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Web plumb influence on skewed I-girder, steel bridges during construction

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Abstract. At different stages during the construction of steel, I-girder bridges having severely skewed abutments, differential deflections between adjacent and interconnected girders cause rotations and deflections out of plane. These deformations are more pronounced during deck placement when appreciable additional dead load is added to the bridge and the girders are non-composite. As a result, girder webs can end up out of plumb at the completion of construction, especially at the supports. Although it is commonly desired by bridge designers and contractors to alleviate this out of plumbness via different erection and detailing strategies, out of plumbness effects on skewed bridge response at the completion of construction are not completely understood. The present research employs finite element analysis to study effects that different detailing methods have on girder stresses, vertical and lateral deformations, and cross-frame forces for single-span bridges with varying skew angles.

Keywords: Skewed, steel, I-girder, web, plumb, construction, finite element analysis

1. Introduction

The use of skewed bridges in highways is becoming more common. At complex intersections or river crossings where it is not possible to change the road alignment and the space limitations require the bridge supports to be non-perpendicular with respect to the bridge longitudinal axis, skewed bridges are useful. There are several publications in the literature that studied the effects of skew on the response of in-service steel structures. Skew effects have been shown to be more significant for skew angles greater than 30° [8, 9]. Other studies found that the maximum bending moments and vertical deformations in skewed bridges are less than those for similar right bridges [11]. However, torsional shears and rotations have been shown to be larger in skewed bridges, especially at the obtuse support corners [17].

Unlike completed skewed bridges, there are limited studies that focus on the behavior of these structures during construction. Norton et al. [16] and Choo et al. [7] examined different concrete pour methods on stresses and deformations in bridges with large skew angles. These researchers showed that the alignment of the screed can induce uneven distribution of dead loads across the superstructure. They found that pouring concrete parallel to skew can reduce the skew effects on superstructure. Other recent studies have developed simplified methods to calculate girders deformations in skewed bridges [4, 18] and investigated the effects of lateral flange bending on girders stresses and deformations at different stages of construction [14].

According to AASHTO and National Steel Bridge Alliance Steel Bridge Collaboration [1], the addition of dead load to the girders in a skewed, steel bridge during construction and the differential deflections that result cause the girders to rotate about their longitudinal axes. This behavior is similar to that in horizontally curved bridges. To compensate for the out of plumbness and to mitigate its possible adverse effects on bridge behavior, the common practice is to impose an initial rotation (twist) camber to the girders when connecting the cross

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frames. This approach requires careful detailing and fabrication of the girders and cross frames to account for the intended rotations. It also necessitates well thought out and strictly followed erection methods where the girders will need to be initially lifted and/or displaced laterally to accommodate and counteract the rotations that they will experience under dead load.

Different strategies may be selected by bridge designers and contractors for detailing and fabricating members that consider the loading condition under which the cross frames should be fit up between the girders, to ensure that the girder webs are vertical after construction. These fit-up conditions are commonly referred to as no-load fit, steel dead load fit and full dead load fit. If cross frames and girders are detailed for no-load fit or steel dead load fit conditions, they will be out-of-plumb after pouring the concrete deck. Thus, for the girders to be plumb at the end of the deck placement, they must be initially erected out of plumb according to the total anticipated girder rotations at the final position. This represents the full dead load fit condition for girders and cross frames. A more detailed discussion on the different detailing methods is provided in the next section.

There is a lack of research that evaluates the effects that web out of plumbness can have on skewed bridge response at the completion of construction. As a result, the necessity related to establishing the right detailing and erection procedure to attain the web plumb girders is unknown for bridges with different skew levels. Therefore, the current study aimed to investigate the effects of different detailing methods and the subsequent web position on skewed bridge behavior during construction. For this, the response of multiple idealized, single span skewed bridges with varying skew angles were investigated computationally.

2. Detailing methods

Based on AASHTO/NSBA [1], there are three common detailing methods for girders and cross frames in horizontally curved and skewed bridges. The first method is no-load fit that represents a theoretical condition in which the cross frames are installed between the plumb girders when no (or small) dead load is applied to the girders. This condition can be approached in construction by appropriate use of temporary bracing and shoring for the girders to mitigate deformations and stresses [5, 13]. Not surprisingly, due to application of steel or concrete dead loads after the temporary supports are removed, the initially plumb girders will rotate out of plumb to their final position. To limit this final out of plumbness, AASHTO/NSBA [1] discusses the steel dead load fit and full dead load fit methods under which the girders will hold a plumb position under steel dead load or full dead load, respectively. These methods require the members to be detailed and fabricated so that installation of the cross frames between the girders at the no-load condition (the shored structure) generates a rotation camber for the girders. That is, girders are rotated in the no-load condition such that the out of plumbness negates the anticipated girder rotations for the specified loading condition that was assumed for the fit method.

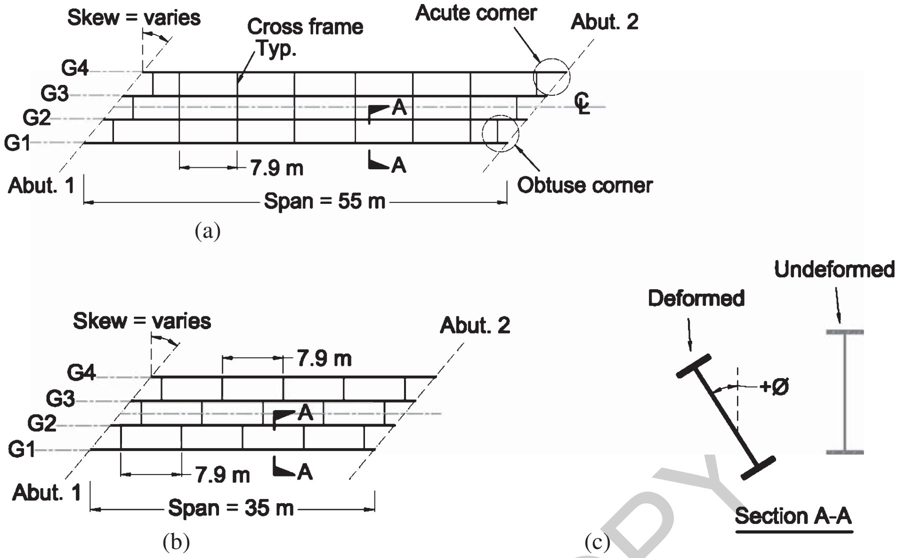
Moreover, to ensure appropriate performance of the detailing methods to reduce or eliminate out of plumbness, the girders and cross framers must be consistently detailed. Inconsistently detailing structural members in curved bridges has been shown to create serious fit-up problems that delay construction and can induce undesirable locked-in stresses on the bridge [6].

3. Bridge models

3.1. Representative bridges geometries

Effects of the different fit up methods on skewed bridge behavior were studied computationally. To establish a set of representative bridges to be analyzed, a statistical study was initially completed on a large inventory of actual bridges from Maryland, New York, and Pennsylvania. The main purpose of this initial study was to obtain statistically significant parameters for skew angles, girder and span numbers, span lengths and girder and cross frame spacings. Results for that initial study were published by Linzell et al. [12]. Based on the statistical results, six idealized, simple span skewed bridges were designed and modeled. Figure 1 shows general geometrical parameters for these bridges.

Single span bridges were selected for the study since skew effects have been shown to have more impact on single span bridge behavior than for multi-span bridges [7]. Other studies have also indicated that the differential deflection between girders and the resulting torsion are more pronounced for skewed bridges with intermediate span lengths (30.5 to 42.7) than those for small or large lengths [4, 10]. Two different span lengths were selected for the bridge models in this study: an intermediate span length of 35 m, and a relatively large span length of 55 m. For each span length, three dif-



(a)

(b)

(c)

Fig. 1. (a) Typical framing plan for span = 55 m; (b) typical framing plan for span = 35 m; (c) lateral girder deformation (out of plumb angle).

ferent skew angles were examined that represented a severely skewed bridge (skew = 60°), a moderately skewed bridge (skew = 20°) and a bridge with a skew angle between the two extreme cases (skew = 40°). In all bridges, four girders were spaced at 3.05 m to provide adequate width for two lanes of traffic with shoulders and barriers. As recommended in AASHTO LRFD Bridge Design Specifications [3] for skew angles more than 20°, cross frames were placed normal to the webs of the adjacent girders in all bridge models. These cross frames were placed in a staggered pattern for the entire length of the girders in the bridges with a span of 35 m, following common design practice for bridges with small to intermediate spans [1]. For the bridges with a span of 55 m, however, staggered cross frames were used only near the skewed abutments. Intermediate sections of the girders in these bridges had the cross frames positioned in a contiguous pattern. This is, again, a common approach for the design and construction of skewed bridges with large span lengths [1]. In all bridge models, the maximum cross frame spacing along the girders was assumed to be 7.9 m. This cross frame spacing was considered large based on skewed bridges examined in the initial inventory study.

The representative bridges were designed following AASHTO LRFD [3], assuming non-composite girder section for construction limit state and fully composite behavior between concrete deck and steel girders in service and strength limit states. A depth to span ratio (D/L) of approximately 27 (where D is the web depth and L is the girder length) and a section aspect ratio (D/bf) of approximately 4.5 (where bf is the flange width) were assumed for the entire girder lengths in all bridge models, following AASHTO proportion limits. X-shaped cross frames were selected to brace the girders.

3.2. *Finite element models*

The effects of different web out of plumb conditions on skewed bridge responses were investigated using the ABAQUS finite element program [2]. Only the steel superstructure of the bridge models were created using ABAQUS S4 R shell elements for the girder webs and ABAQUS B31 beam elements for the top and bottom flanges, stiffeners and cross frame members (see Fig. 2). Aspect ratios of approximately 1 were considered for all shell elements in the models. Element types and mesh sizes were selected based on Nevling [15].

All steel members were initially designed to stay within elastic range under the construction loads and therefore, an elastic modulus of 200 GPA was assigned to the steel elements in the models. The concrete decks were not modeled and only the loads due to concrete self weight were applied to the top flange of the girders. This in other words means that the entire deck was assumed to remain plastic with no composite action between the girders and the deck during placement. Although this assumption is not necessarily representative of actual field conditions, especially for long span bridges, incorporation of time dependent change in concrete modulus of elasticity has been shown to be insignificant for predicting stresses in the superstructure at the end of the

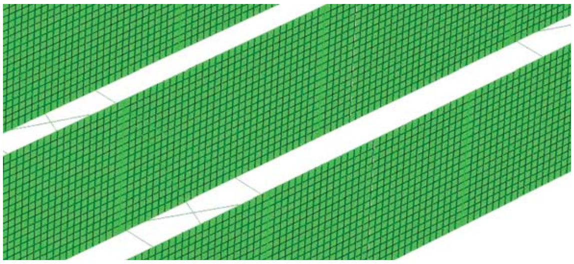


Fig. 2. Representative three-dimensional ABAQUS finite element model.

pour [7]. Nonlinear geometric effects were included for all analysis steps to account for higher order stresses and deformations in the superstructure.

To model the no-load fit condition, the bridge models were initially created considering all girders and cross frames were plumb; with zero web rotations. This initial condition represented, in an idealized fashion, the construction stage where the entire superstructure was erected and temporary supports were present under all girders. Steel dead load and concrete dead load were then applied to the bridges through two separate ABAQUS analysis steps.

Unlike the models for no-load fit, for steel dead load fit and full dead load fit conditions girders were generated with an initial rotation camber. The cross frames were assumed to be consistently detailed and fabricated for this condition and no locked-in stress or force were developed. Results from the two analysis steps in the no-load fit models assisted with finding the proper rotation angles for the initial twist camber for the other two methods. This camber was modeled by laterally moving the girder top flange nodes and changing the geometry of the other element nodes accordingly. Again, the initial condition for these two detailing methods corresponded to the position of the completed steel superstructure in presence of temporary shoring. Two analysis steps were also considered in these models for the application of steel dead load and concrete dead load.

4. Analysis results

Girder response in each bridge model was investigated for each of the fit up conditions that were studied for the two stages of construction discussed above; after erection of the girders and after placement of concrete deck. These two stages will be referred to as Stage A and Stage B, respectively.

4.1. Girder web rotations

For the first detailing method; no-load fit, Figs 3 and 4 show web rotations for external girders G1 and G4 in the bridge model having the smaller span length (span = 35 m) and maximum skew (60°). The sign convention for the rotations is based on the deformed shape depicted in Fig. 1c. Results in the figures show that after stages A and B, large rotations occurred at the girder abutments. Rotations for girders nearer the acute corners at each abutment (Abutment 1 for G1 and 2 for G4) are slightly larger than those for the obtuse corners (Abutment 2 for G1 and 1 for G4). Due to asymmetry of the bridge plan with respect to the longitudinal axis, maximum web rotations in the two girders have almost the same magnitude but opposite sign. The maximum rotation magnitudes for the six bridge models are shown in Table 1.

As discussed in the modeling section, findings from Figs 3 and 4 and Table 1 were also used to model the steel dead load fit and full dead load fit conditions. Figs 5–8 show web rotation angles for G4 in the bridges with the different span lengths and with skew = 20° and

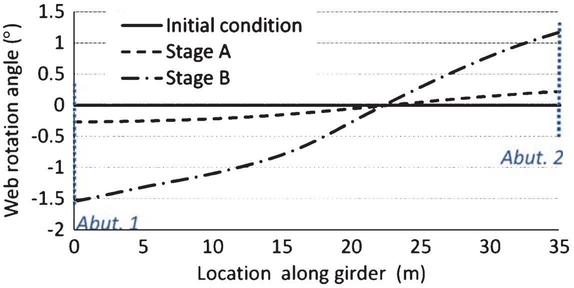


Fig. 3. G1 web rotations, no-load fit, span = 35 m, skew = 60°.

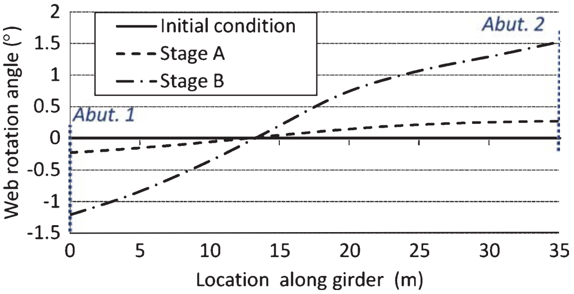


Fig. 4. G4 web rotations, no-load fit, span = 35 m, skew = 60°.

Table 1
Maximum girder web rotations, no-load fit

Span length	Skew	Web rotation angle	
		Stage A	Stage B
35 m	20°	0.06°	0.31°
	40°	0.13°	0.63°
	60°	0.27°	1.54°
55 m	20°	0.09°	0.30°
	40°	0.17°	0.60°
	60°	0.35°	1.00°

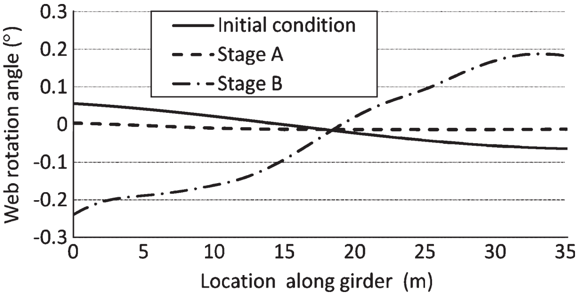


Fig. 5. G4 web rotations, steel dead load fit, span = 35 m, skew = 20°.

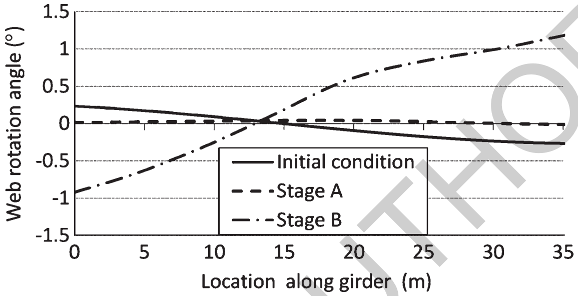


Fig. 6. G4 web rotations, steel dead load fit, span = 35 m, skew = 60°.

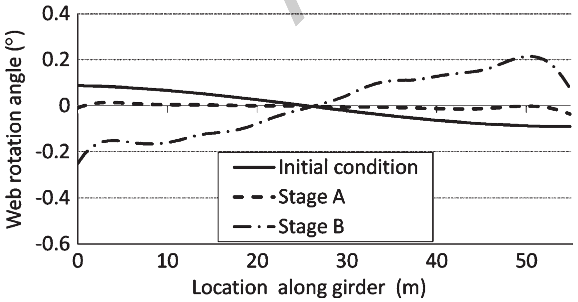


Fig. 7. G4 web rotations, steel dead load fit, span = 55 m, skew = 20°.

60° for the steel dead load fit condition. The girders were initially modeled out of plumb based on their anticipated web rotations after applying the steel dead loads. As expected, when compared against web rotations for no-load fit (Figs 3 and 4, Table 1), using a steel dead load fit can somewhat reduce web rotations at the final position. However, this reduction is insignificant for small span lengths (span = 35 m) and also for large skew angles when final rotations due to application of the full concrete dead load are very large.

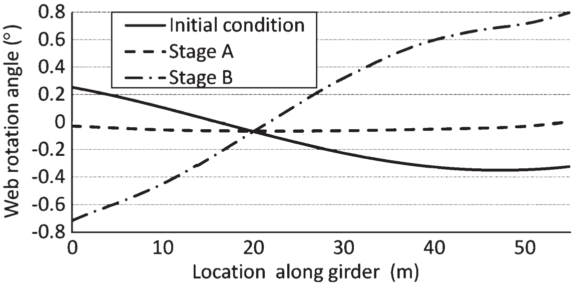


Fig. 8. G4 web rotations, steel dead load fit, span = 55 m, skew = 60°.

Full dead load fit web rotations for G4 in bridges with varying span lengths and skew = 60° are shown in Figs 9 and 10. For this method, generation of the initial rotation camber in the girders is shown to be largely able to accommodate the girder rotations at the final position for all bridges studied. These results confirm the effectiveness of the full dead load fit method for achieving girder web plumb conditions at the end of construction for a large range of skew angles and different span lengths.

4.2. *Girder vertical deformations*

Similar to web rotations, vertical deformations of the girders were also compared for the different detailing methods. The results show no marked effects on the vertical deformations for the bridges that were studied. The different detailing methods mainly affect the web rotations in girder sections near the abutments. At mid span locations, where the vertical deformations were larger and web rotations were small (see Figs 3–10), the effects of twist on vertical deformations were generally insignificant.

4.3. *Girder flange stresses*

Girders flange normal stresses in skewed bridges have two components; normal stress due to vertical bending and normal stress due to lateral bending of the flanges. The lateral bending stress is caused by girder differential deflections and the resulting twist. To study the effect of each detailing method on final girder stresses, top and bottom flange vertical and lat-

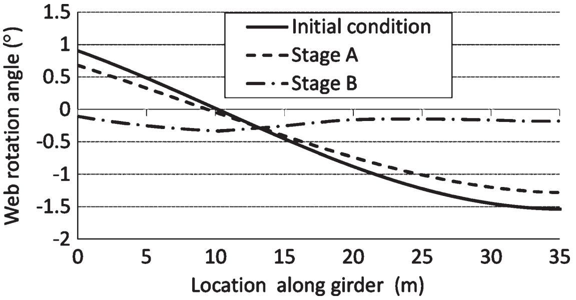


Fig. 9. G4 web rotations, full dead load fit, span = 35 m, skew = 60°.

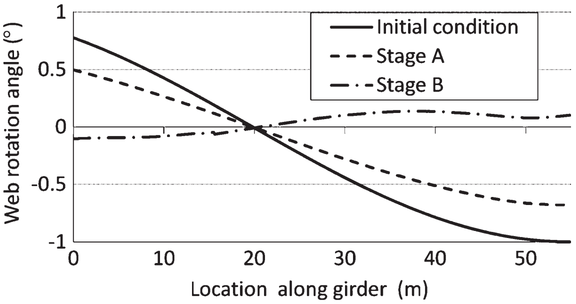


Fig. 10. G4 web rotations, full dead load fit, span = 55 m, skew = 60°.

eral bending stresses were determined for each method in the bridge models of this study.

Similar to the findings for vertical deformations, no beneficial or adverse effects were observed for vertical bending stresses for the different methods. Maximum bending stress for all bridges studied and for the three detailing methods ranged between 120 and 140 Mpa which occurred at mid-span. The same reason discussed for vertical deformations is valid here.

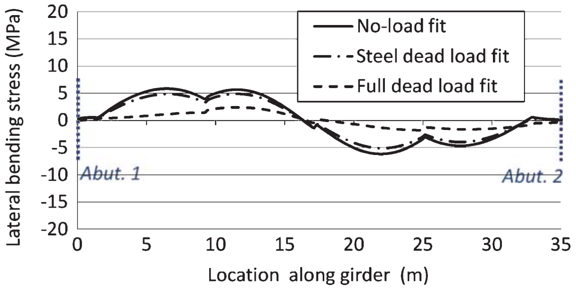


Fig. 11. G4 top flange lateral bending stress, span = 35 m, skew = 20°, stage B.

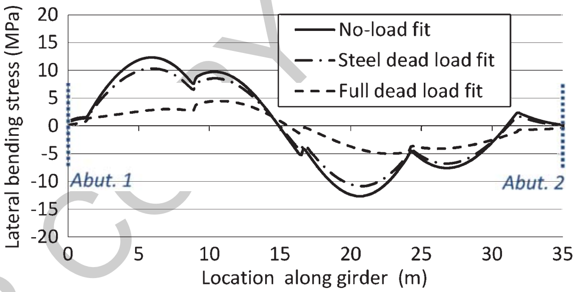


Fig. 12. G4 top flange lateral bending stress, span = 35 m, skew = 40°, stage B.

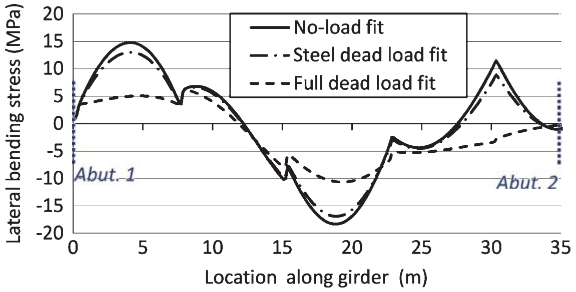
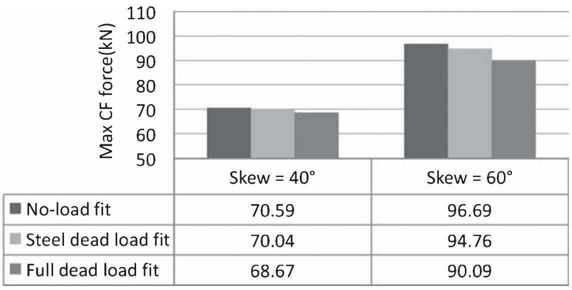


Fig. 13. G4 top flange lateral bending stress, span = 35 m, skew = 60°, stage B.

Results for the lateral bending stresses at the top flange tips (left tips of the top flange in the girder cross section in Fig. 1c) are shown in Figs 11–13 for G4 in the bridges with a span of 35 m and varying skew angles. The figures indicate that, for all detailing methods, maximum stresses occurred for girder sections at the obtuse corners near each abutment (Abutment 1 for G4) and also at mid span locations. These trends are more evident for the 60° skew bridge. In general, the full dead load fit and its resulting web plumbness, compare to the other two fit methods, can produce smaller lateral bending stresses in the girder flanges for almost the entire length of the girders in bridges with varying skew angles. This reduction is, however, more important for girder sections near the supports, where vertical bending stresses are small. At mid span, vertical bending stress dominates the total stress level in the girder flanges and, subsequently, changes in lateral bending stresses have less influence, especially for smaller skew angles. Also from Figs 11–13, the steel dead load fit method produced slightly smaller stresses in most of the girder locations, when compared to the no-load fit results. However the amount of change was not significant. Moreover, due to small lateral bending stresses in the girders of 20° skew bridge the effects of the different detailing methods in reducing the flange stresses is also insignificant for these bridges.



	Skew = 40°	Skew = 60°
■ No-load fit	70.59	96.69
■ Steel dead load fit	70.04	94.76
■ Full dead load fit	68.67	90.09

Fig. 14. Maximum force in cross frames, span = 55 m, stage B.

4.4. *Cross frame forces*

Unlike straight bridges, where cross frames and diaphragms are considered "secondary members", the interaction of bending and torsion in horizontally curved and skewed bridges renders these components primary load carrying members. During construction, cross frames play an especially important role in maintaining integrity, geometric control and stability by increasing girder torsional stiffness via the formation of a pseudo-box section and, as a result, can experience rather significant forces. Any changes to those force levels would be of interest from a design perspective. So, the effects of the different fit up methods on induced forces in cross frames were examined for the studied bridges.

As can also be inferred from flange tip stress results, larger forces occurred at cross frames near the obtuse corners and also mid span of the bridge models studied. When the maximum force in all cross frame members in each model was compared, a general trend could be observed for the effects of the different fit up conditions. Fig. 14 shows maximum force in the cross frames at the final stage of construction for the three fit up conditions in bridges with a span of 55 m. Full dead load fit, in all cases, resulted in the lowest maximum forces and this result was more pronounced for the 60° skew angle bridge. For this bridge the maximum full dead load fit axial force was 7% smaller than that for the no-load fit condition. However, for the other skew angles that were examined the effects of different fit up methods and corresponding web plumb conditions were not significant on cross frame forces at the end of construction.

5. Conclusions

Due to the differential deflections between girders of skewed bridges, the girders may end up with large lateral rotations. The effects of the web out of plumbness on girder behavior during construction were studied using FEA models for multiple idealized bridges with varying span lengths and skew angles. In these models, three common detailing methods and fit up conditions for cross frames and girders in skewed bridges were examined. The significance of achieving the web plumb condition in bridges with different skew angles was investigated by comparing girder deformations and stresses and cross frame axial forces.

No significant change was observed for girder vertical deformations and vertical bending stresses when the level of web out of plumbness varied as a result of the different fit up methods. The full dead load fit condition (detailing the girders based on the anticipated girder rotations after placing the concrete deck) produced smaller lateral bending stresses in the girder flanges and this effect is more pronounced for bridges having severely skewed supports. Also, using a full dead load fit generated slightly smaller cross frame axial forces in the 60° skew bridge in comparison to the other fit up conditions. However, no marked difference was observed between maximum cross frame forces for the different fit up conditions for the 20° and 40° skew bridges.

For the steel dead load fit condition (detailing the girders based on the anticipated girder rotations after applying dead load from steel member self-weights), the girders will end up with smaller out of plumb rotations at the completion of construction compare to the no-load fit condition. However, this method was generally found to have small changes on stresses and forces in structural members for the different skew levels studied.

To summarize, irrespective of span length, bridges with large skew angles (60° here) that have out of plumb girders at the end of construction can be expected to experience increased stresses and forces in structural components due to large lateral deformations in the girders that can induce higher order stresses and forces. For these bridges, care should be taken when detailing and fabricating the members and also during erection to reduce the web out of plumbness. However this study showed that for a large range of skew angles (smaller than 40°) web out of plumb effects on bridge response are limited.

Acknowledgments

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