



Influence of staggered cross-frame layout on the behavior of horizontally-curved steel I-girder bridges

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Abstract

Cross-frames are typically provided contiguously in the radial direction in horizontally curved I-girder systems. The radial arrangement of cross-frames results in larger unbraced lengths in the outermost girder and smaller unbraced lengths in the innermost girder. Because cross-frames act as primary load-carrying members in curved girder bridges, altering cross-frame layouts can improve load distribution between girders. This paper investigates the effects of providing a staggered cross-frame layout on the behavior of a single-span horizontally curved steel I-girder bridge during construction. A staggered cross-frame arrangement, which is observed to be advantageous in skewed I-girder bridges, is similarly examined here for curved I-girder bridges. These studies compare deflections, web rotations, cross-frame stresses, and bottom flange stresses for staggered cross-frame layouts with those from a radial contiguous layout using finite element analyses. Results indicate that a staggered cross-frame layout provides nearly the same buckling strength as a radial layout. However, increased web rotations and deflections in the outer girders and reduced web rotations in the inner girders are observed. Additionally, cross-frame normal stresses decrease slightly. The studies suggest that a strategically selected combination of radial and staggered cross-frame layouts can result in an overall improvement across design parameters.

1. Introduction

Horizontally curved steel I-girder bridges provide an economical solution for highway system crossings where roadway alignment requires a smooth, curved transition across the bridge and limited space is available for interior piers. When vertical loads are applied on a horizontally curved I-girder, a torsional moment is generated about the girder's longitudinal axis. This torsional moment is because of the offset of the center of loading of each span in a curved girder from the imaginary chord drawn between the supports for that span. When multiplied by the vertical load, this offset or eccentricity results in a torsional moment, which varies along the span of the girder.

I-girders have relatively small St. Venant torsional stiffnesses and resist torsion through warping, typical of thin-walled open sections. The total state of normal stress in an I-shaped girder is a combination of any axial stress, primary in-plane flexural stress, lateral/out-of-plane bending

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stress, and warping normal stress (Coletti and Yadlosky 2005). Lateral flange bending is a consequence of curvature. Figure 1 shows a typical plot of the stresses versus the normalized length of the middle girder in a three-girder curved bridge (the bridge layout is shown in the top right corner of the plot). Lateral bending stresses are clearly a significant part of the total stresses in curved girders. These stresses can be restricted by placing enough cross-frames in the structure.

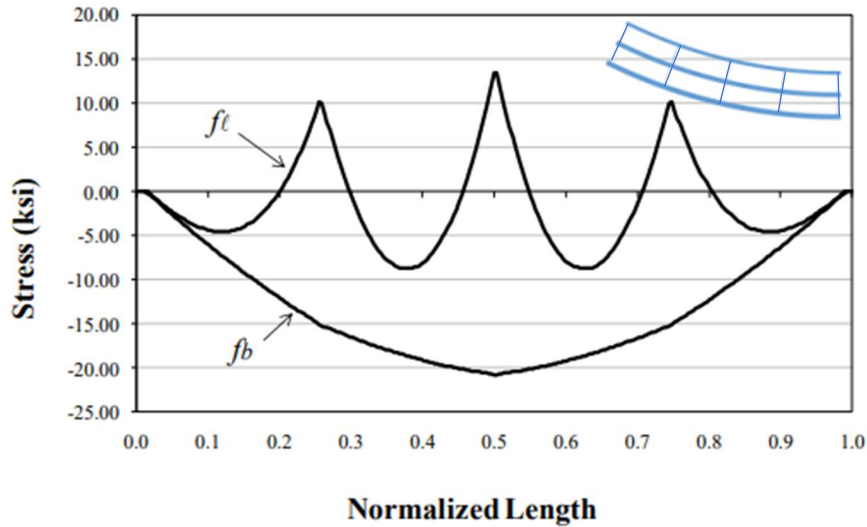


Figure 1: Lateral flange bending stress, f_l & major-axis bending stress, f_b in a curved girder (Grunauer 2011)

Additionally, torsion causes significant deformations in I-girders. Horizontally curved girders deflect vertically and undergo significant twisting and warping. The same behavior in a curved girder system results in the global load-shifting effect. The torsional moment arising due to the offset of the center of loading of the curved girder system is resolved into force couples, which are additive to the primary load in certain girders and relieving in others. Fig. 2 illustrates how the load shifts from the innermost to the outermost girder due to this effect.

Global load shifting is accomplished by transferring the loads from one girder to another via cross-frames, making cross-frames primary load-carrying members. Given that cross-frames act as primary load-carrying members in curved bridges, the cross-frame layout can potentially modify the behavior of an I-girder bridge during construction and service.

In bridges with skew supports, right cross-frames connect two girders at points with differential vertical deflections. In such cases, the cross-frames force the girders to rotate together to accommodate the differential vertical deflections. This behavior may develop large forces in the cross-frame members, especially in those near the supports. Similar to curved bridges, the cross-frames in skewed bridges provide a secondary load path, which considerably affects the system's behavior.

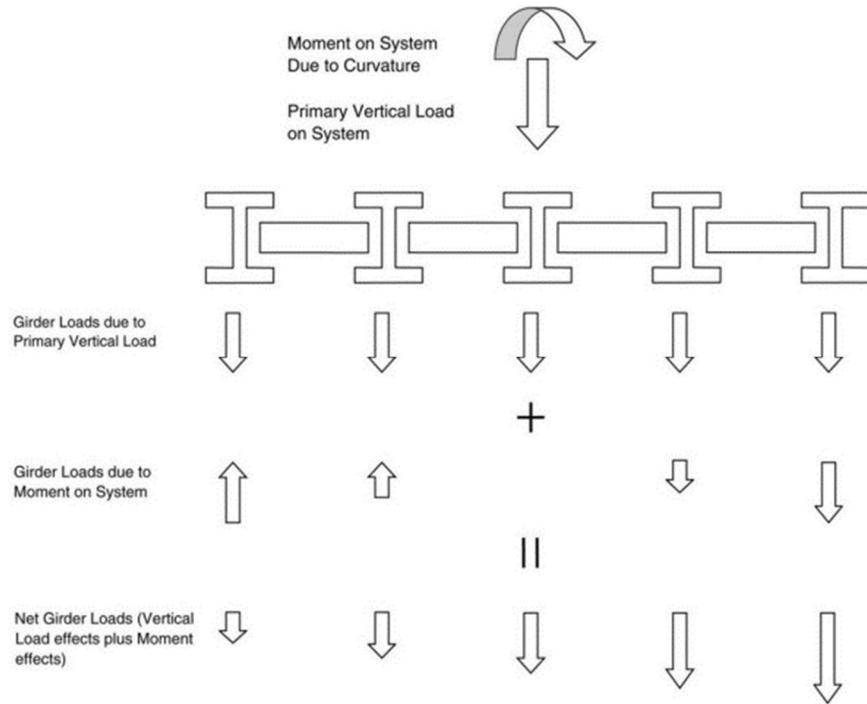


Figure 2: Global load shifting phenomenon in a curved bridge system (Coletti and Yadlosky 2005)

Straight girder bridges with skewed supports and horizontally curved bridges with normal supports show similar behavior when subjected to vertical loading. In horizontally curved bridges, braces are commonly placed between girders in the radial direction and normal to the girder webs. This pattern results in smaller brace spacings for interior girders, which generally experience lesser deformations and rotations, and larger brace spacing for exterior girders with greater deformations and rotations. This means using a radial arrangement for the cross-frames could result in a less-than-optimal design. Staggered cross-frame layouts, wherein the cross-frames are not along the same radial line, have been previously found effective in skewed girder bridges and may also benefit horizontally curved bridges.

This paper presents the effects of providing staggered cross-frame layouts in horizontally curved bridges with normal supports. All the bridge models considered in this study have the same girder depth-to-spacing ratio and a “V-type” or a “K-type” cross-frame configuration. This paper does not consider the effect of cross-frame detailing, and all the models studied herein employ no-load fit detailing of cross-frames.

2. Brief review of cross-frame layouts previously studied for curved and skewed bridges

The effect of a skewed cross-frame plan, such as shown in Fig. 3, was studied by Sharafbayani and Linzell (2012), where the skew was oriented in such a way that the cross-frame spacing at interior and intermediate girders was greater than that when the cross-frames were placed radially.

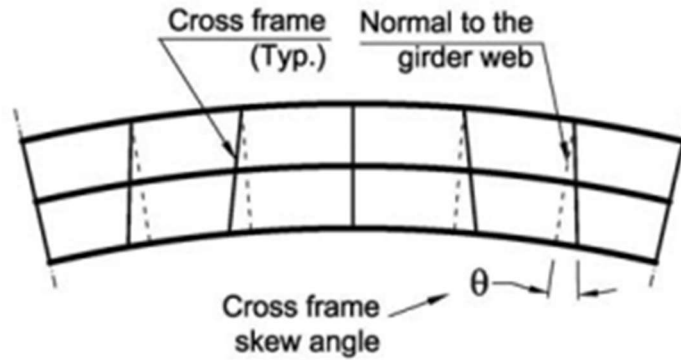


Figure 3: Schematic of a skewed bracing layout (Sharafbayani and Linzell 2012)

They first analyzed a single-span three-girder bridge model with cross-frames skewed at 10° and 20° and observed that the web rotations for the outer and middle girders, along with the in-plane vertical deflections of the outer girder, reduced significantly. In contrast, the deflections in the innermost girder increased (implying that the skewed cross-frame arrangement has led to a more uniform distribution of loads between the girders). Further, a significant rise in the flange tip stresses for the interior girder was observed (however, these were well below the maximum allowable stress), while the maximum stresses in cross-frames were slightly reduced. All these observations were more pronounced when the skew angle was 20° . This study was extended to a single-span bridge with larger cross-frame spacing and a two-span bridge with skewed cross-frames (Sharafbayani and Linzell 2014), where they made similar observations.

Using skewed bracing appeared to transfer the loads more effectively, in part, from the exterior girders to the interior girders, and, as a result, deformations and stresses decreased in more critical components that experienced more significant curvature effects. It could also reduce the required number of intermediate cross-frames for a given curved bridge geometry while maintaining necessary stress and geometric control during construction.

Grunauer (2011) and Wang et al. (2011) studied cross-frame layouts in skewed bridges. Wang et al. (2011) compared the behavior of skewed bridges with a staggered cross-frame and a continuous cross-frame layout. Laboratory tests were initially conducted on a three-girder system with skewed supports, having only one line of intermediate cross-frames at midspan. The axial forces in the cross-frames for the staggered layout were nearly one-tenth of the axial forces for the continuous layout. The authors then tested analytical models of bridges with multiple intermediate cross-frames considering two staggered layouts. The buckling analyses suggested that the staggered layouts did not significantly affect girder stability, i.e., the eigenvalues obtained from the bridge with a staggered layout and the continuous one were nearly the same. A staggered layout with increased spacing (30 ft or 9.14 m, the upper limit specified by AASHTO (2020)) did not particularly affect girder stability either. This means that it is possible to use fewer cross-frames when a staggered arrangement is considered.

This paper aims to understand the effects of providing a staggered layout in horizontally curved bridges with normal supports.

2. Finite Element Modeling

The bridge models presented here are analyzed using ABAQUS (2018). The results are validated with the experimental results from the Curved Steel Bridge Research Project (CSBRP, Jung 2006). ABAQUS S4R shell elements are used to model girder webs and flanges. S4R shell elements are 4-node reduced integration elements employing reduced integration to compute the stiffness matrix. ABAQUS B31 beam elements are used to model transverse stiffeners, connection plates, bearing stiffeners, lower lateral bracing, and cross-frame members.

All the connections in the bridge are modeled as rigid-type connections. These include cross-frame to connection plate, transverse stiffener to girder web and flanges, and girder flange to web connections. The gusset plates are not modeled explicitly, and the cross-frame pipe members are connected at the midpoint of the bottom chord using a rigid connection. Cross-frames are connected to connection plates using a rigid connection at the depth mentioned in the Curved Steel Bridge Research Report (Jung 2006; Grubb and Hall 2019). No weld is modeled anywhere. Full-depth transverse stiffeners are used, and their placement and orientation details are taken from the Curved Steel Bridge Research Report. A rigid-type connection connects the lower lateral bracing to nodes at the bottom web-flange junction.

Boundary conditions resemble the experimental conditions adopted from previous research (Linzell 1999). These are shown in Fig. 4. The bottom flange node at the flange-web junction at each bearing location is restrained against vertical displacement. These nodes for G2 are restrained against radial displacement as well. A tangential restraint is provided at the neutral axis of G2 at Station 1L to represent the effect of the end frame used in the experiment that prevented the structure from rigid body rotation in the tangential direction.

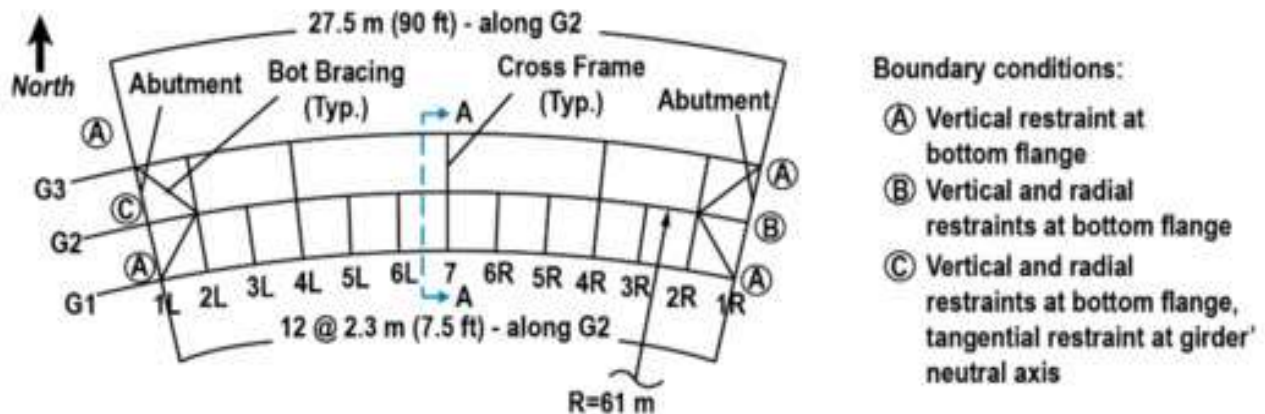


Figure 4: Framing plan and boundary conditions used for CSBRP phase-1 bridge (Linzell 1999)

Linear elastic material properties are used as all the tests were completed in the elastic range (Grubb and Hall 2019; Sharafbayani 2012). However, non-linear geometric effects are included to account for higher-order stresses and displacements resulting from the curvature of the bridge. Thus, for each section defined in ABAQUS, the properties defined are density, Young's modulus of elasticity, and Poisson's ratio of steel.

Following a mesh convergence study, a mesh with 12 elements along the web depth, four elements along the interior flange widths, and six elements along the exterior flanges are used. This is similar to the recommendations by Chang (2006).

A four-girder single-span bridge with normal supports selected for the current study was designed by Sharafbayani (2012) for the AASHTO (2012) strength limit state. The FE model of this bridge employs the same modeling techniques validated earlier. This bridge is a tightly curved I-girder bridge with a centerline radius of 61 m and a span of 27.5 m. It consists of four curved girders spaced at 2.67 m. The dimensions of the webs and flanges of all four girders are listed in Table 1. Full-depth stiffeners are used at cross-frame locations (connection plates), in-between connection plates (intermediate transverse stiffeners), and at bearing locations (bearing stiffeners). Each stiffener is 0.5 inch (1.27 cm) thick and is provided on both sides of the web. Cross-frames are made of hollow pipe sections of 5 in (127 mm) diameter and 0.25 in (6.35 mm) thickness, and are placed at a uniform subtended angle of 0.075 (i.e., $L_b = 0.075R$).

Table 1: Girder dimensions of the 4-girder curved bridge used for the study

Girder	Top flange ($b_f \times t_f$) in cm	Web ($h_w \times t_w$) in cm	Bottom flange ($b_{fc} \times t_f$) in cm
G1 (innermost)	30.5×2.5	122×0.95	30.5×2.5
G2 (intermediate)	35.6×2.5	122×0.95	35.6×2.5
G3 (intermediate)	40.6×2.5	122×0.95	40.6×2.5
G4 (outermost)	45.7×2.5	122×0.95	45.7×3.5

The bridge is analyzed for loading during construction. Therefore, the weight of the plastic concrete deck, formwork, and reinforcement is also considered in addition to the self-weight of all the steel components. Other construction loads due to equipment and machinery are not considered for simplicity. A uniform pressure load is modeled on the top flange of each girder. Line loads representing the couple due to deck overhang are modeled at the innermost and outermost girders. The detailed calculation of loads is adopted from Jung (2006) and given in Table 2. Fig. 5 shows the FE model with the applied loading.

Table 2: Construction loading considered

Girder	Pressure load (Pa)	Line load (top flange, N/m)	Line load (0.921m below, N/m)
G1	43997	2635	2635
G2	41789	NA	NA
G3	36565	NA	NA
G4	29331	2635	2635

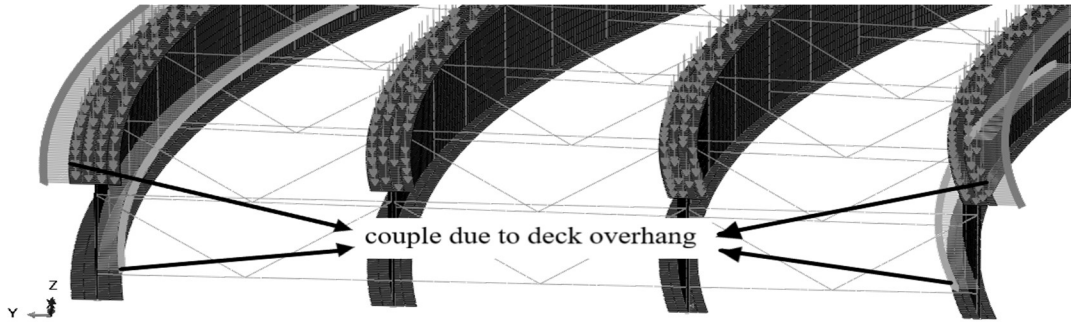


Figure 5: Loading during construction: pressure loads and line loads

Boundary conditions similar to those used for the CSBRP bridge are also used in this model. The bottom flange nodes at the flange-web junction at each bearing location are restrained against vertical displacements. These nodes for G2 are restrained against radial displacement as well. Tangential restraint is provided at the neutral axis of G2 at one end (refer to Fig. 6).

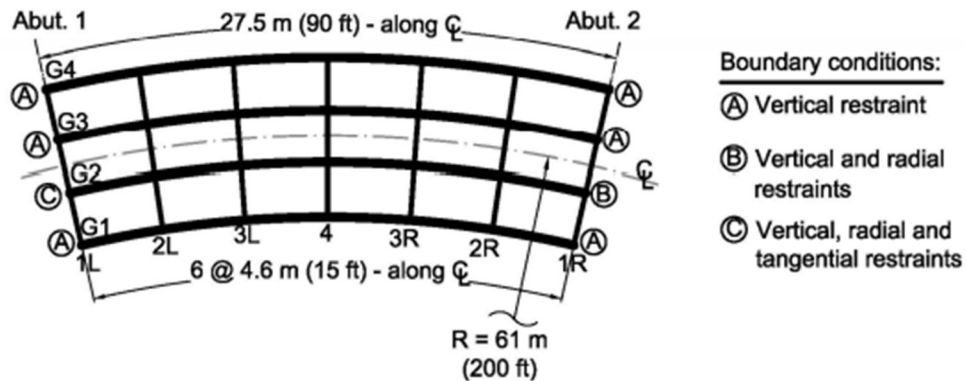


Figure 6: Framing plan and boundary conditions – Test Bridge (Sharafbayani (2012))

3. Different cross-frame layouts

This section examines the effect of staggering the cross-frames in horizontally curved bridges. The parameters studied include – the system stability, web rotations of all four girders, girder vertical deflections, the maximum axial stresses in the cross-frames, and the bottom flange tip stresses.

3.1 Staggered layouts

The cross-frame spacing is maintained in studying the staggered layout as in the test bridge model (except at the supports). The total number of cross-frames is the same in the two models studied – staggered layouts 1 and 2, as shown in Fig. 7. The first eigenvalues for staggered layouts 1 and 2 are 2.11 and 2.13, respectively. Both these values are less than the first eigenvalue, 2.16, for the test bridge (Fig. 6). This implies that the staggered layout does not significantly affect the overall bridge stability.

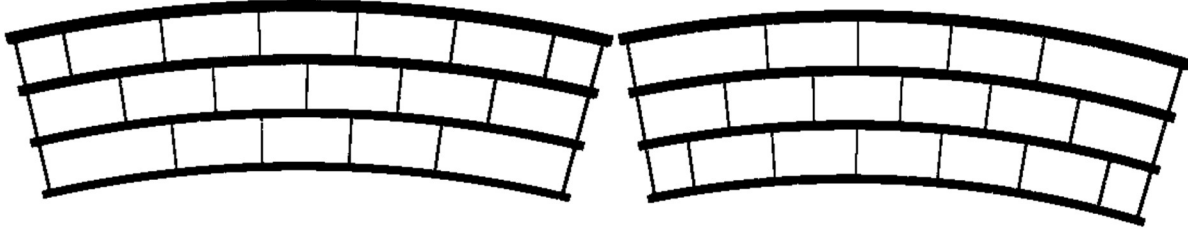


Figure 7: Staggered Layout 1 (left) and Staggered Layout 2 (right)

3.2 Web Rotations

Staggering the cross-frame layout results in reduced peak web rotations in the inner girders G1 and G2 (shown in Fig. 8) and increased peak web rotations in the outer girders G3 and G4 (shown in Fig. 9).

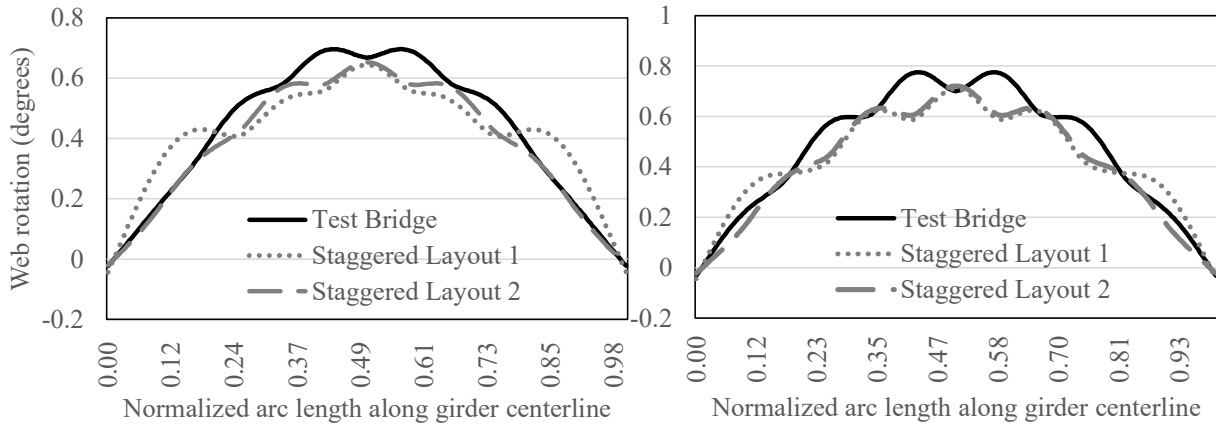


Figure 8: G1 (left) and G2 (right) web rotations – staggered layouts

In staggered layout 1, this behavior could be attributed to the uneven distribution of cross-frames – eight in the outer bay (between G3 and G4) and six in the inner bay (between G1 and G2). However, a similar behavior was also observed in staggered layout 2. This suggests that the reduced peak web rotations in inner girders and increased peak web rotation in outer girders result from staggering the cross-frame layout, which decreases the bridge's transverse stiffness.

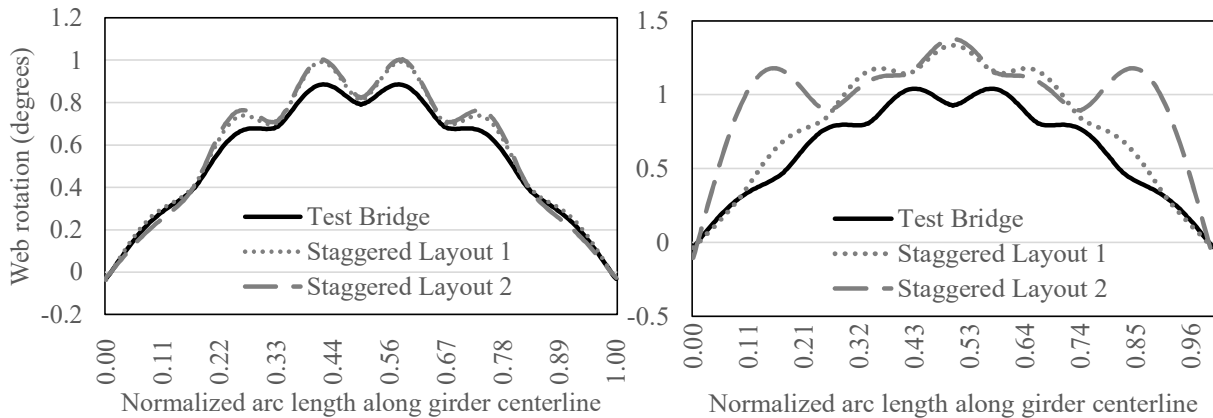


Figure 9: G3 (left) and G4 (right) web rotations – staggered layouts

3.3 Girder maximum vertical deflections

Staggered layout 1 and staggered layout 2 produce nearly the same maximum vertical deflections in each of the four girders (G1, G2, G3, G4). It is observed from Fig. 10 that in the intermediate girders G2 and G3, the maximum vertical deflections decrease compared to those of the girders in the test bridge. In contrast, the maximum vertical deflections increase in the fascia girders G1 and G4. This increase is more prominent in the outermost girder G4.

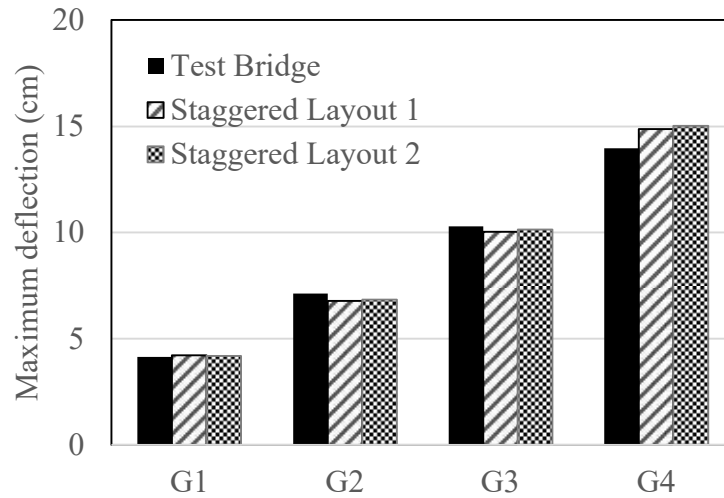


Figure 10: Girder maximum vertical deflections – staggered layouts

3.4 Maximum normal stress in the cross-frame bottom chord

Fig. 11 shows that staggered layout 2 produces smaller bottom chord normal stresses than the test bridge at similar locations, i.e., 2L, 3L, 4, or 4L for the cross-frames between the innermost girders G1 and G2. Staggered layout 1, however, results in a slight increase in stress.

Nevertheless, the maximum stress in layout 1, between G1 and G2, which occurs at 3L (40 MPa), is still 11% smaller than in the test bridge, between G1 and G2, which occurs at 4L (45 MPa).

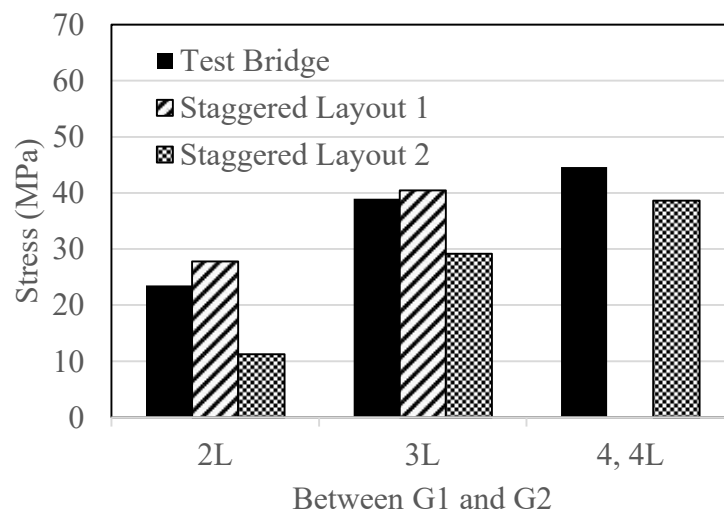


Figure 11: Maximum normal stresses in bottom chords of cross-frames between G1 and G2 for different layouts

In the cross-frames between G2 and G3, both staggered layouts 1 and 2 result in nearly the same bottom chord normal stresses at each location (2L, 3L, 4) as shown in Fig. 12. Both the staggered layouts result in slightly lower stresses than the test bridge.

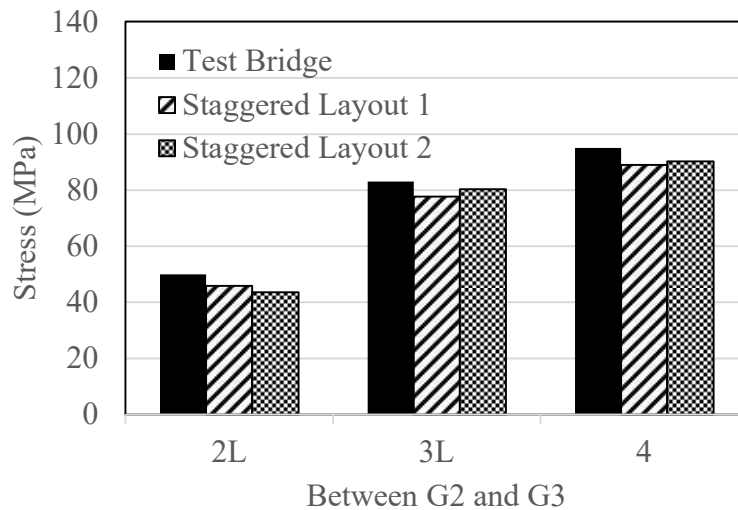


Figure 12: Maximum normal stresses in bottom chords of cross-frames between G2 and G3 for different layouts

Fig. 13 shows that the maximum cross-frame bottom chord normal stress between G3 and G4 occurs at 4L for staggered layout 1, and it is nearly equal to that of the test bridge at 4, which is 115 MPa. Staggered layout 2, however, results in a slight decrease in these stresses. The maximum stress in layout 2, between G3 and G4, is 107 MPa, which is 7% smaller than the maximum stress in the test bridge (115 MPa).

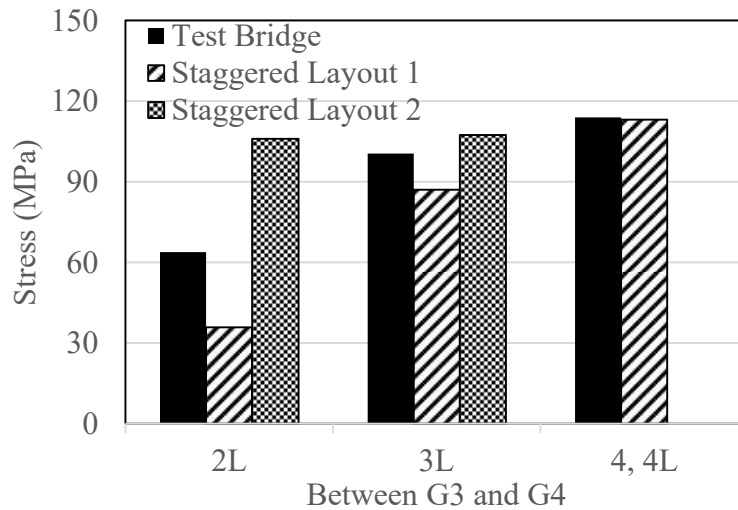


Figure 13: Maximum normal stresses in bottom chords of cross-frames between G3 and G4 for different layouts

3.5 Bottom flange exterior tip stresses

The variation of bottom flange exterior tip normal stresses across the span is studied for all four girders, and it is observed from Figs. 14 and 15, that for G1 and G3, there is a slight increase in the peak stress values when staggered layouts are used, whereas the Figs. indicate that the two layouts result in similar peak stresses for G2 and G4. Interestingly, layouts 1 and 2 result in nearly the same stress distribution for all four girders despite the different cross-frame locations.

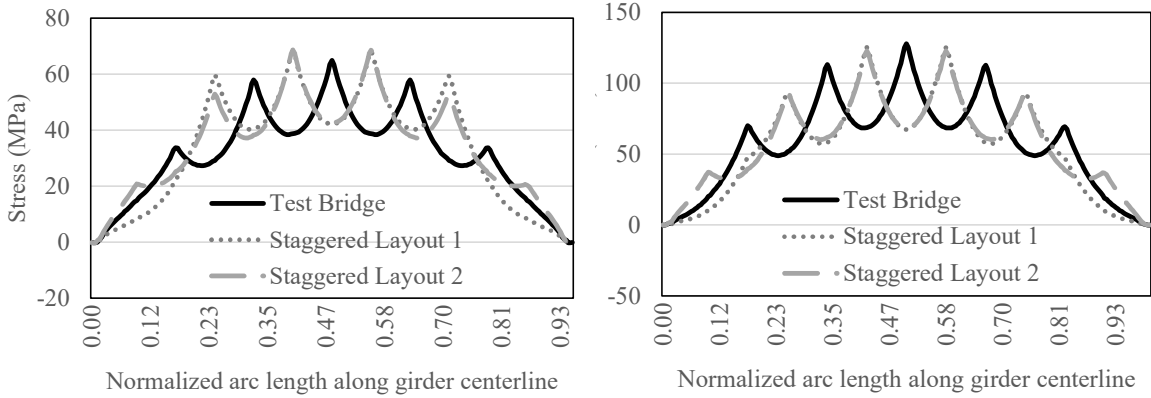


Figure 14: G1 (left) and G2 (right) bottom flange exterior tip normal stresses - Staggered Layouts

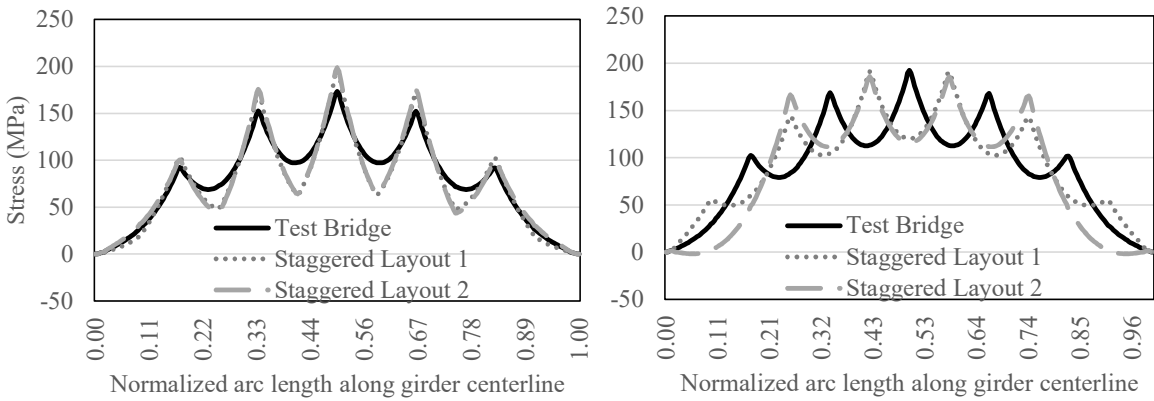


Figure 15: G3 (left) and G4 (right) bottom flange exterior tip normal stresses - Staggered Layouts

The local peaks in each plot depend on the location of the cross-frames. Therefore, the local peaks of the staggered layouts do not coincide with the local peaks of the test bridge. However, this is not true for G3, where local peaks of the staggered layouts and the test bridge coincide. This implies that the cross-frames that lie towards the inside of a girder dominantly decide where the local peaks of flange tip stresses occur.

4. Conclusions

This paper examines the effect of using staggered cross-frame layouts on the response of horizontally curved I-girder bridges. The cross-frames are oriented radially, or normal to the curved I-girder webs, but are not aligned in a contiguous line at any bridge cross-section. The paper reports the influence of two different staggered layouts compared to a contiguous radial layout using the “K-type” cross-frames in a single-span four-girder bridge used in the CSBRP. The cross-frame spacings are kept uniform in all studies reported here. The key parameters used in these comparisons include the overall stability, the web rotations, the vertical deflections, the bottom chord stresses, and the bottom flange tip stresses. The important findings are summarized below:

1. Using a staggered cross-frame layout has a negligible impact on the buckling strength of the bridge (a decrease of 1.4% is observed compared to a contiguous radial layout).

2. Staggering the cross-frames reduces the peak web rotations in the inner girders G1 and G2, and increases the peak web rotations in the outer girders G3 and G4.
3. The vertical deflections decrease in the inner girders G2 and G3, while they increase in the fascia girders G1 and G4 for the staggered configurations in the present studies.
4. Staggering the cross-frames has little influence on the bottom chord stresses compared to the stresses in contiguous layouts.
5. When using staggered layouts, the bottom flange tip stresses increase for some girders while they decrease or remain the same for others.

The preliminary findings presented here suggest that one may use a strategic combination of contiguous and staggered cross-frame arrangements, along with non-uniform brace spacing, to arrive at a more optimal layout.

Acknowledgments

We acknowledge the support of the Science and Engineering Research Board of India and the Indian Institute of Technology Madras for their support of this work.

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