically plumb when connected to the cross-frames. The total cross-frame forces and girder flange lateral bending stresses are ideally zero in the NL condition. However, for NLF, the girders are laid over, and the cross-frame forces and the girder flange lateral bending stresses are non-zero under any of the dead load conditions.
- Steel Dead Load Fit (SDLF): The cross-frames are detailed to fit to the girders in an idealized plumb SDL condition. To achieve SDLF, the cross-frame drops are set by sub-

tracting the SDL camber profiles provided on the engineering plans from the fabricated fully-cambered girder elevations. The girders are laid over, the cross-frames are stressed and the girder flanges are subjected to lateral bending in the NL and TDL conditions (in the NL condition, the layovers, forces and stresses are in the direction opposite from the changes due to the dead load). However, ideally, the girders are plumb, and the cross-frame forces and flange lateral bending stresses are zero under the SDL.

- Total Dead Load Fit (TDLF): The cross-frames are detailed to fit the girders in an idealized plumb TDL condition. To achieve TDLF, the cross-frame drops are set by subtracting the total dead load camber profiles provided on the engineering plans from the fabricated fully-cambered girder elevations. The girders are laid over, the cross-frames are stressed, and the girder flanges are subjected to lateral bending (all in the opposite direction from the changes due to the dead load) in the NL and SDL conditions. However, ideally, the girders are plumb, and the cross-frame forces and flange lateral bending stresses are zero in the TDL condition.

It should be noted that the girder vertical deflections and layovers in the partially erected structure are generally different from those at the completion of the steel erection. The SDLF condition is always based on the completed steel framing. The TDLF condition is generally based on the final TDL condition. It should be noted that the girder TDL deflections can vary significantly depending on what constitutes the TDL. The TDL typically is assumed to include all dead loads that are present when the bridge is open to traffic, or the as-constructed dead loads. Future wearing surface loads and their effects generally are not considered as a part of the TDL. Lastly, it is important to recognize that twist deflections are a natural occurrence in skewed girder bridges. Twisting is unavoidable as the bridge deflects under the dead loads. The girder webs can be plumb only in a single selected condition.

## 3. 3D Finite Element Modeling

ABAQUS 6.12 (Dassault Systems, 2012), which is a general purpose FEA software system used extensively for simulation of nonlinear structural response, is used in this paper to determine benchmark responses for an example highly-skewed I-girder bridge. The subject bridge is discussed in Section 4. All the bridge components are explicitly modeled. The following are some of the important attributes of the 3D FEA model. A general purpose 4-node quadrilateral Reissner-Mindin shell element is used to model the girder webs. A 2-node beam shear-deformable element compatible with the shell element is used to model the flanges, stiffeners, and chords of V or inverted V cross-frames to which the diagonals are connected. The cross-frame chords in this case are modeled with moment releases where the chords frame into the girder webs. A truss element is used to model the cross-frames everywhere except in the case of the chords mentioned above. The axial stiffness of the single-angle cross-frame members is taken as 0.65 of the nominal $EA/L$ to account for the additional flexibility associated with the eccentric bending of the angles, as specified in the 2014 Interims to the AASHTO LRFD Specifications. The weight of the steel is modeled as a weight density. The concrete weight is based on tributary widths and is modeled as distributed line loads applied to the top of the girders. Super-elevation and grade are neglected. The girder cambers are modeled explicitly. The bridge is analyzed as a geometrically nonlinear elastic system.

In this paper, the camber profiles based on 3D FEA are determined by creating the 3D FEA model and then turning the gravity loads on. Camber profiles based on 1D Line Girder Analysis (LGA) are determined by analyzing the individual girders in isolation, accounting for the cross-frame weights via concentrated nodal loads at their connection points to the girders.

## 4. Effects of Camber Calculations on Fit Responses

The bridge shown in Figure 1 is used as an illustrative example in this paper. The selected bridge was studied in Project NCHRP 12-79 (White et al. 2012) and was designated as bridge NISSS54 in that research. This bridge has a 300 ft. simple span, 9 girders spaced at 9.25 ft., and an 80 ft. wide deck. Both bearing lines are skewed at 70 degrees. Due to its severe skew relatively wide deck, and long span length, the bridge was one of several straight-skewed bridges with the greatest potential fit-up difficulty in the 12-79 research. Girder 1 is the fascia girder on the bottom of the framing plan and Girder 9 is the fascia girder on the top of the plan. The fascia and interior girders are identical. All the girder webs are 12 ft. deep and 1 in. thick. The girder flange thicknesses are stepped at four locations.

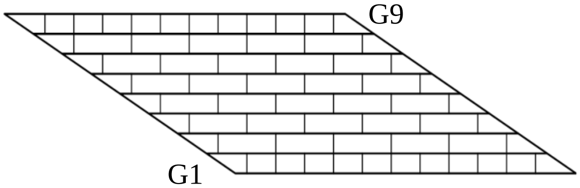


Figure 1: Framing plan of NISSS54

Table 1 shows the girder plate lengths and the girder flange dimensions. The intermediate cross-frames are X-type, framed perpendicular to the girders and with L6x6x1 sections used for all their members. The end cross-frames are inverted V-type and are parallel to the skew. The intermediate cross-frames are placed in a staggered pattern that follows the same angle as the bearing lines. The framing arrangement shown in Figure 1 actually is different from the original framing studied in NCHRP 12-79. This alternate arrangement was chosen to mitigate the effects of "nuisance" transverse stiffness associated with the bridge's severe skew. The behavior of the bridge with the original framing arrangement is discussed subsequently.

Table 1: NISSS54 girder plate lengths and girder flange dimensions

| Length (ft.) | Top flange | | Bottom flange | |
|---|---|---|---|---|
| | Width (in) | Thickness (in) | Width (in) | Thickness (in) |
| 45 | 28 | 1.25 | 30 | 1.25 |
| 45 | 28 | 2 | 30 | 2.25 |
| 12 | 28 | 2 | 30 | 2.75 |
| 45 | 28 | 2 | 30 | 2.25 |
| 45 | 28 | 1.25 | 30 | 1.25 |

### SDLF Behavior Using Line Girder Analysis Cambers

The practice of SDLF detailing using the cambers obtained from a Line Girder Analysis (LGA) theoretically gives exactly plumb girder webs, zero cross-frame forces, and zero flange lateral bending stresses under the targeted dead load. This fact is explained below by two hypothetical erection sequences.

**Erection Sequence 1**

In straight-skewed bridges, the girders deflect only vertically under their self-weight and the self-weight of the cross-frames, 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. Therefore, if all the girders are theoretically placed on their vertical supports, just the top chords of all the cross-frames are attached to the girders (such that there is no shear and moment transfer via the cross-frames), and the girders are allowed to deflect under the full steel self-weight, the resulting girder vertical deflections are exactly equal to the SDL deflections obtained from a LGA.

If the SDL cambers are set based on the above deflections, and the cross-frames are then de-tailed for SDLF using these cambers, then the cross-frames will fit exactly to the girders in the above SDL geometry. In other words, for the structure in the above hypothetical deflected geometry under the steel self-weight, the cross-frame connections match up perfectly with the corresponding positions on the girders. Therefore, the connections to the girders can be completed without any forcing. These statements apply to all straight I-girder bridges with either parallel skew or non-parallel skew. However, they do not apply to curved I-girder bridges. The corresponding behavior of curved I-girder bridges is beyond the scope of this paper. The reader is referred to White et al. (2012) for a detailed discussion of the fit behavior of these bridge types.

It is common for the girder camber profiles to be calculated from a 1D Line Girder Analysis (LGA) for some bridges, a 2D-grid analysis for others, and in some cases from a 3D FEA. To simplify the discussion, only cambers based on LGA and 3D FEA are discussed in this paper. The cambers calculated from a 2D-grid analysis are practically the same as those calculated from 3D FEA if the 2D-grid analysis employs the improvements recommended by NCHRP Project 12-79 for I-girder bridges. The results obtained using 3D FEA based cambers are discussed subsequently.

All the cross-frames are assumed inactive and the girders deflect only in the plane of their webs in a LGA. The girders deflect independently of each other under the dead loads in this analysis. Figure 2 shows the girder vertical deflections due to SDL in the NISSS54 bridge, calculated by LGA. The horizontal axis is the horizontal "x" coordinate in the plan view, measured from the bearing at the left-hand acute corner. The SDL and TDL camber profiles on the engineering drawings are taken simply as the inverse of the vertical deflections under SDL or TDL, respectively.

One can observe that all the girder vertical deflections are nearly identical in Figure 2. This is because the girders are all of the same size and length, such that the SDL is the same for all the interior girders. The SDL applied to the fascia girders is only slightly less since the cross-frames connect to only one side of the fascia girders. The cross-frame weights, applied as concentrated nodal loads to the fascia girders, are one-half of those applied to the interior girders.

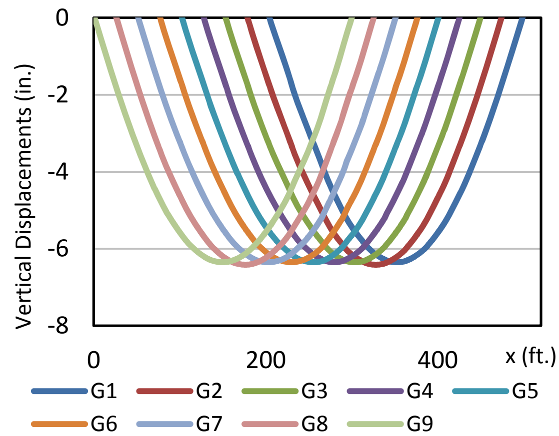


Figure 2: NISSS54 girder vertical displacements due to SDL calculated by LGA

Table 2 shows the maximum girder layovers, the maximum cross-frame stresses, and the maximum flange lateral bending stresses for NISSS54 under SDL, including SDLF effects based on the LGA cambers. The girder layovers and internal stresses closely match the theoretical ideal zero values. The reason for the minor deviation from zero is due to intermediate connection plates. They are not placed symmetrically along the web of each girder due to the staggered cross-frame pattern. Because of the weight and stiffness of the connection plates, the girder lateral deflections under self-weight, before the cross-frames are connected to the girders, are very slightly non-zero.

Due to stability considerations, the NISSS54 bridge would not be erected in the hypothetical fashion explained above, where all the girders are allowed to deflect under the full steel self-weight without any cross-frame connections. It would be erected in stages in which individual girders or girder pairs would be placed and the cross-frames would be connected to the erected girders successively after each of the girder lines or girder pairs are placed.

Table 2: NISSS54 maximum responses (girder layovers, cross-frame (CF) stresses, and flange lateral bending stresses ($f_\ell$)) under SDL, including SDLF effects based on LGA cambers

| Layovers(in) | CF stress (ksi) | $f_\ell$ (ksi) |
|---|---|---|
| 0.0072 | 0.023 | 0.053 |

Once the cross-frames are connected to the girders, the interconnected girders deflect as a three-dimensional system under subsequent dead 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 subsequent dead loads. This behavior of straight skewed bridges is different from the behavior of a right bridge. In a right bridge, the girders deflect predominantly only in a vertical fashion. This is because there are no significant differential deflections between the girders and there is no interaction between the girders and the displacements of the bearing line cross-frames. However, in a straight skewed bridge, such as NISSS54, there are substantial non-zero differential deflections between the girders at each of the cross-frames, since the cross-frames connect to different positions within the span of each of the girders. In addition, to maintain compatibility between the cross-frames and the girders along the skewed abutment bearing lines, the girders have to twist substantially at the skewed abutments (White et al. 2012).

### Behavior Independent of Erection Sequence

Regardless of the sequence in which the bridge is erected, if the SDL cambers are calculated from LGA, and the cross-frames are detailed for SDLF using these cambers, the girder layovers and internal stresses are theoretically equal to the above ideal values. This is because as long as (1) all the bridge components are kept elastic, (2) the influence of the girder splice and cross-frame-to-girder connection tolerances is assumed to be negligible, and (3) there are no effects such as friction providing unintended restraint at the supports, the bridge is what is referred to in structural mechanics as a conservative elastic structural system. Within these limits, the response of the structure for any given erection stage is independent of the erection sequence up to that point. In mechanics terms, the behavior at any given erection stage is unique and path independent.

### Erection Sequence 2

To further understand the fit behavior, the NISSS54 responses can be examined assuming that all the cross-frames are connected to the girders first before the dead loads are applied to the bridge. For SDLF, the cross-frames are fabricated to fit to the girder connection work points in a conceptual geometry in which the girders are plumb and the SDL cambers have been removed from the girders. As such, the cross-frames do not fit up with the girders in the reference no-load geometry. This initial lack-of-fit between the cross-frames and the girders in the reference no-load geometry induces girder layovers (i.e., relative lateral displacements of the top and bottom flanges) in the opposite direction from the layovers due to the SDL. These SDLF effects are shown in Figure 3. In addition, beneficial locked-in stresses are produced within the structural system that are associated with these deformations.

When the SDL is subsequently applied to the bridge in the above conceptual scenario, the girders deflect vertically and twist under the application of the SDL to the three-dimensional structural system, as discussed above. Figure 4 shows the girder layovers due to the SDL. The girder layovers are substantial. This is due to the compatibility between the girders and the heavily skewed bearing line cross-frames as well as the differential deflections between the girders within the span.

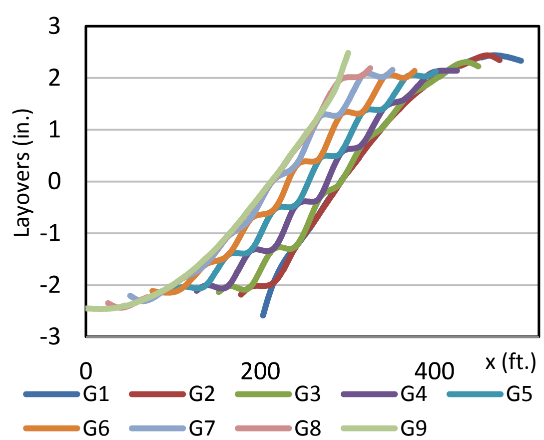


Figure 3: NISSS54 girder layovers due to SDLF effects based on LGA cambers

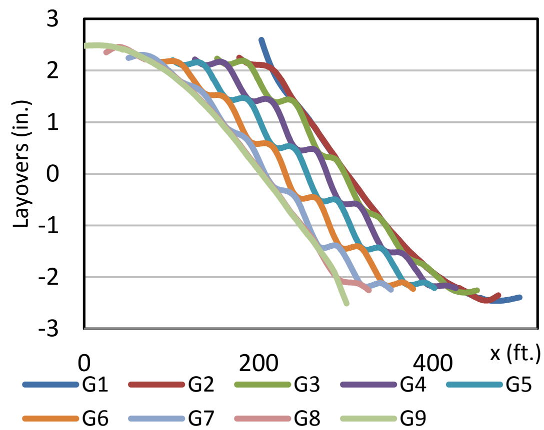


Figure 4: NISSS54 girder layovers due to SDL when the bridge deflects as a system

One can observe that the layovers in Figure 3 due to the SDLF locked-in forces based on the LGA cambers, are equal in magnitude and exactly opposite in direction to the layovers in Figure 4 due to the SDL. That is, these two sets of layovers completely cancel one another. As such, the girder flanges are completely straight in the final SDL condition. Since the girder flanges are straight, their lateral bending is exactly zero. Furthermore, since the girder flange lateral bending is exactly zero, the cross-frame forces are all zero as well.

**Summary**

One can view the above behavior as a beneficial effect of lack-of-fit between the cross-frames and the girders in the reference no-load bridge geometry. The lack-of-fit effects cancel the SDL effects, resulting in plumb girders, zero lateral bending and zero cross-frame forces in the SDL condition. Alternatively, one can consider the earlier hypothetical erection scenario, in which the cross-frames fit to the girders in their ideal SDL deflected geometry without any forcing, if the girders and cross-frames are all placed first without engaging the cross-frames in resisting any internal forces. Both idealized sequences, or any other erection sequence, produce the same result, since under the previously stated assumptions, the bridge is a conservative elastic structural system.

## SDLF Behavior Using 3D FEA Cambers

For the parallel skew NISSS54 bridge, the differences in the cambers obtained from LGA versus 3D FEA are substantial. Figure 5 shows the NISSS54 girder vertical deflections due to SDL, calculated by 3D FEA. The vertical deflections are much smaller near the center of the bridge width in the three-dimensional structural system. This is due to the substantial transverse load path between the obtuse corners of the bridge, developed via the cross-frames.

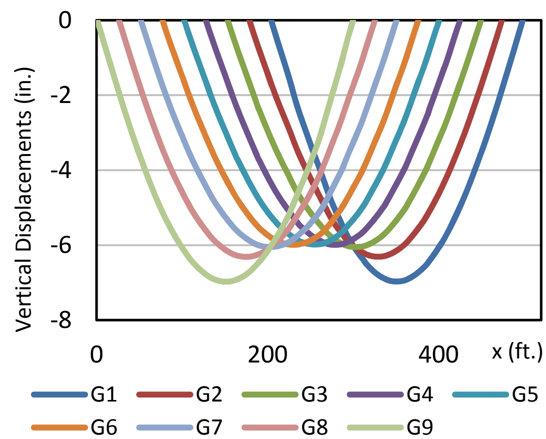


Figure 5: NISSS54 girder vertical displacements due to SDL, calculated by 3D FEA

The common current structural practice, when using 2D-grid or 3D FEA, is to build a model of the structure and then simply “turn the gravity load on.” This practice captures the behavior of the bridge if the cross-frames could be fully connected to all the girders, in a no-load (e.g., a shored) condition, without any forcing (i.e., cross-frames detailed for NLF), followed by removal of the shoring. This practice does not account for the actual behavior of the bridge if the girders and cross-frames could be placed first and allowed to deflect under the steel self-weight, followed by connection of the cross-frames fabricated for SDLF to the girders in their SDL condition without any forcing. Furthermore, it does not account for any other erection scenario with detailing of the cross-frames for anything other than NLF. In fact, one should recall that given the previously stated assumptions, the bridge is a conservative elastic structural system; hence, the erection sequence does not influence the completed state of the bridge. However, the fit method, for instance SDLF versus NLF, certainly does influence the response. Also, the SDL deflections assumed in setting the cambers definitely influence the completed state of the bridge.

If the girder cambers are set using the vertical deflections from an accurate 2D-grid or a 3D FEA of the interconnected bridge structural system (commonly conducted by just "turning gravity on"), the girders tend to be close to plumb, and the cross-frame forces and girder flange lateral bending stresses will be relatively small. However, these quantities will generally differ from the targeted ideal zero values. The LGA based camber is the only vertical camber that produces the targeted ideal in a straight skewed I-girder bridge. In addition, the final girder elevations will match theoretically with the targeted final girder profiles only when the LGA cambers are used. When the cambers are based on the above mentioned 3D FEA, the girders generally will be slightly out-of-plumb, their final SDL elevation profiles will be slightly different from the targeted profiles, the girder flange lateral bending stresses will be relatively small but non-zero, and the cross-frame forces will be relatively small but non-zero.

Beneficial lack-of-fit effects are generated by using SDLF based on the 3D FEA based girder vertical cambers; however, the lack-of-fit effects based on the assumption that the girders are plumb under the SDL but are deflected vertically according to the behavior of the interconnected three-dimensional structure cannot possibly produce the ideal theoretical perfectly plumb girders, perfectly zero girder flange lateral bending, perfectly zero cross-frame stresses, and the targeted girder profiles under the SDL.

It should be emphasized that a 2D grid or 3D FEA in which the SDL is simply "turned on," without accounting for the lack-of-fit effects from SDLF detailing, basically gives the "full" SDL girder flange lateral bending stresses and the "full" SDL cross-frame forces, without accounting for any of the above beneficial effects of the SDLF detailing.

In the context of a conceptual model in which the cross-frames are connected to the girders first, including the SDLF detailing effects, and then the SDL is subsequently applied (recall that the sequencing of these steps has no influence on the final result since the response is path independent within the limits of the previously stated assumptions), SDLF detailing based on the 3D FEA based cambers (referred to as just the 3D FEA cambers for simplicity) induces layovers in the girders in the opposite direction from those due to the SDL. However, these layovers are not exactly equal and opposite to the layovers caused by the SDL.

Figure 6 demonstrates this point by showing the final layover of the girders in the NISSS54 bridge under the SDL, when SDLF based on the 3D FEA cambers is used. The maximum girder layover in this case is 0.21 in. These results show that, for practical engineering purposes, these 12 ft. deep girder webs can be considered plumb. However, strictly speaking, they are not exactly plumb.

Since the girders are not exactly plumb under SDL, for SDLF based on the 3D FEA cambers, the associated cross-frame axial forces and girder flange lateral bending stresses are not exactly zero either. However, these stresses are relatively small. Figures 7 and 8 show a maximum stress magnitude of only 0.76 ksi in the cross-frames of NISSS54 and maximum girder flange lateral bending stresses of only 1.12 ksi under the SDL condition. For clarity, only the flange lateral bending stresses from the fascia Girder 1 and the interior Girder 5 are shown in Figure 8. The maximum flange lateral bending stress is in the fascia girders.

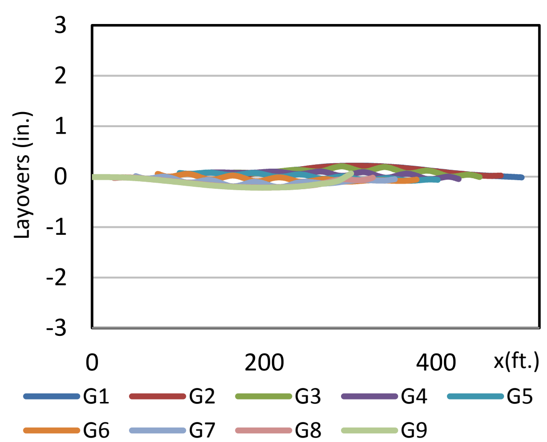


Figure 6: NISSS54 girder layovers under SDL using SDLF based on the 3D FEA cambers

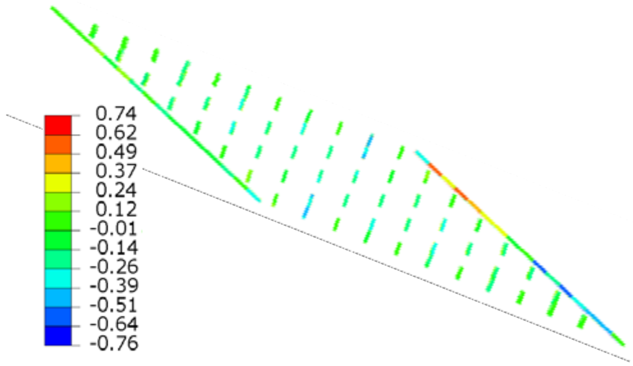


Figure 7: NISSS54 cross-frame stresses under SDL due to SDLF based on the 3D FEA cambers

Clearly, the use of the SDL camber profiles from 3D FEA gives a reasonably close match to the ideal zero dead load internal forces and girder layovers under the SDL condition. However, the use of SDL camber profiles from LGA gives the closest match to the ideal.

Although it can be seen from Figures 2 and 5 that the SDL cambers calculated from LGA and 3D FEA are substantially different, the final bridge geometries and internal stresses are very similar under the targeted dead load condition. One explanation for this is as follows. Assuming all the cross-frames are connected to the girders before the dead loads are applied to the girders, the locked-in forces due to SDLF twist the girders in the opposite direction from the layovers due to SDL. The girder twists due to SDLF based on the 3D FEA cambers are essentially the same pattern as the girder twists due to SDLF based on the LGA cambers. However, while the girder twists due to SDLF based on the LGA cambers completely cancel the layovers due to the SDL, the girder twists due to SDLF based on the 3D FEA cambers are in the opposite direction from the SDL layovers but are not exactly the same pattern as the SDL layovers. As such, the resulting final girder layovers, cross-frame forces and girder flange lateral bending stresses are close to zero under the targeted dead condition. However, they are not exactly equal to zero. The use of the SDL cambers calculated from LGA gives the closest match to the ideal zero girder layovers and internal stresses under the targeted dead load condition.

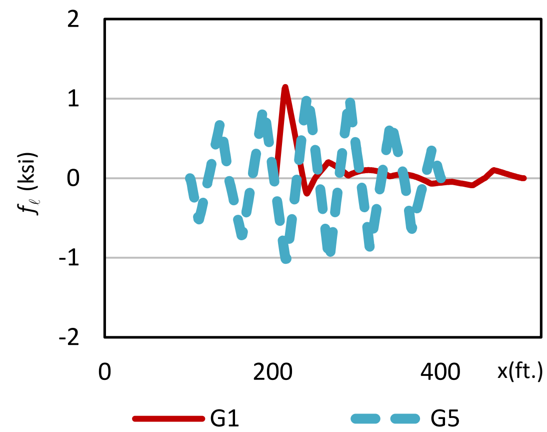


Figure 8: NISSS54 girder lateral bending stress under SDL due to SDLF based on the 3D FEA cambers

As noted previously, the final girder elevations due to SDLF based on the LGA cambers closely match with the ideal targeted girder elevations. This is because if the girders were allowed to deflect under SDL before all the cross-frames were connected to the girders, the resulting girder vertical deflections would be exactly equal to the SDL deflections obtained from a LGA. However, the final girder elevations due to SDLF based on the 3D FEA cambers deviate slightly from the ideal targeted elevations under the SDL. The final girder elevations under the SDL condition, due to SDLF based on 3D FEA cambers, can be considered as the summation of three independent components: the 3D FEA cambers, the change in elevations due to SDLF effects from the 3D FEA cambers, and the system vertical deflections due to the SDL effects alone. The 3D FEA cambers are taken commonly as the negative of the vertical deflections due to the SDL effects. This does not include the minor changes in the vertical elevations due to the SDLF effects. Therefore, the final girder elevations in this scenario are equal the change in elevations due to the SDLF effects. Figure 9 shows the final girder elevations under SDL for SDLF based on the 3D FEA cambers. It can be observed that maximum deviations from the ideal zero elevation line are +0.21 and -0.22 in. This is quite a bit less than the differences between the cambers shown in Figures 2 and 5 (note that the same scale is used for the vertical axis in Figure 9 as used in the previous Figures 2 and 5).

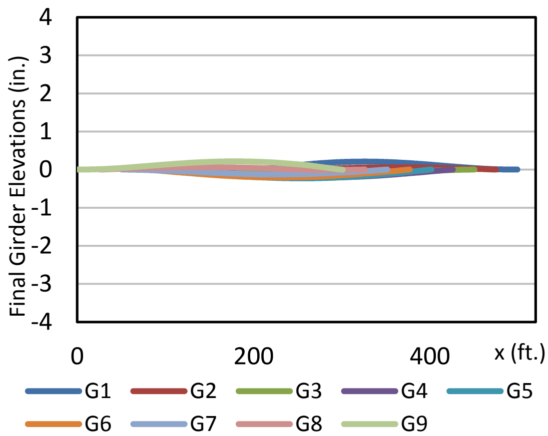


Figure 9: NISSS54 final girder elevations under SDL for SDLF detailing based on the 3D FEA cambers

## TDLF Behavior

Similar conclusions to the above can be drawn for TDLF detailing. The final bridge geometries and internal stresses are very similar for TDLF regardless of whether the cambers are calculated by LGA, 2D-gird analysis, or 3D FEA. This is because the behavior of a skewed I-girder bridge is very similar under both SDL and TDL within the context of the following assumptions:

(1) The volume of the deck concrete is small enough such that the deck can be placed entirely in one stage and the concrete dead weight must be resisted entirely by the noncomposite steel structural system (or alternately, if the influence of staged deck placement is assumed to be negligible). The concrete weight is calculated based on the tributary widths and is applied as vertical line loads at the tops of the girders.

(2) The overhang loads predominantly affect only the fascia girders and the adjacent cross-frame lines. These effects cause non-zero flange lateral bending in the fascia girders, and non-zero forces in the adjacent cross-frames; however, these torsional effects from the overhangs may be calculated by a structural analysis separate from the one used to determine the required girder cambers. The overall analysis of the bridge, corresponding to the ideal zero girder flange lateral bending stresses and zero cross-frame forces, would then involve the consideration of the overhang bracket loads only as a part of the line loads applied directly over the top of the fascia girders.

Within the context of the first of the above assumptions, the composite stiffness of the bridge does not need to be considered in calculating the dead load effects. As a result, the TDL effects on the bridge are very similar to the SDL effects discussed earlier, except that the response magnitudes due to the TDL are typically larger.

For TDLF based on the 3D FEA cambers, the TDLF detailing induces twists that are in the opposite direction from the TDL layovers and are approximately the same magnitude as the TDL layovers. However, as discussed earlier for SDLF, these twists are not exactly equal and opposite. Therefore, for TDLF based on the 3D FEA cambers, the girders will not be perfectly plumb under the TDL. Consequently, the corresponding cross-frame forces and flange lateral bending stresses are not zero either. Table 3 shows the maximum corresponding responses for NISSS54. The layovers, cross-frame stresses, and flange lateral bending stresses are relatively small, but for this severely skewed bridge, they are indeed measureable.

Table 3: NISSS54 maximum responses under TDL (layovers, cross-frame (CF) stresses, and flange lateral bending stresses ($f_\ell$)) for TDLF based on 3D FEA cambers or LGA cambers

| 3D FEA | | | LGA | | |
|---|---|---|---|---|---|
| Lay-overs (in) | CF stress (ksi) | $f_\ell$ (ksi) | Lay-overs (in) | CF stress (ksi) | $f_\ell$ (ksi) |
| 0.61 | 2.4 | 4.7 | 0.019 | 0.071 | 0.15 |

For TDLF based on LGA cambers, the girder layovers and internal stresses under the TDL condition are a close match to the ideal zero values. This can be understood as follows. If theoretically all the girders are placed on their supports, all the cross-frames are connected to the girders just at their top chord such that they are not yet engaged, and all the concrete loads are applied to the girders, the resulting girder vertical deflections due to the TDL are equal to the TDL deflections obtained from LGA. If the cross-frames are detailed for TDLF based on these LGA cambers, the cross-frames then can be connected to the girders without any forcing. As explained earlier, the bridge is a conservative elastic structural system under the stated caveats. Therefore, its response is independent of the sequence of erection (and construction). Within the context of these idealizations, the TDL cambers from LGA give ideally zero girder layovers and ideally zero internal stresses under the TDL condition, regardless of the actual construction sequence for the bridge.

The above statements are true even if the interior and fascia girder dimensions are not identical, even if the bearing lines do not have equal skew, and even if the TDL applied to each girder is significantly different. Given the above assumptions, the resulting vertical deflections for each girder under the TDL are equal to the TDL deflection obtained from LGA for that girder. As a result, the cross-frame connections match up with the corresponding TDL positions of the girders if the cross-frames are detailed for TDLF using the TDL cambers from LGA, regardless of the girder sizes, the skew of the bearing lines, and the relative magnitude of the TDL on each of the girders.

It is important to note from Tables 2 and 3 that while the girder layovers and internal stresses under the targeted dead load condition, for SDLF and TDLF based on LGA, are theoretically zero, the final results from are not exactly zero. These responses are roughly 3% of the corresponding results obtained when the detailing is based on the 3D FEA cambers. These non-zero results, where the theoretical results should be exactly zero, are due to attributes such as the fact that there are some small transverse strains in the girder webs of the physical structure.

In addition, from Tables 2 and 3, it can be observed that the TDLF responses under the TDL are approximately three times the corresponding SDLF responses under the SDL. This is because the magnitude of the TDL is approximately three times that of the SDL for the NISSS54 bridge.

# 5. Sensitivities of the Fit Responses to Camber and Deck Thickness Tolerances

The cross-frame drops for SDLF or TDLF are set by subtracting the corresponding SDL or TDL camber profiles from the fully cambered girder elevations. As a result, the girder layovers and the internal stresses potentially can be affected significantly by any tolerances applied to the dead load camber profiles.

SDLF and TDLF detailing relies on the dead load cambers provided on the engineering drawings. For dead load fit detailing, the girders are theoretically plumb under the targeted dead load condition, in a straight skewed I-girder bridge, if the girders are cambered exactly according to the specified LGA cambers. Any deviations from the specified cambers make the ideal girder layovers and internal stresses nonzero. The larger the deviations of the actual from the specified cambers, the more the girder layover and internal stresses are affected.

Fabricators generally impose positive tolerances on the girder camber profiles. The negative camber tolerance is always zero for single-span bridges. Fabricated girders that are under-cambered may be rejected. The maximum allowable tolerance at the mid-span is +1.5 in and -0 in. for girders that are greater than 100 ft. long (AWS, 2010). For other positions along the girders, the maximum allowable tolerance varies parabolically between 1.5 in. at mid-span and 0 in. at the supports.

The girder cambers generally may vary within the above range. However, it is anticipated that for a bridge such as NISSS54, the fabricator would typically target a specified positive over-camber possibly within the middle of the above range. The impact of this practice is investigated below by assuming LGA cambers and scaling the NISSS54 camber profiles by the factors ($1 + T / C$), where $T$ is the maximum over-camber at the girder mid-span and $C$ is the specified girder camber at its mid-span. For example, for the fascia girder G1 the specified SDL camber at mid-span is C = 6.35in. The G1 camber is then scaled by the factor (1 + T/6.35). The maximum over-camber at the girder mid-span T is taken as

0.5., 1.0., and 1.5in. The parameter T is assumed to be the same for all the girders in this base study (the effect of deviations in the over-camber between girders are discussed subsequently). Figures 10 and 11 show the corresponding maximum layovers, cross-frame stresses and girder flange lateral bending stresses under the targeted dead load condition in NISSS54 for SDLF and TDLF respectively ,(Note that all of these responses are ideally zero under the targeted dead load condition.)

Interestingly, the maximum responses increase in a nearly linear fashion with increases in the camber tolerance. This is because the material is assumed to be linear elastic and the geometric nonlinearity in the bridge structural system is very minor under the targeted dead load conditions.

Also, it can observed from Figures 10 and 11 that the maximum cross-frame stresses and girder layovers, under the TDL for TDLF based on LGA, are very similar to the corresponding values under the SDL, for SDLF based on LGA. However, the flange lateral bending stresses are slightly larger under the TDL, for TDLF based on LGA cambers compared to the corresponding stresses under the SDL, for SDLF based on LGA cambers. These behavioral characteristics are related to subtleties in the different pattern and magnitude of the TDL and SDL responses.

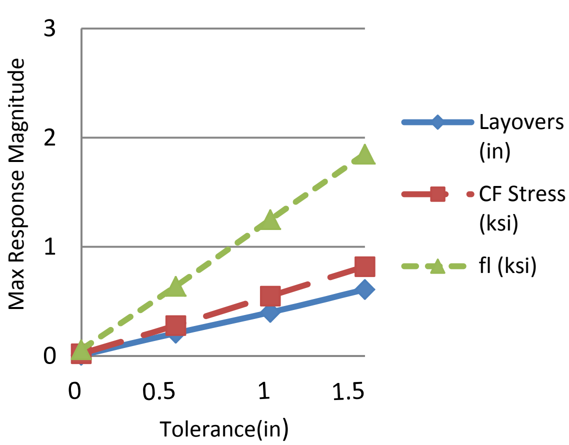


Figure 10: NISSS54 maximum responses under SDL, for SDLF based on LGA cambers, versus the camber tolerance

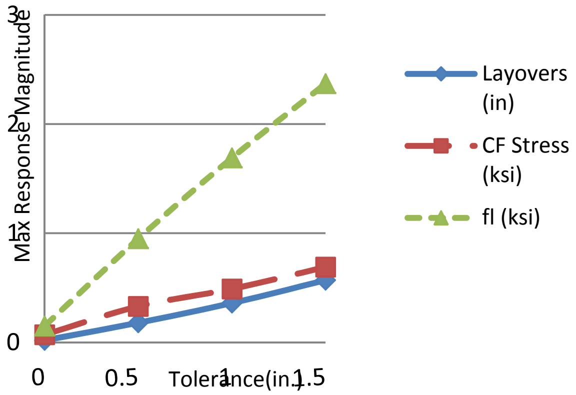


Figure 11: NISSS54 maximum responses under TDL, for TDLF based on LGA cambers, versus the camber tolerance

The camber tolerances have similar effects on the responses for TDLF or SDLF based on the 3D FEA cambers. Any deviations from the specified cambers change the final girder layovers and internal stresses. These increases are nearly linear since the nonlinearity in the structural system is minor.

The authors also studied the influence of one of the fascia girders being over-cambered relative to the other girders, as well as the influence of one of the interior girders being over-cambered relative to the other girders. For the case of SDLF based on LGA cambers, the maximum effect was caused by an increase in the camber of one of the fascia girders. For this case, when one of the fascia girders was over-cambered by 1.5 inches relative to the other girders, the maximum change in the girder layovers, cross-frames stresses and girder flange lateral bending stresses was 0.31 inches, 0.61 ksi, and 0.50 ksi.

One other tolerance that can have an important influence on the response is the concrete deck thickness tolerance. For TDLF, the cross-frames are detailed such that, ideally, the girders are plumb under TDL. Changes in the deck thickness cause a change in the concrete weight. An increase in the concrete weight leads to a nearly linear increase in the different responses. Figure 12 shows the maximum responses under TDL, for TDLF based on LGA cambers, versus the deck thickness tolerance. The corresponding responses for TDF based on 3D FEA are similar and are not shown for the sake of brevity.

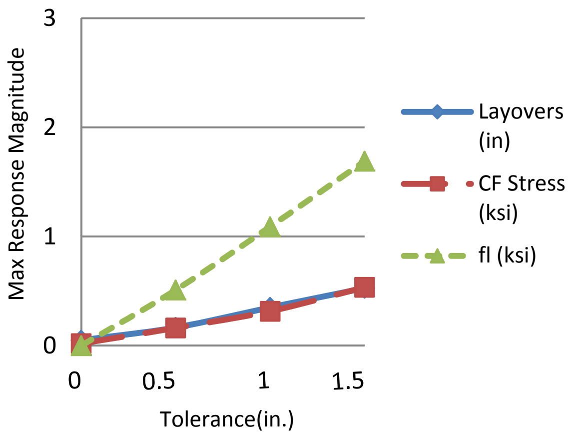


Figure 12: NISSS54 maximum responses under TDL, for TDLF based on LGA cambers, versus the deck thickness tolerance

It is important to note that while the above potential increases in the above cambers and deck thicknesses lead to measurable changes in the bridge TDL responses, these changes are relatively small compared to the overall bridge responses.

# 6. Effects of Framing Arrangements on Dead Load Fit Detailing Responses

The cross-frame arrangements can play an important role in the dead load detailing responses. A common concern in straight skewed bridges is the nuisance stiffness characterized as unwanted stiffness in secondary and primary members producing undesirable load paths in a structural system (Krupicka and Poellot 1993). This nuisance stiffness can occur near skewed supports. The original framing plan of NISSS54 that was studied in NCHRP 12-79 is shown in Figure 13. This framing has a significant amount of nuisance stiffness due to the close offset from the bearing lines to the first intermediate cross-frames as well as a large number of cross-frames that are staggered only a small distance from one another within the span.

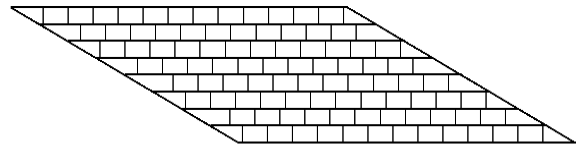

Figure 13: NISSS54 original NCHRP 12-79 framing plan

To simplify the discussion, this section only focuses on the effects of framing arrangements on the TDL responses of the NISSS54 bridge, for TDLF based on the 3D FEA cambers. Figures 14 and 15 show the girder vertical deflections due to TDL, calculated by “turning gravity on” in a 3D FEA, for the framing plans shown in Figures 13 and 1 respectively. These analyses are conducted without considering any dead load fit detailing effects. This is the type of 2D-grid or 3D FEA that is typically used to determine the girder camber profiles. One can observe that the girder vertical displacements in Figure 14 differ substantially from those in Figure 15. In Figure 14, the maximum displacements at the mid-span of the fascia girder differ from the corresponding displacements for the inner-most Girder 5 by 6.2 in. This behavior is due to the large number of cross-frames that are staggered by only a small distance apart.

The framing arrangement in Figure 13 provides a significantly stiffer transverse load path than the one in Figure 1. This causes the fascia girder to deflect more and the interior girder to deflect less under the TDL (compare the deflection profiles in Figure 14 to those in Figure 15). The framing plan shown in Figure 1 was chosen to mitigate this substantial transverse stiffness. Correspondingly, it can be seen from Figure 15 that the interior girder vertical displacements are almost identical, and the difference between the fascia girder mid-span displacements and the corresponding displacement of the most interior girder is only 1.2 in.

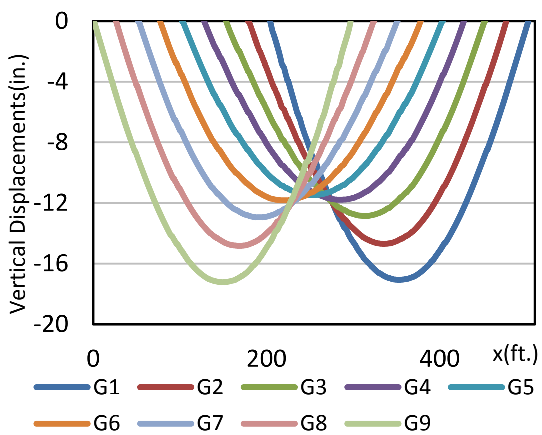


Figure 14: NISSS54 girder vertical displacements due to TDL for the original NCHRP 12-79 framing plan, calculated by 3D FEA without the consideration of any dead load fit detailing effects

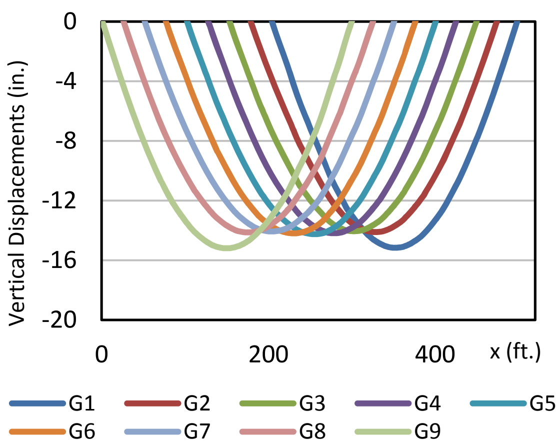


Figure 15: NISSS54 girder vertical displacements due to TDL for the alternative framing plan shown in Figure 1, calculated by 3D FEA without the consideration of any dead load fit detailing effects

It is of interest to investigate the effects of the above framing arrangements on the final girder elevations. These elevations are important to setting the deck elevation profiles. Figures 16 and 17 show the final girder elevations under TDL for TDLF based on 3D FEA for the framing plans shown in Figures 13 and 1 respectively. It can be observed that changing the framing arrangement causes a substantial change in the camber diagrams and a measurable but smaller change in the pattern of the final girder elevations. The effects of the TDLF detailing on the maximum final girder elevations are small.

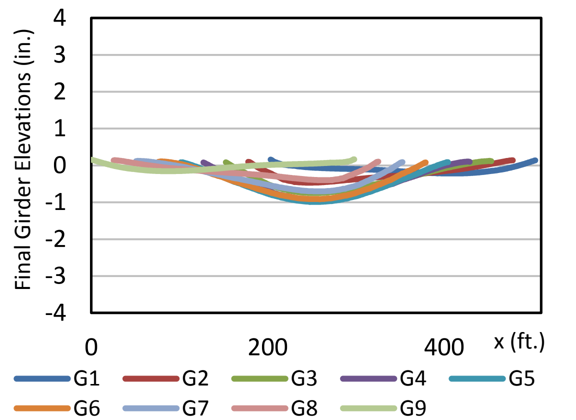


Figure 16: NISSS54 final girder elevations under TDL for the original NCHRP 12-79 framing plan, for TDLF detailing based on 3D FEA cambers

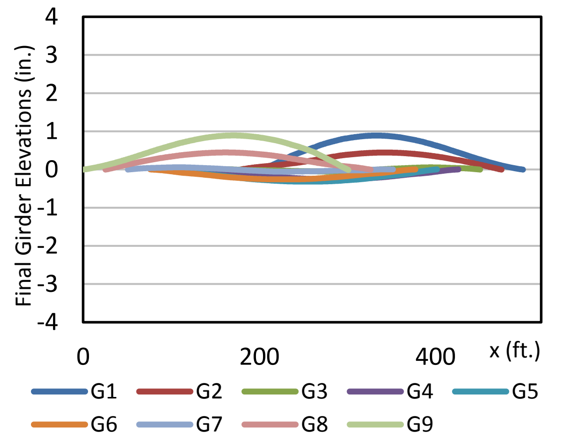


Figure 17: NISSS54 final girder elevations under TDL for the alternative framing plan shown in Figure 1, for TDLF detailing based on 3D FEA cambers

Table 4 shows the maximum responses due to TDLF for the original NCHRP 12-79 framing plan. From Tables 3 and 4, it can be observed that changing the framing arrangement of NISSS54 back to the original framing plan increases the cross-frame and lateral flange bending stresses significantly when the cambers are calculated from 3D FEA. However, when the cambers are calculated from LGA, the girder layovers and internal stresses are always close to the ideal zero under the targeted dead load condition, regardless of the framing arrangement.

Table 4: NISSS54 original framing plan maximum responses (layovers, cross-frame (CF) stresses, and flange lateral bending stresses ($f_\ell$)) under TDL, for TDLF based on 3D FEA and LGA cambers

| 3D FEA | | | LGA | | |
|---|---|---|---|---|---|
| Lay-overs (in) | CF stress (ksi) | $f_\ell$ (ksi) | Lay-overs (in) | CF stress (ksi) | $f_\ell$ (ksi) |
| 0.53 | 5.8 | 6.9 | 0.025 | 0.051 | 0.21 |

## 7. Conclusions

This paper has demonstrated that the camber profiles calculated from 1D LGA, 2D grid analysis, and 3D FEA for a straight skewed bridge can be substantially different. However, the final bridge geometries and responses obtained with SDLF or TDLF detailing are very similar. In fact, the use of cambers from 1D LGA gives the closest match to the ideal zero girder layovers and internal stresses under the targeted dead load conditions while the use of cambers from 2D grid and 3D FEA gives girder layovers and internal stresses that are small compared to the overall dead load responses under the targeted conditions. The paper has also shown that positive camber tolerances and deck thickness tolerances lead to a nearly linear increase of fit responses that are also relatively small. Finally, the framing arrangement is shown to have a significant effect on the bridge response. By properly arranging the cross-frames to alleviate the "nuisance" transverse stiffness, the girder layovers and internal stresses in the targeted dead load condition are decreased significantly for the different camber calculations and detailing methods.

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