Steel and Composite Structures, *Vol. 32, No. 3 (2019) 325-336*
DOI: https://doi.org/10.12989/scs.2019.32.3.325

Improved bracing systems to prevent exterior girder rotation during bridge construction

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(*Received November 8, 2018, Revised April 29, 2019, Accepted July 3, 2019*)

Abstract. Concrete placement and temporary formwork of bridge deck overhangs result in unbalanced eccentric loads that cause exterior girders to rotate during construction. These construction loads affect the global and local stability of the girders and produce permanent girder rotation after construction. In addition to construction loads, the skew angle of the bridge also contributes to girder rotation. To prevent rotation (in both skewed and non-skewed bridges), a number of techniques have been suggested to temporarily brace the girders using transverse tie bars connecting the top flanges and embedded in the deck, temporary horizontal and diagonal steel pipes placed between the webs of the exterior and first interior girders, and permanent cross frames. This study includes a rigorous three-dimensional finite element analysis to evaluate the effectiveness of several bracing systems for non-skewed and several skewed bridges. In this paper, skew angles of 0°, 20°, 30°, and 45° were considered for single- and three-span bridges. The results showed that permanent cross frames worked well for all bridges, whereas temporary measures have limited application depending on the skew angle of the bridge.

Keywords: bracing systems; deck overhang deck; exterior girder rotation; skewed bridge; non-skewed bridge; construction loads; steel girders; finite element analysis

1. Introduction

During the construction of bridge decks, transient construction loads on the overhanging portion of the deck are supported by steel brackets which are usually spaced at 0.91 to 1.83 m (3 to 6 ft.) along the length of the bridge. The overhang is typically proportioned so that the same size section can be used for both the interior and exterior girders. This practice leads to economical designs but can lead to excessive rotation of the exterior girders. In addition, the girders are assumed by designers to be temporarily braced against longitudinal rotation during constriction. In reality, construction of deck overhangs often results in torsional moments and rotations act on the exterior girders that are not generally considered during design. These moments can cause permanent rotations of the exterior girders leading to differential vertical deck edge deflection, structurally weaker decks, less concrete cover for rebars, and overall structural instabilities during construction, to name a few, as shown in Fig. 1.

Triangular steel brackets are commonly used as supporting elements for bridge deck overhang to transfer loads to the supporting exterior girders. For steel girder bridges, these loads can result in local instabilities (Shokouhian and Shi 2015, Gupta *et al*. 2006, *Kim et al*. 2018) leading to permanent stresses or rotations between diaphragms. Global instability, which can lead to a complete failure of the bridge during construction, is generally considered for concrete girder bridges which tend to rotate as rigid bodies (Yang *et al*. 2010, Haskett *et al*. 2009, Fasl 2008). The efficiency of individual elements including overhang steel brackets and threaded hangers is investigated in previous studies (Ariyasajjakorn *et al*. 2006, Clifton and Bayrak 2008, Grubb 1990), but the effectiveness of girder rotation prevention systems is not typically evaluated and is the focus of this paper.

Exterior girder rotation (shown in Fig. 1) primarily depends on the overhang deck width, total construction loads (fresh concrete, bridge deck finishing screed and rails, overhang formwork, labourer, and other construction-related live loads), span length, overhang dimensions, bridge cross section details (Schilling 1988), and the lateral bracing system and effectiveness (Helwig and Yura 2012, Roddis *et al*. 2008). The width of the overhang deck is typically 30-50% of the interior girder spacing. Construction loads are usually applied to the outer edge of the deck overhang (as per the contractor's preference) which is transferred to the exterior girders through steel brackets placed along the length of the bridge (Fig. 1).

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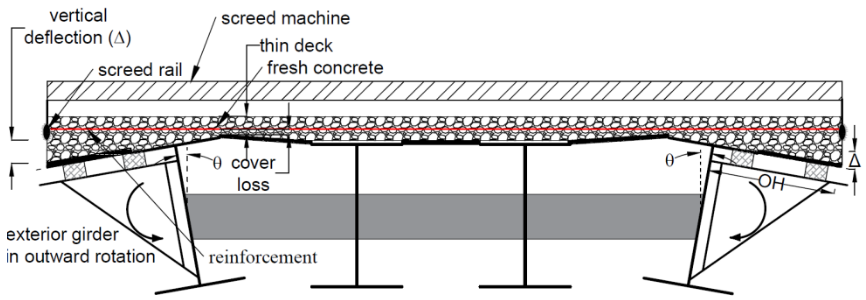
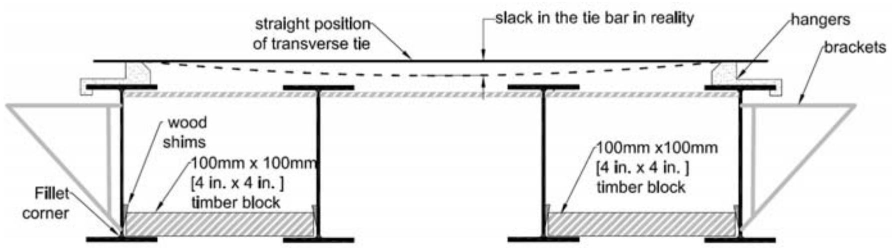
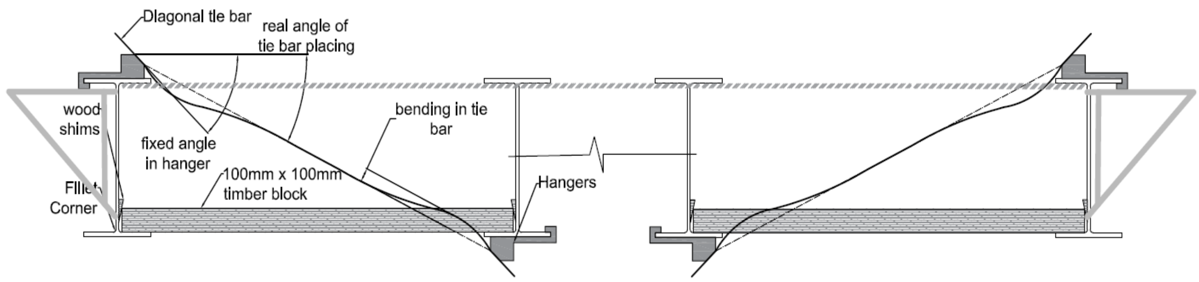
http://www.techno-press.org/?journal=scs&subpage=6
ISSN: 1229-9367 (Print), 1598-6233 (Online)



(a) Exterior girder rotation



(b) Conventional rotation prevention system: Horizontal tie bar + Timber block



(c) Conventional rotation prevention system: Diagonal tie bar + Timber block

Fig. 1 Exterior girder rotation under overhang construction loads and conventional rotation prevention systems

In addition to these parameters, the skew angle has a significant effect on the performance of the exterior girder.

Skewed bridges are useful when roadway alignment changes are not feasible or economical due to the topography, local development, or in areas with environmental concerns. There is an increasing demand for skewed steel bridges throughout the world as the need for complex intersections in constrained urban areas rise (Kar 2012). The effects of skew on bending moments and deflections are well documented with significant differences observed when skew angles exceed 30° (Ebeido and Kennedy 1996, Gupta and Kumar 1983). Critical values for vertical deflections and bending moments for in-service skewed bridges have been shown to be lower when compared to similar non-skewed bridges (Menassa *et al*. 2007, Linzell *et al*. 2010, *Apirakvorapinit et al*. 2011, Choo *et al*. 2005).

Bracing systems used to prevent exterior girder rotation during construction can vary significantly depending on the magnitude of loading, access to the deck, and preference of the contractor. n the state of Illinois, there are two different systems (as shown in Figs. 1(b) and (c)) used by contractors (Ashiquzzaman *et al*. 2016a). he first includes 100×100 mm (4×4 in.) timber blocks (abbreviated T_B) placed between girder webs (and resting on the bottom flanges) to act as struts combined with No. 13 (No. 4) transverse tie bars which connect the tops of the two exterior girders (abbreviated T_T). The second system also includes the 100×100 mm (4×4 in.) timber blocks combined with No. 13 (No. 4) diagonal tie bars (D_T) which connect the top flange of the exterior girder to the bottom flange of the first interior girder. Both of these systems are typically spaced at 0.91 to 1.22 m (3 to 4 ft.) along the length of the bridge. Previous research indicates that several factors can lead to a reduction in effectiveness of these systems including (i) loose tie bars in the field due to difficulties tightening the bars and keeping them tight as the deck is being formed, (ii) for the first tie-bar system, bending of the tie bars as they span across the deck and interfere with deck reinforcement and the change in the profile, (iii) for the second tie-bar system, the angle of the bars depends on the depth and spacing of the girders which was not always properly accounted for during fabrication of the hangers, and (iv) gaps between the girder webs and the timber blocks due to improper shim placement or movement during forming (Ashiquzzaman *et al*. 2016a).

As a result of these observations, three improved bracing systems were proposed to prevent exterior girder rotation during construction (Ashiquzzaman *et al*. 2016a, 2017). In this paper, these improved bracing systems were assessed using bridge deck models with different skew angles to determine their effectiveness in reducing exterior girder rotation in skewed bridges.

2. Improved bracing systems

Previous studies showed that the traditional bracing systems used to prevent exterior girder rotation do not always work effectively to prevent rotation during deck construction (Ashiquzzaman *et al.* 2016a, b). The traditional bracing systems described previously showed poor performance due to a number of factors including bending, sagging, improper placement, etc. A previous experimental field study on three bridges (labeled bridge A, bridge B, and bridge C) with W30 steel girders and three spans is shown in Fig. 2 (Ashiquzzaman *et al.* 2016a). The bridges have skew angles of 0°, 3.8°, and 24° and utilize traditional bracing systems. In all three examples cases shown here, the rotations far exceeded the limit required by the Illinois Department of Transportation (IDOT 2012, Ashiquzzaman *et al.* 2016a).

As a result, three improved bracing systems were developed as alternatives to the traditional systems to prevent exterior girder rotation (Ashiquzzaman *et al.* 2016a, 2017). These improved systems include (i) a transverse tie bar (connected from the exterior girder to the first interior girder) with an adjustable horizontal pipe (TT+DP) to replace the timber block, as shown in Fig. 3(a), (ii) a combination of the straight diagonal tie bar (connected from the top flange of the exterior girder to the bottom flange of the first interior girder) and an adjustable diagonal pipe (ADT+HP), as shown in Fig. 3(b), and (iii) intermediate cross frames placed between permanent lateral supports (diaphragms or cross frames that are currently in use) and only in the exterior panels, as shown in Fig. 3(c).

For this study, ADT+HP and TT+DP are spaced at 1.2 to 2.4 m (4 to 8 ft.) along the length of the span as shown in Fig. 4a. The placement of the intermediate cross frames depends on the ratio between the spacing of permanent lateral supports and the depth of the girder (B/D), as recommended by Ashiquzzaman *et al.* (2016a) which limited the B/D ratio to less than or equal to 3.94 for exterior panels. If the B/D ratio exceeds 3.94, intermediate cross frames between the permanent lateral supports in the external panels are recommended to reduce the B/D ratio, as shown in Fig. 4(b). These intermediate cross frames can be temporary or permanent depending on the design criteria.

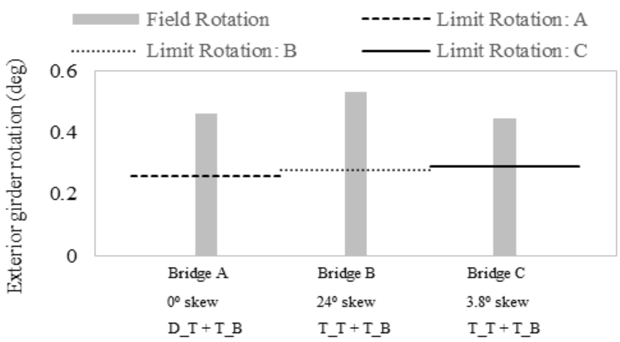


Fig. 2 Ineffective performance of traditional bracing systems (Ashiquzzaman *et al.* 2016a)

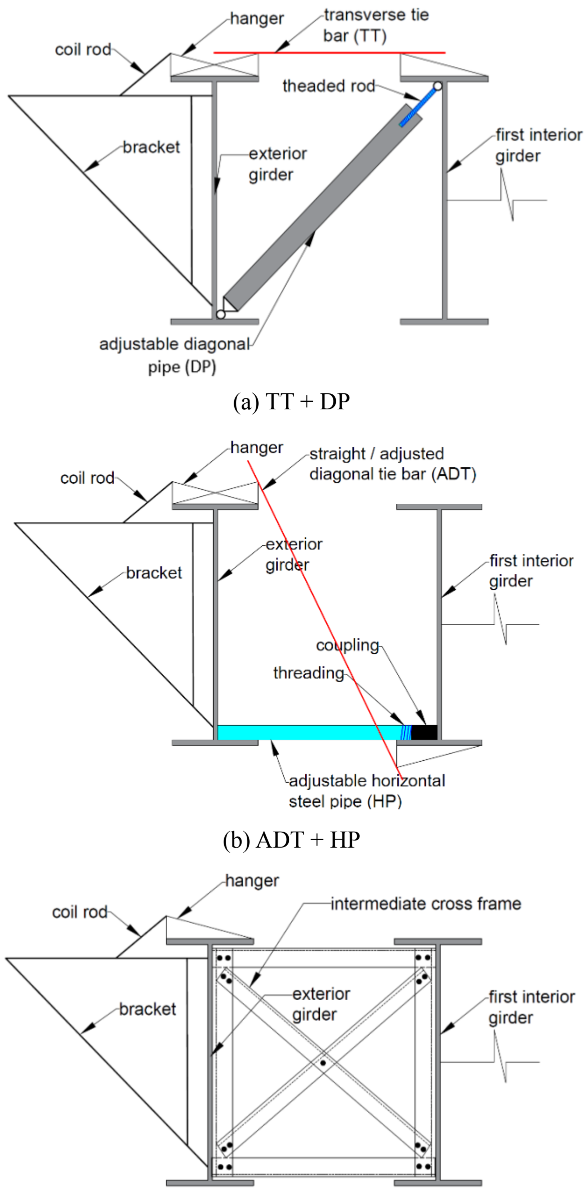


Fig. 3 Three proposed alternate bracing systems (Ashiquzzaman *et al*, 2017)

3. Finite element analysis

3.1 Numerical simulation procedure

Four-girders steel girder bridge were modelled with W760 × 147 (W30×99) longitudinal girders and W360 × 44 (W14×30) diaphragms, which are the most common sections used by the Illinois Department of Transportation. The longitudinal girders and diaphragms are 30, and 14 inches in depth, respectively. The girders are spaced at1.8 m (6 ft.) and both skewed (20°, 30° and 45°) and non-

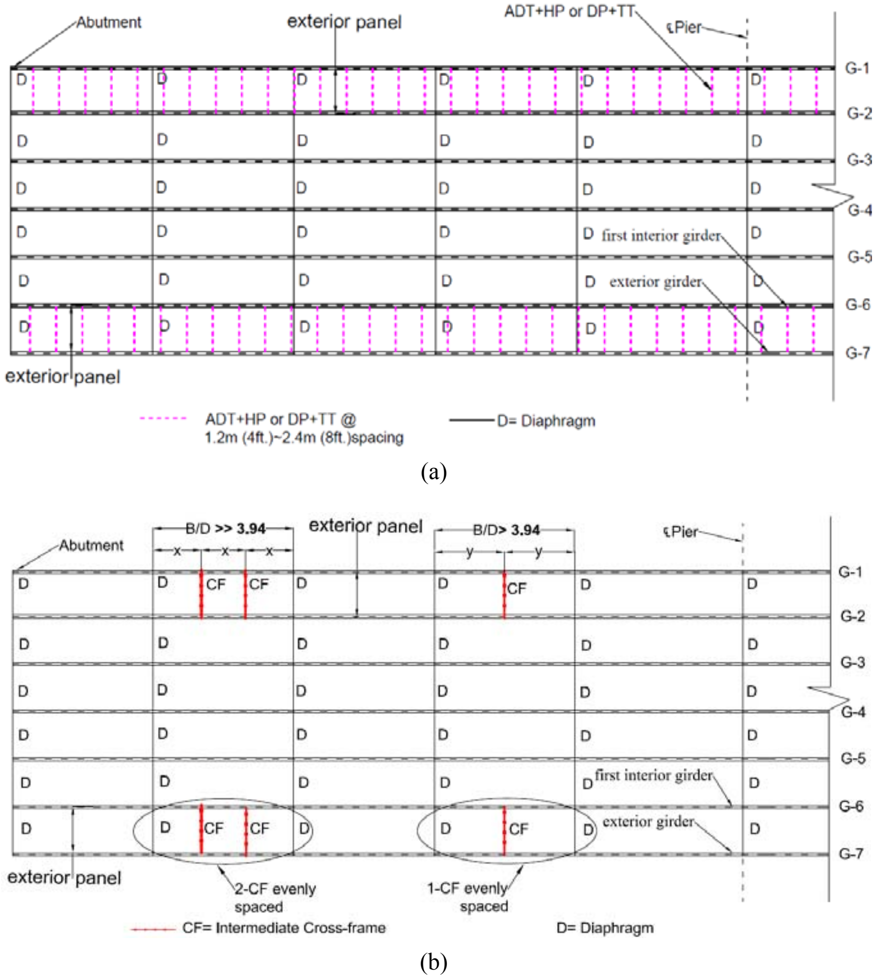


Fig. 4 Arrangement of bracing elements (Ashiquzzaman *et al*. 2017)

skewed (0°) bridges are included in the analysis. Bridges were modeled with either single or three spans to investigate the effect of the number of spans in combinations with the bracing system used.

The overhang deck width is 0.9 m (3 ft.) for all bridges, and the spacing between permanent lateral supports (diaphragms) is constant at 6.1 m (20 ft.), as shown in Fig. 5. The other diaphragm spacing varies depending on the skew angle. A summary of the bridges evaluated is shown in Table 1 and Fig. 5.

3.1 Finite element mod eling

A three-dimensional finite element model was developed to perform elastic analysis using Abaqus 6.13. The girders, diaphragms and cross frames were modeled as shell elements (S4R: A 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains), steel brackets were modeled as shear flexible beam elements (B31: A 2-node linear beam in space), and truss elements (T3D2: A 2-node linear 3-D truss) were used to model tie bars (transverse and diagonal) and pipes (horizontal and diagonal). A surface-to-surface contact (standard) was used if there were two structural elements are in contact by their surfaces. For simple contact pairs consisting of two deformable surfaces, where the following guidelines are used: (i) comparatively larger surface should act as the master surface; (ii) if the surfaces are of similar size, the surface on the stiffer element should be considered as the master surface; (iii) if the surfaces are of comparable size and stiffness, the surface with the coarser mesh should act as the master surface.

The modulus of elasticity and Poisson's ratio were 199947.96 MPa (29000 ksi) and 0.3, respectively. Concrete strength was not considered in the analysis since wet concrete does not gain any strength during construction. Therefore, weight of wet concrete (22.78 kN/m^3) was directly applied to the top flange of the longitudinal girders.

Tie constraints (ties two separate surfaces together so that there is no relative motion between them) were used to connect girders to diaphragms and girders to cross frames. Rigid "translation" link elements were used to connect girders with tie bars (transverse and diagonal) and pipes (horizontal and diagonal).

The distributed construction load was applied up to the section of the span where the rotation is being calculated (the direction of load placement is shown in Fig. 5) to simulate concrete deck placement during construction. The wet concrete weight (22.78 kN/m^3) was calculated based on the tributary area of the girders and distributed over the top

Table 1 Description of the bridges

No. of spans	Span length	No. of girders	Girder spacing	Overhang width	Skew angle	Diaphragm spacing based on Fig. 5 a	b	c	d
1-span and 3-span	18.3 m (60 ft.)	4	1.8 m (6 ft.)	0.9 m (3 ft.)	0º	6.1 m (20 ft.)	6.1 m (20 ft.)	0	b/2
					20º	5.7 m (18.7 ft.)		0.8 m (2.5 ft.)	
					30º	5.5 m (18 ft.)		1.2 m (4.1 ft.)	
					45º	5.0 m (16.5 ft.)		2.1 m (7 ft.)	

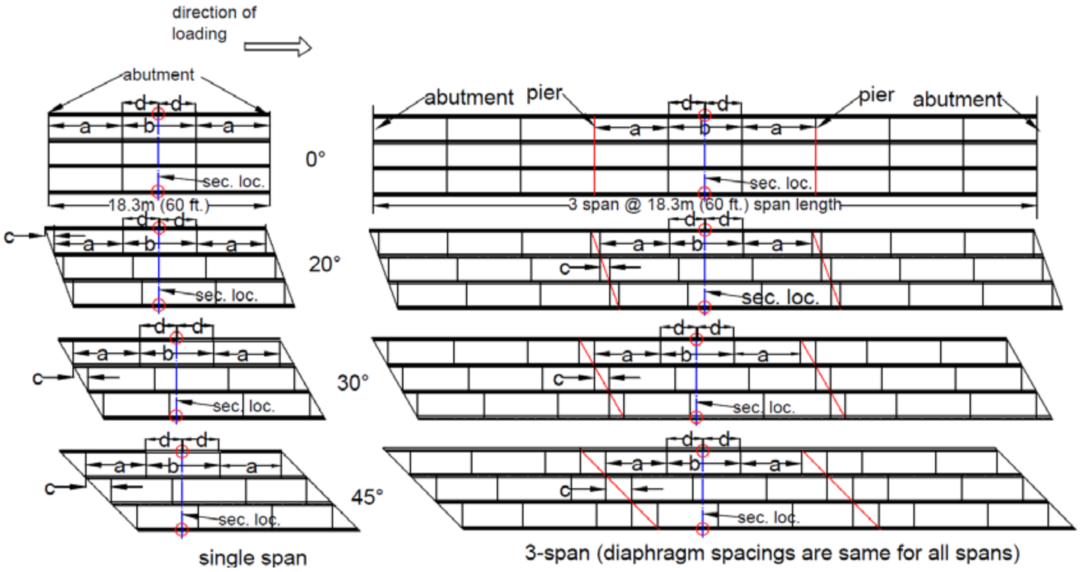


Fig. 5 Configuration of bridges included in this study

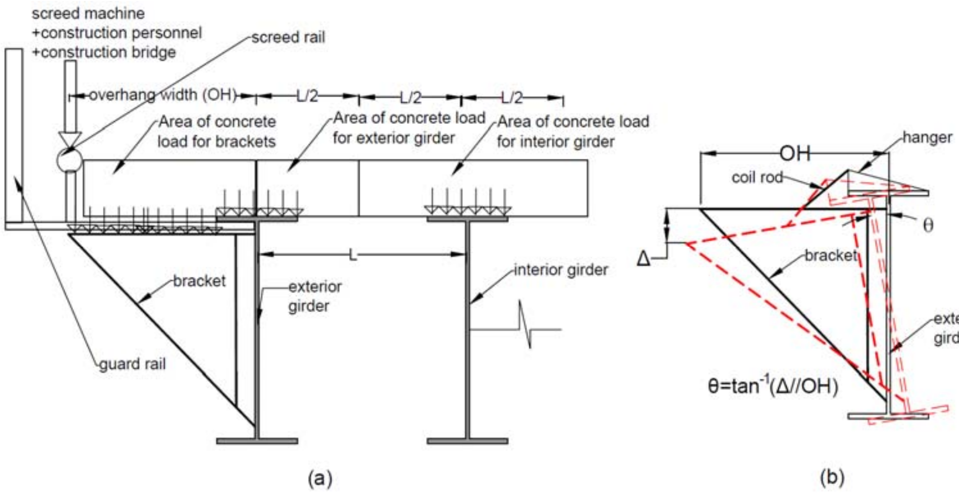
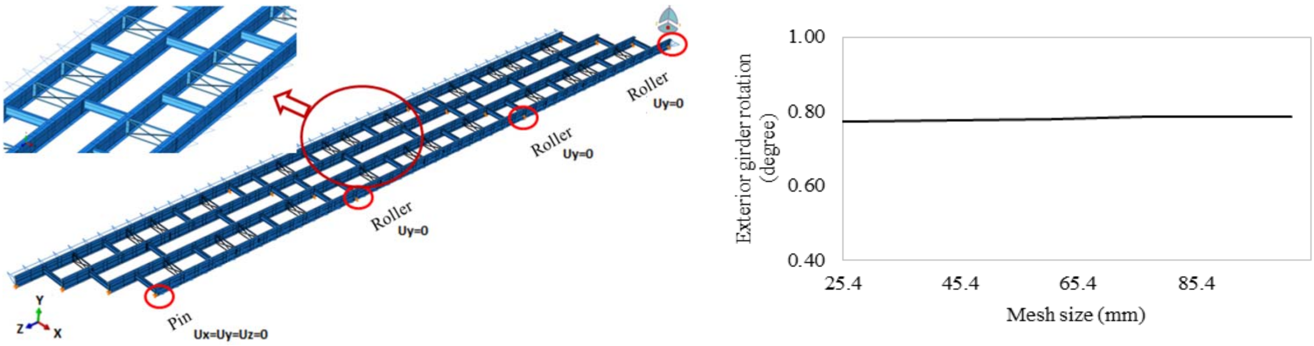


Fig. 6 Overhang construction load consideration and placement in FEA (a); and rotation in exterior girder (b)

flange of the girders, as shown in Fig. 6(a). Fresh concrete on the overhang deck was calculated using the tributary area of each bracket [brackets were placed every 1.2 m (4 ft.) along the length of the span] and distributed as a line load on the horizontal legs of the brackets. The load from the screed, construction personnel, and work bridge was considered as a point load and applied on the bracket at mid-span, as shown in Fig. 6(a). The subsequent rotation



(a) (b)

Fig. 7 Finite element model: (a) Abaqus model for finite element analysis; (b) Mesh convergence study

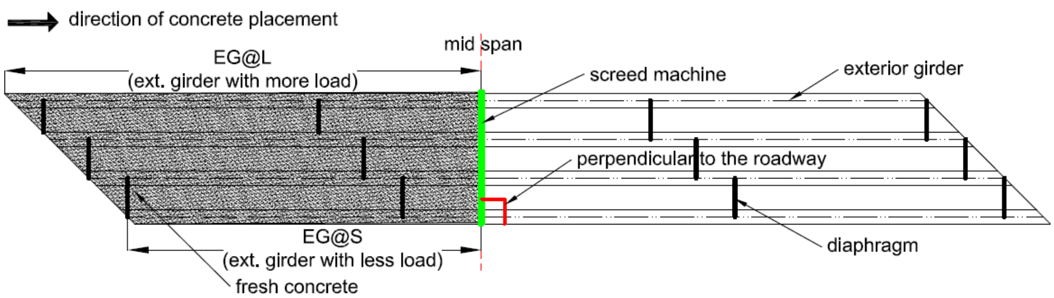


Fig. 8 "Perpendicular to the roadway positioning" of screed machine for both skewed and non-skewed bridges

induced by the construction loads is shown in Fig. 6(b). The rotation was calculated at mid-span of the bridge as shown in Fig. 5. The rotation was calculated at the top of the web since this part of the web represents the maximum rotation during bridge deck construction. The single-span bridge is modeled as simply supported, and for the 3-span bridge, boundary conditions were assigned to simulate a continuous three-span bridge, as shown in Fig. 7(a). A mesh convergence study has been performed, as shown in Fig. 7(b). Based on the mesh convergence study, a mesh size of 58.42 mm (2.4 inch) was selected for the longitudinal girders.

As reported by Ashiquzzaman *et al*. (2016a), a non-skewed full-scale 3-span bridge was modeled and validated with field data. Additional details regarding the model verification are available elsewhere (Ashiquzzaman *et al*. 2016a). The validated bridge model developed as part of that work is used here as the base model with modifications performed in order to conduct the parametric study to evaluate the effect of bridge skew on improved bracing systems.

4. Parametric studies

This study evaluates the effects of multiple parameters to obtain the efficacy of the improved exterior girder rotation prevention systems. Rotation was calculated in both exterior girders of the skewed and non-skewed bridges at mid-span (the section is indicated by two circles) of the bridge as shown in Fig. 5. The rotation was calculated at the top of the web since this part of the web undergoes the maximum rotation during bridge deck construction.

Screed placement on the overhang deck can also introduce unexpected issues during construction. In many cases, screeds are placed on the outside of the overhang deck and perpendicular to the roadway for both skewed and non-skewed bridges, as shown in Fig. 8. This positioning introduces similar rotations for both exterior girders in non-skewed bridges, but depending on the skew angle, may result in significantly different rotations (sometimes significantly higher girder rotation) in skewed bridges due to the uneven overhang load distribution and support conditions. In the case of a mid-span section (as shown in Fig. 8), the exterior girder furthest from the abutment (labeled as "EG@L" in Fig. 8) must carry higher construction loads compared to the opposite girder (labeled as "EG@S") which is closer to the abutment. The presence of diaphragms (not shown here) at any section will also affect rotation.

4.1 Exterior girder rotation without a bracing system

Maximum exterior girder rotation for skewed and non-skewed bridges without any bracing under construction loads is shown in Fig. 9. Very little difference is observed between the single span and three-span bridges with the largest difference (0.06°) occurring for the bridge with a 20° skew. The EG@L girder rotation (as shown in Fig. 9(a)) increases slightly with the increase in skew angle, but more importantly, all of the exterior girder rotations are at least 50% more than the limit (0.30°) specified by Illinois Department of Transportation. The lowest exterior girder rotations were (single-span: 0.64° and 3-span: 0.65°) found in non-skewed bridges with the largest found for the 45° skewed bridges (single-span: 0.88° and 3-span: 0.88°). The EG@S girders showed an opposite trend as the skew angle increases, as shown in Fig. 9(b). The largest rotations were achieved in non-skewed bridges (single-span: 0.64° and 3-span: 0.65°), whereas the smallest exterior girder rotations (single-span: 0.29o and 3-span: 0.33o) were found in 45o

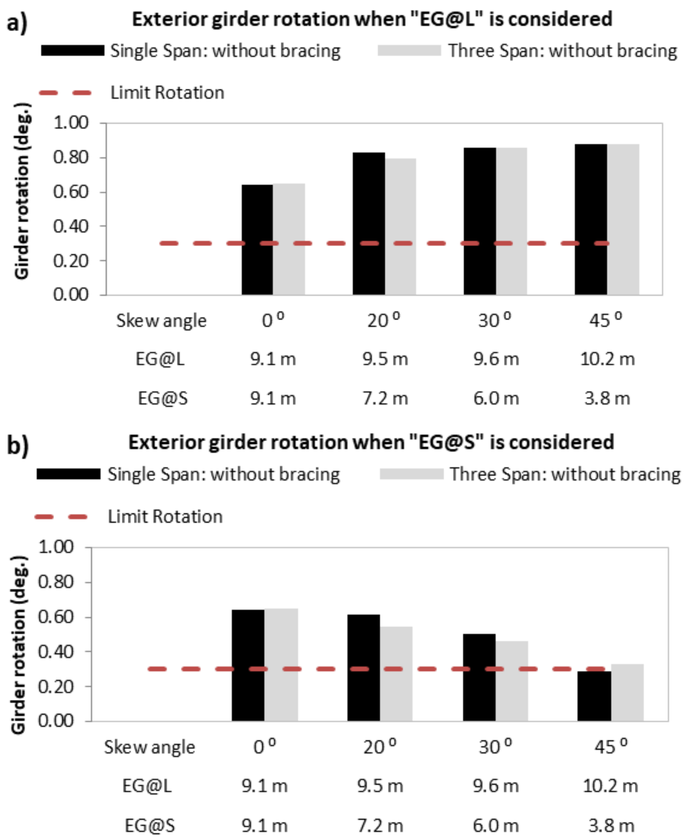


Fig. 9 Exterior girder rotation when no bracing system is employed

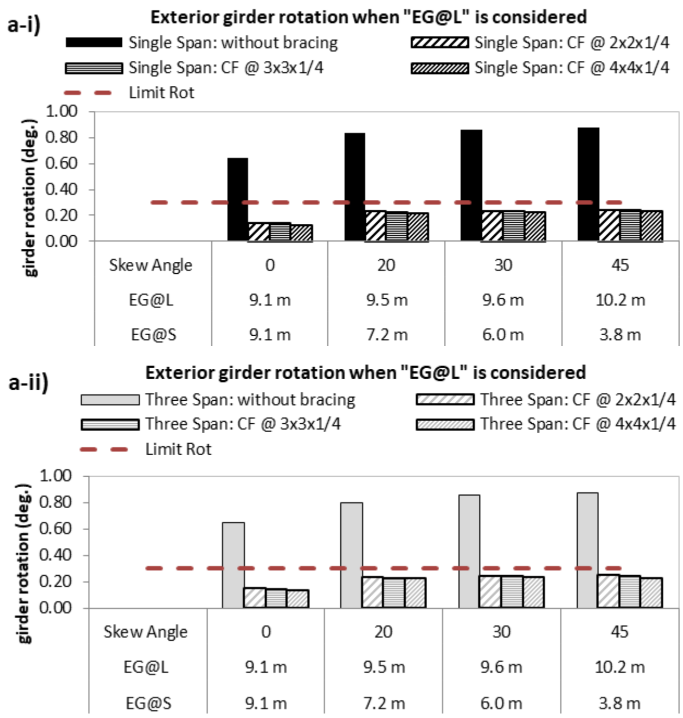


Fig. 10 Effect of TT+DP in preventing exterior girder rotation

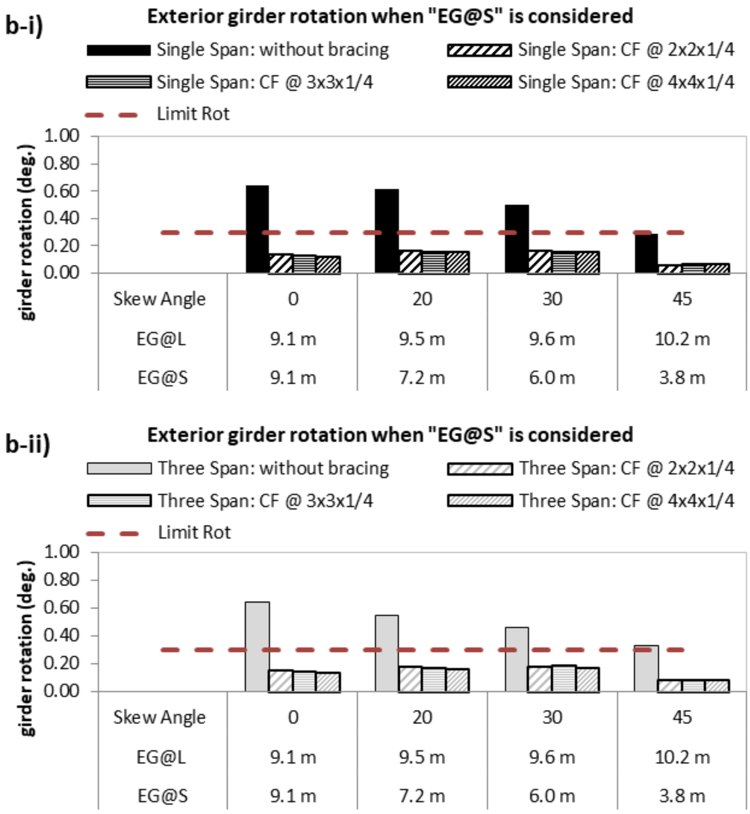


Fig. 10 Continued

skewed bridges. These rotations were the result of the combined effect of skew angle, differential stiffness, and the direction of concrete placement. During deck construction, concrete placement was normally performed perpendicular to the roadway (as shown in Fig. 8) regardless of skew angle, which can create unbalanced construction loads in the two exterior girders (but minimizes the required length of the work bridges and placement and finishing machines). These unbalanced construction loads in the EG@L girder introduced comparatively more rotation at the mid span. On the other hand, the reason for a reduction in rotation of the EG@S girder is the proximity to the pier or diaphragm with the increase of the skew angle.

4.2 Effectiveness of TT+DP in preventing exterior girder rotation

The effectiveness of the transverse tie and adjustable diagonal pipe (TT+DP) is shown in Fig. 10. For both exterior girders, very little difference is observed between rotations obtained for the single span and three-span bridges. As shown previously for bridges without bracing, rotation increases for EG@L girders with an increase of skew angle and decreases for the EG@S girders. It is important to notice, however, that applying the TT+DP results in a significant reduction in girder rotation compared to bridges without bracing. In the case of the EG@S girders, as shown in Figs. 10(b-i) and (b-ii), exterior girder rotations were all well below the rotation limit (0.30°) for all skew angles with TT+DP at 1.2 m, 1.8 m, and 2.4 m spacing. Also, based on Figs. 9(b-i) and (b-ii), 60-80% of the exterior girder rotation can be reduced by applying TT+DP.

In the case of EG@L girders, as shown in Figs. 10(a-i) and (a-ii), implementing TT+DP (spaced at 1.2 m, 1.8 m, or 2.4 m) in non-skewed bridges shows favorable results by keeping all the exterior girder rotations below the limit. Although the TT+DP spaced at 1.2 m appears to only limit rotation for bridges skewed by up to 30°, the exterior girder rotation only slightly exceeds (0.32°) the limit for bridges with a 45° skew. As the spacing is increased to 1.8 m and 2.4 m, the TT+DP bracing system did not perform effectively for the skewed bridges in preventing exterior girder rotation as the exterior girder rotations exceeded the rotation limit in all cases.

4.3 Effectiveness of HP+ADT in preventing exterior girder rotation

The effectiveness of placing horizontal pipe and adjustable diagonal tie (HP+ADT) at the exterior panels is shown in Fig. 11. In all bridges, the HP+ADT bracing systems were placed at a spacing of either 1.2 m, 1.8 m, or 2.4 m. The results were similar to those obtained for the transverse tie and adjustable diagonal pipe (TT+DP). The number of spans did not present any noteworthy difference in exterior girder rotation.

In the case of the EG@S girders, as shown in Figs. 11(b-i) and (b-ii), exterior girder rotations were below the limit (0.30°) for all skew angles due to the combined effect of permanent bracing systems (diaphragms) and implementing HP+ADT at 1.2 m, 1.8 m, or 2.4 m. Based on Fig. 10(b),

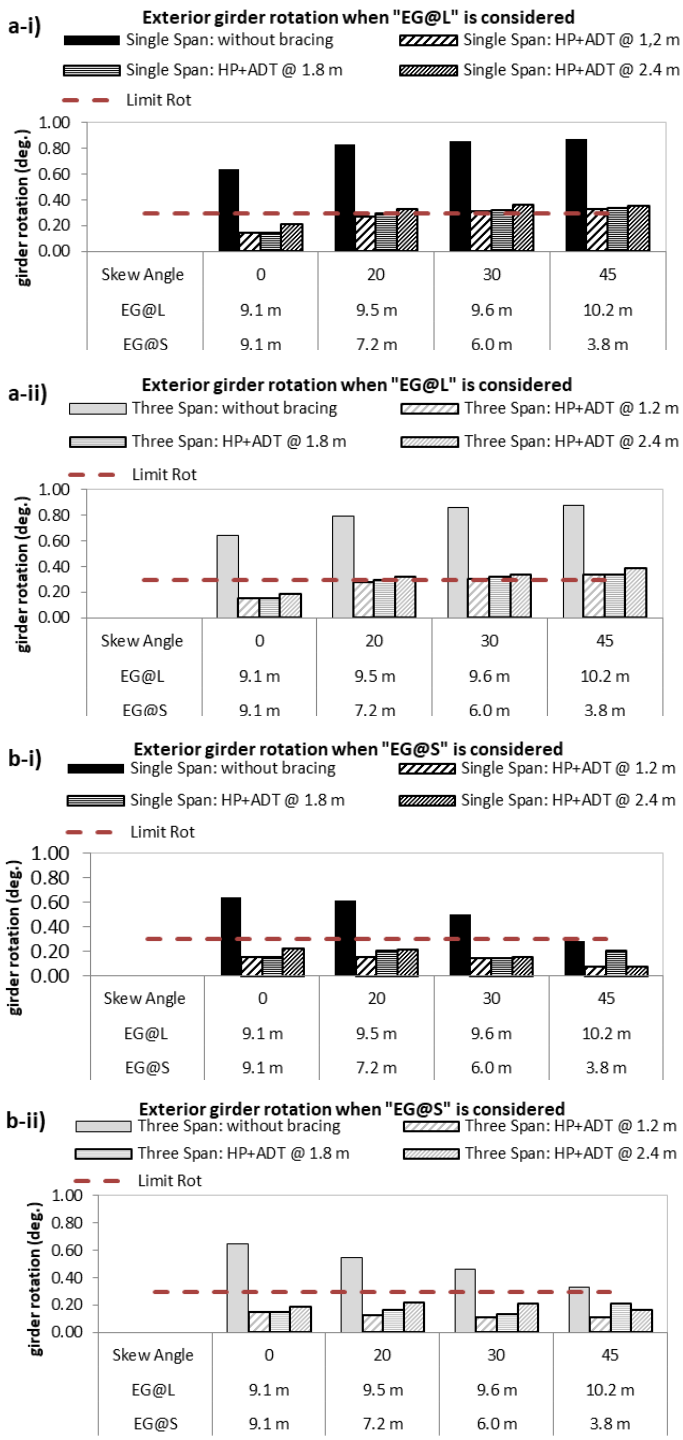


Fig. 11 Effect of HP+ADT in preventing exterior girder rotation

60-80% of the exterior girder rotation can be reduced by using the HP+ADT setup.

For the EG@L girders, as shown in Figs. 10(a-i) and (a-ii,) installing HP+ADT (spaced again at 1.2 m, 1.8 m, or 2.4 m) in non-skewed bridges limited exterior girder rotations below the rotation limit (0.30°). The system was appropriate when spaced at 1.2 m and on bridges with a skew angle of 30° or less, but should be avoided for bridges with skew angles more than 30° or at a spacing greater than 1.2 m where the exterior girder rotations exceed the rotation limit in all analyses.

4.4 Effectiveness of intermediate cross-frames in preventing exterior girder rotation

The effectiveness of intermediate cross frames in the exterior panels is shown in Fig. 12. In all bridge models, placing intermediate cross frames depends on the B/D ratio (3.94). For this study, two intermediate cross frames were

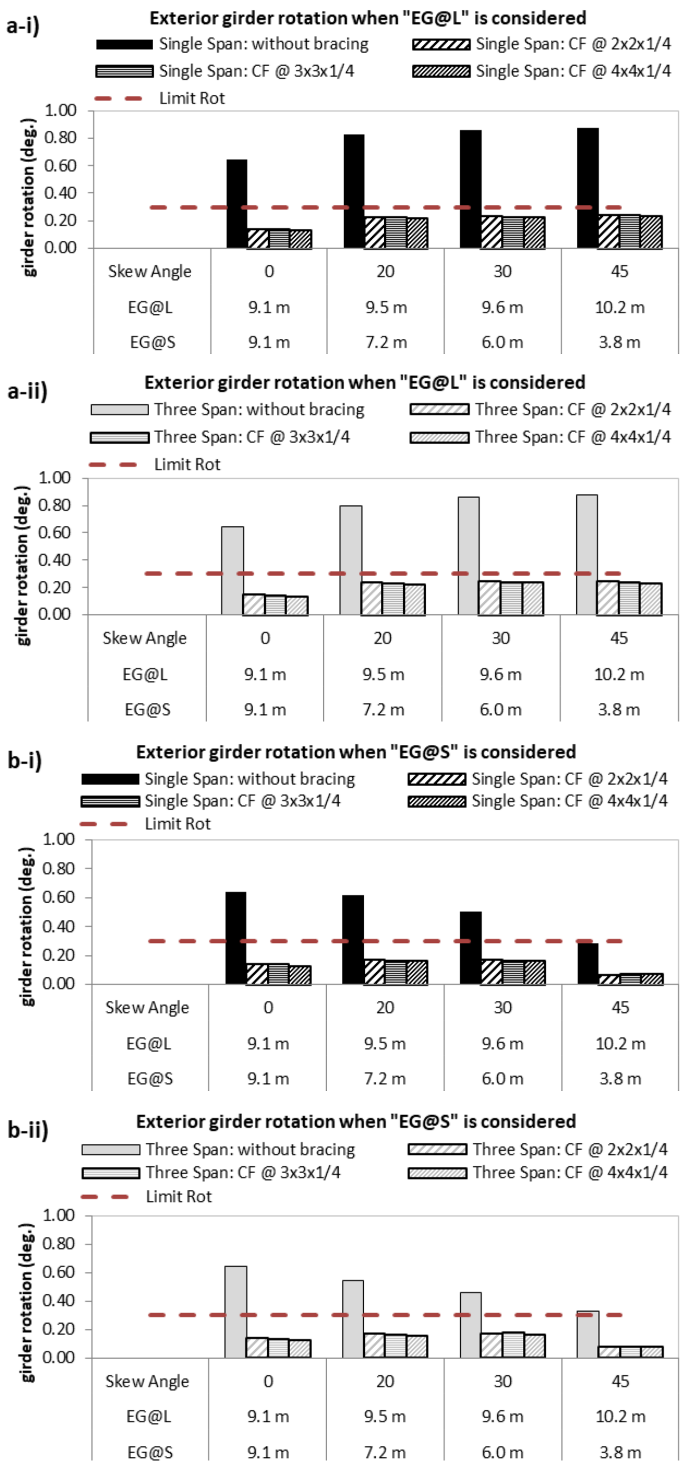


Fig. 12 Effect of intermediate cross frames in preventing exterior girder rotation

used when the diaphragm spacing is labeled "a" (as shown in Table 1), and one intermediate cross frame is used when the diaphragm spacing is labeled "b" (as shown in Table 1). Based on Fig. 12, it can be seen that there is only a minor difference in rotation based on the number of spans.

Using intermediate cross frames depending on the B/D ratio showed outstanding performance regardless of bridge skew and keeps the exterior girder rotation (both EG@S and EG@L) well below the rotation limit (0.30°). Different sizes of angle sections were used for the cross frames (2×2×1/4, 3×3×1/4 and 4×4×1/4) in order to evaluate if the section size influences the effectiveness. In these bridges, the size of the angle section has a minimal influence on girder rotation under the applied deck overhang loadings. The primary reason is the capacity of the cross frames with smallest angle sections is already more than the applied deck overhang loads. Most importantly, the rotation at the cross frame locations is nearly zero (0°) degrees. As a result, the measured rotation was similar for every case even though the angle sections are different.

5. Conclusions

The following conclusions were based on the research presented in this paper:

- The bridge skew angle and concrete placement technique is an important factor to consider when designing or selecting a bracing system to prevent exterior girder rotation.
- Based on the results of this study, skew angle can create a considerable amount of additional rotation in the exterior girders that depends on the direction of the skew and concrete placement. Without bracing, girders in highly skewed bridges (45°) experience 37% additional rotation compared with a similar non-skewed bridge.
- Alternative bracing systems, including a transverse tie and adjustable diagonal pipe (TT+DP) and horizontal pipe and diagonal tie (HP+ADT) spaced at 1.2 m, 1.8 m or 2.4 m, works effectively for non-skewed bridges. In the case of skewed bridges, however, TT+DP and HP+ADT spaced at 1.2 m only limit rotation to less than 0.3° if the skew angle is less than 30°. Based on the context of this paper, bracing spaced greater than 1.2 m are not recommended for skewed bridges.
- Intermediate cross frames placed in the exterior panels significantly limit rotation and work regardless of the skew angle for at least up to 45°. Additional work is recommended for bridges with a skew larger than 45°.

Acknowledgments

Funding for this work was provided by the Illinois Department of Transportation as part of the research project “Exterior Beam Rotation Prevention Systems for Bridge Deck Construction (R27-140)”.

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