



## **Impact of Lean-on Bracing Layouts on System Stability**

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### **Abstract**

Lateral torsional buckling is a limit state for steel bridges that is critical during construction. The buckling resistance is improved by providing intermediate bracing, which commonly consist of cross-frames comprised of single-angle members. In bridges with support skew, the installation and long-term maintenance of cross-frames can be complicated due to the skewed geometry. Lean-on bracing concepts, which selectively remove cross-frames in place of utilizing only top and bottom struts are becoming an attractive design option. Lean-on bracing significantly improves the ease of installation during erection and also minimizes long-term fatigue issues. Past studies have provided guidance on the distribution of cross-frames as well as the stiffness and strength behavior of the cross-frames in lean-on applications. However, additional investigation on improved guidelines can lead to further refinement on the bracing behavior.

This paper provides an overview of the impact of the distribution of cross-frames in lean-on bracing systems on the overall stiffness and strength behavior. The performance of different cross-frame distributions was quantified by conducting an extensive study that integrated the effects of bridge geometries with varied width and number of girders. This paper summarizes the findings of the investigation and provides design recommendations.

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## 1. Introduction

There are a number of limit states that must be considered at various stages in the life of a bridge by designers. The critical stage for stability generally occurs during the early stages of erection, when not all bracing is present or during construction of the concrete deck when the steel girder alone supports the entire construction load. Stability is typically controlled by lateral-torsional buckling (LTB), illustrated in Fig. 1 (Figure 1, which is a limit state that involves lateral translation of the compression flange and twist of the girder cross-section. LTB is not generally a problem in the completed bridge since the girders are laterally and torsionally restrained by the concrete bridge deck. The elastic lateral torsional buckling capacity,  $M_{cr}$ , of a doubly symmetric girder is given by the following expression derived by Timoshenko (Timoshenko and Gere, 1961):

$$M_{cr} = C_b \frac{\pi}{L_b} \sqrt{EI_y GJ + \left(\frac{E\pi}{L_b}\right)^2 I_y C_w} \quad (1)$$

Where  $E$  is the elastic modulus;  $G$  is the shear modulus;  $J$  is the torsional constant;  $I_y$  is the moment of inertia about the weak axis;  $C_w$  is the torsional warping constant, and  $L_b$  is the unbraced length defined by the spacing between braced points.

There are two ways of providing effective stability bracing of beams: lateral bracing that controls the lateral movement of the compression flange or torsional bracing that controls twist of the section. The most common form of bracing in steel bridges are cross-frames such as those depicted in Fig. 2a that control the twist of the girders. Bridge systems that employ cross-frames between each adjacent girder as depicted in Fig. 2a, are referred to as conventionally braced.

Historically, cross-frames were restricted to a maximum spacing of 25 ft. (7.62 m.). However, primarily due to fatigue concerns around brace locations, the 1<sup>st</sup> edition of the AASHTO LRFD removed the spacing limit in-place of a requirement for the spacing dictated by a rational analysis. Practical design considerations for girder stability during construction often lead to a required spacing between cross frame lines of 25 ft. (7.62 m.) to 40 ft (12.19 m.).

Due to high fabrication and installation costs, cross-frames and diaphragms often represent the most expensive component on the bridge per unit weight. During erection, installation of these cross-frames can cause several complications due to fitting. Furthermore, support skew can exacerbate these issues due to difficulty installing cross-frames near the supports. Larger live-load induced forces are also common in bridges with high support skew, compared to bridges with normal supports, elevating concerns regarding fatigue performance of cross-frame members. In addition, the cross-frames are often comprised of single angle members, which are categorized as E' details – the worst performance in AASHTO. To minimize live load induced forces and facilitate girder erection, lean-on bracing concepts strategically remove redundant diagonal bracing members as shown in Fig. 2b.

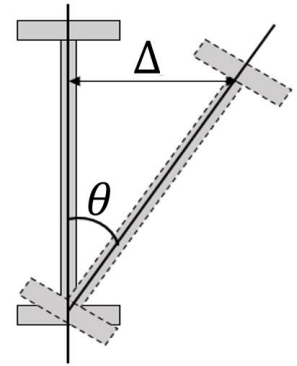


Figure 1: Cross-section of I-girder undergoing lateral torsional buckling

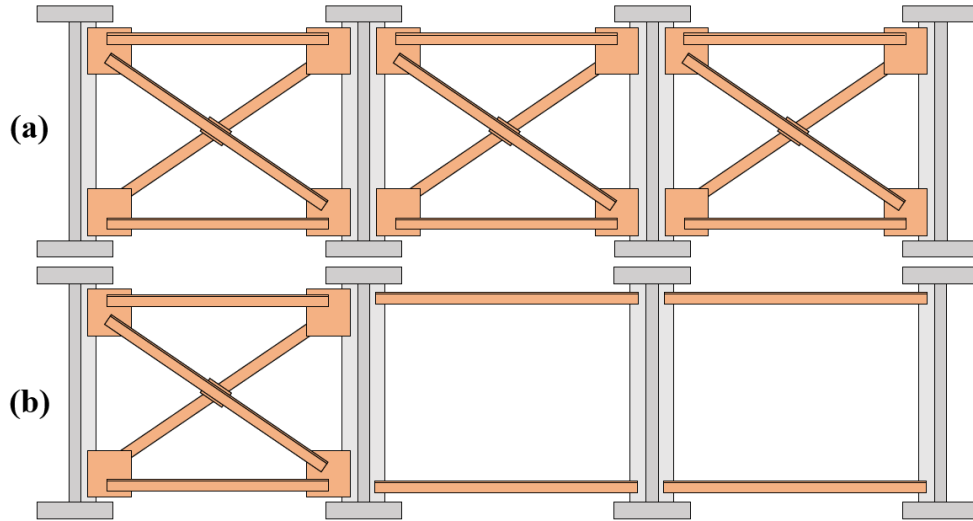


Figure 2: Example of typical bracing systems with full cross-frames (a) and using lean-on bracing (b)

Pursuing a method to reduce live-load induced forces, lean-on bracing concepts were first developed for steel bridges in TxDOT Study 0-1772 (Helwig and Wang 2003). Following the 0-1772 study, several skew and nonskew bridges were designed and constructed to leverage the unique properties of lean-on bracing. As TxDOT Study 0-1772 was not focused on cross-frame layout, bridge designers lacked adequate guidance on how to determine an optimum layout of cross-frames throughout the bridge system. In contrast, this paper focuses on studying the unique stiffness and strength behavior of cross-frame lines in order to propose guidance on cross-frame layout.

Before beginning the investigation, an ABAQUS (2023) modeling procedure was developed using the data from two instrumented lean-on bridge systems. These systems were monitored while undergoing live load testing utilizing four loaded dump trucks. The monitoring supplied cross-frame forces and deflection measurements along the bridge systems for model validation. ABAQUS models of the bridge systems were benchmarked against the gathered data and the modeling procedure was adjusted until the bridge models produced results comparable to the in-situ conditions. The modeling procedure was further refined using data from the bridge instrumented in TxDOT Study 0-1772 (Helwig and Wang 2003).

The next section of this paper will provide further background information on stability and lean-on bracing. This information includes the necessary stiffness and strength requirements for bridge systems. The third section of the paper outlines the finite element modeling procedure, including key modeling information on the boundary conditions, loading, and girder geometry. The final section provides an outline of the parametric study conducted and the analysis results of that study. These results were gathered from a combination of linear eigenvalue buckling and geometric imperfection analyses. The paper concludes with a summary of the results and the future work to be conducted.

## 2. Background

Stability bracing has seen several investigations over the past 100 years, with the most significant contributions being made by Winter (1960) and Yura (2001). The dual criteria of stiffness and strength requirements was first demonstrated by Winter's (1960) work on stability bracing systems. Additionally, Winter highlighted the impact of initial imperfections on the brace strength requirements. Yura (1992) built off the foundation laid by Winter by developing comprehensive formulations for column and beam systems. Yura summarized his research for beam bracing systems in his 2001 paper.

Fundamentally, effective stability bracing requires sufficient strength and stiffness. The American Institute of Steel Construction (AISC - 2016) has outlined the modern provisions in its specifications. Recent work documented in Reichenbach et al. (2021) resulted in stability bracing provisions that are included in the 10<sup>th</sup> Ed. of the AASHTO Bridge Design Specifications (BDS). Many stability bracing systems follow the behavior of springs in series as outlined in Yura et al. (1992), the equation of which is presented in Eq. 2. The torsional brace stiffness of the system,  $\beta_T$ , of the system is a function of three components: the in-plane girder stiffness,  $\beta_g$ , the brace stiffness,  $\beta_{br}$ , and the cross-section stiffness,  $\beta_{sec}$ .

$$\frac{1}{\beta_T} = \frac{1}{\beta_{br}} + \frac{1}{\beta_{sec}} + \frac{1}{\beta_g} \quad (2)$$

There are a number of different cross-frame geometries that might be specified by a designer, including X-frames, K-frames, and Z-frames. Examples of an X-frame or a K-frame are shown in Fig. 3. Some states have details consisting of a single diagonal cross-frame, which are referred to as Z-frames. Because single angle members often have a relatively low buckling strength, in design the compression diagonal can be conservatively neglected, which also results in a Z-frame.

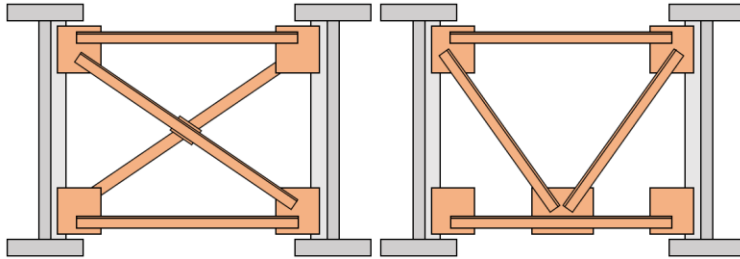


Figure 3: Examples of lateral torsional braces: (a) X-frame and (b) K-frame

The brace stiffness for a Z-frame system is calculated using Eq. 3 where  $s$  is the spacing between girders,  $A_d$  is the area of the diagonal bracing members,  $A_h$  is the area of the horizontal members, and  $L_d$  is the length of the diagonal bracing members.

$$\beta_{br} = \frac{Es^2h_b^2}{\frac{2L_d^3}{A_d} + \frac{s^3}{A_h}} \quad (3)$$

The research paper herein employs adjustments to  $\beta_g$  and  $\beta_{br}$  outlined in Fish et al. (2024). Using the new formulation of the in-plane girder stiffness expression shown in Eq. 4 and the multi-cross-frame adjustment factor,  $C_{nc}$  for Z-frames displayed in Eq. 5, the system stiffness properties can be more accurately captured.

$$\beta_{g,2024} = C_{bs}^2 \frac{\pi^4 E I_x s^2}{2n_g (KL)^3 (n+1)} \alpha_x \quad (4)$$

$$C_{nc,z} = 1 + \frac{n_c - 1}{n_c + 1.75} \quad (5)$$

Where  $C_{bs}$  is a moment gradient factor;  $n_g$  is the number of girders;  $K$  is the effective length factor;  $n$  is the number of cross-frame lines;  $\alpha_x$  is a warping stiffness factor, and  $n_c$  is the number of cross-frames in a cross-frame line.  $C_{nc}$  is multiplied directly to the brace stiffness expression to account for multiple in-line cross-frames in a conventional system. The system torsional brace stiffness is smaller than the smallest of the three components. AISC (2017) provides the following expression for the required system brace stiffness,  $\beta_{T,req}$ :

$$\beta_{T,req} = \frac{2.4LM_u^2}{\varphi nEI_{eff}C_b^2} \quad (6)$$

Where  $L$  is the span length;  $M_u$  is the ultimate design moment;  $\varphi$  is the LRFD resistance factor equal to 0.8;  $E$  is the Young's Modulus;  $n$  is the number of intermediate braces;  $C_b$  is the moment gradient factor;  $I_{eff}$  is the effective moment of inertia about the weak axis given by  $I_{eff} = I_{yc} + t/c \cdot I_{yt}$ .  $I_{yt}$  is the lateral moment of inertia of the tension flange,  $t$  is the distance from the centroid of the tension flange to the neutral bending axis, and  $c$  is the distance from the centroid of the compression flange to the neutral bending axis.

The expression given in Eq. 6 represents twice the ideal stiffness. As shown initially by Winter (1960), providing twice the ideal stiffness is assumed to result in a twist at the brace location that is approximately equal to the initial imperfection,  $\theta_o$ , when the girder is subjected to the maximum design moment,  $M_u$ . The stability brace moment, based upon this assumption, is given by the following expression:

$$M_{br} = \beta_{T,req}\theta_o = \frac{2.4LM_u^2}{\varphi nEI_{eff}C_b^2} \frac{L_b}{500h_o} \quad (7)$$

Where  $h_o$  is the distance between flange centroids. The other terms in Eq. 7 are as defined previously.

Wang and Helwig (2005) demonstrated the most critical imperfection shape is a lateral translation of the compression flange at the brace location (assumed magnitude of  $L_b/500$ ) with straight tension flange at the location of maximum moment. Fig. 4 shows the exaggerated imperfection shape that was used in this paper's study. A slight asymmetry was applied to the imperfection shape due to recommendations by Prado and White (2015), and Liu and Helwig (2020) in their studies related to torsional brace strength requirements.

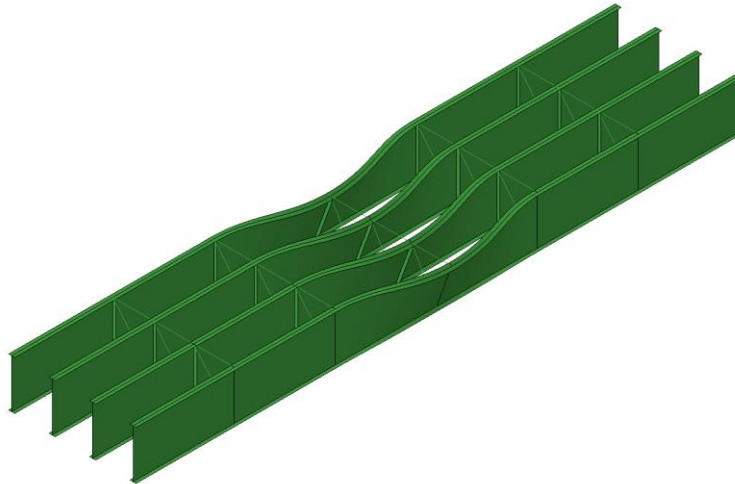


Figure 4: Exaggerated shape of critical imperfection located in maximum moment region

Effective stability bracing system aims for the girder to buckle between the brace points. However, narrow girder systems are susceptible to another buckling mode: the system buckling mode. The system buckling mode was first discussed in Yura et al. (2008) and later incorporated into the AASHTO BDS in 2015. The system mode of buckling is insensitive to the spacing between cross-frames as the girders tend to buckle in a half-sine curve. Additionally, narrow girder systems are often susceptible to significant second order amplification as shown by Sanchez and White (2012). Initially this susceptibility led AASHTO to limit the maximum moment during construction to 50% of the elastic critical buckling load. However, work conducted by Han and Helwig (2020) demonstrated that system buckling of girders was related to the initial imperfection. This research resulted in raising the AASHTO limit from 50% to 70% of the critical system buckling capacity. Ultimately, the imperfections utilized in Han and Helwig provided guidance on the current study.

### 3. Finite Element Model and Analysis Types

The general-purpose finite-element analysis program ABAQUS (2023) was used in the computational studies conducted on representative bridge geometries. For this paper, the analysis was focused on determining fundamental behavior of cross-frame layouts in respect to the previously discussed strength and stiffness requirements.

S4 linear shell elements were used to model the girders. The elements were sized such that the flanges of the girders were modeled with one element on either side of the web and that the aspect ratio was as close to unity as possible. Bracing members were modeled using T3D2 linear truss elements connected at the web-flange junctures to prevent the effects of cross-sectional distortion. Web stiffeners, modeled using S4 linear shell elements, were included for completeness and located along the web at each brace location.

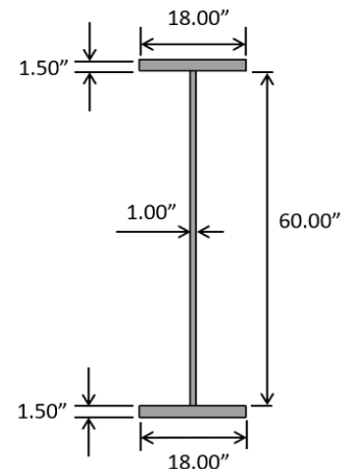


Figure 5: Illustrations of the girder section used for study

The typical girder section used for the studies is displayed in Fig. 5. Although a variety of loading conditions have been used in the study, the results outlined in this paper focus on girders with

uniform moment loading. The bridge models featured simply-supported girders that were free to warp at the supports. The pin and roller supports were placed at the bottom flange-web juncture and restrained vertical and lateral movement. The pin supports additionally restrained longitudinal movement of the girder.

This modeling procedure was validated by benchmarking instrumentation data of three bridges constructed using lean-on concepts. Live load testing was conducted on two of the bridges, a nonskew and a skew bridge, using loaded dump trucks. Additionally, live load and construction data of the third bridge from TxDOT study 0-1772 (2003) was utilized. The validation data included cross-frame forces and girder displacements at measured locations along the length of each bridge. Models of each bridge were made in ABAQUS (2023), with adjustments being made to the modeling methodologies to minimize discrepancies between the experimental and model results.

Two analysis types were used in the study: linear eigenvalue buckling analyses and nonlinear geometric imperfection analyses. Linear eigenvalue buckling was used to identify the ideal stiffness, the minimum brace stiffness required to reach buckling between brace points, of the bridge systems. Utilizing the ideal stiffness, geometric imperfection analyses were conducted using the Riks Arclength method to determine the effects of cross-frame layout on girder displacement and brace stresses. The imperfection was modeled by selecting nodes within a bounding box and translating those nodes based upon the imperfection equation shown in Eq. 8.

$$\frac{\sin\left(\frac{[x-(x_{crit}+L_b)]\pi}{L}-\frac{\pi}{2}\right)}{2} \cdot \frac{L_b}{500} \text{ where } x_{crit} - L_b \leq x \leq x_{crit} + L_b \quad (8)$$

Where  $x_{crit}$  is the location of the critical cross-frame line and  $L_b/500$  is the imperfection magnitude. The imperfection was altered to be slightly asymmetric to increase the severity of the imperfection by reusing and multiplying Eq. 8 over part of the imperfection as illustrated in Fig. 6.

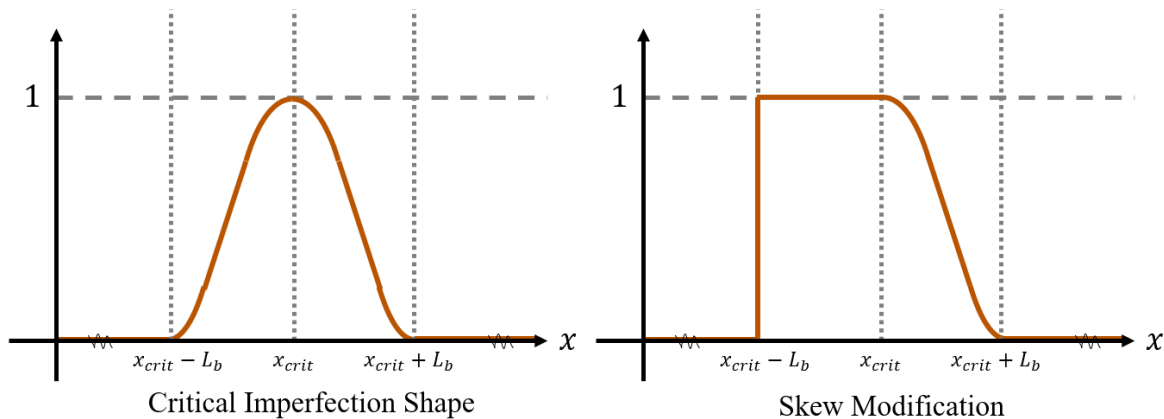


Figure 6: Illustration of critical imperfection shape produced by Eq. 8. and skew modification

#### 4. Layout Effect Study with Isolated $\beta_{br}$

Quantifying the layout effects of lean-on systems requires individual elements of the system stiffness to be isolated. As stated in the background, the total system stiffness is a function of the stiffness of the brace ( $\beta_{br}$ ), the in-plane stiffness of the girders ( $\beta_g$ ), and the cross-sectional stiffness to control distortion ( $\beta_{sec}$ ). Because full depth cross-frames were utilized, the cross-sectional distortion term ( $\beta_{sec}$ ), can be taken as infinite, which only leaves the brace stiffness and in-plane stiffness. The remaining two stiffness components can be individually isolated by maximizing the stiffness of the other component such that the component acts infinitely stiff:

1.  $\beta_{br}$  can be isolated by maximizing the bridge width ( $\beta_g$ ).
2.  $\beta_g$  can be isolated by maximizing the brace area ( $\beta_{br}$ ).

A stiffness component acts infinitely stiff if the resultant component is above a certain multiplier of the ideal stiffness ( $\beta_{T,ideal}$ ), the minimum system stiffness required to get buckling between the brace points. A modeling configuration was chosen that enabled  $\beta_g$  to act as infinitely stiff such that the brace stiffness behavior could be directly related to  $\beta_{T,ideal}$  (other term drops out of the equation).

Girder systems with varying geometries were tested to ensure the  $\beta_g$  acted as an infinitely stiff component. Table 1 highlights the results of the sensitivity study conducted for these girder systems. Based upon the sensitivity analysis, all the systems had sufficient  $\beta_g$  such that the  $\beta_{br}$  stayed constant for a given unbraced length. This indicates  $\beta_{T,ideal}$  was insensitive to the changes in  $\beta_g$  in these system configurations. For the study, the girder to girder spacing selected was 80' and the unbraced length was set to 25'.

Table 1: Bridge parameters and calculated  $\beta_g$  compared to  $\beta_{T,ideal}$

Girder Spacing	Total width of girder system	Span Length	# of Cross Frame Lines	Unbraced Length	$\beta_{g,eq,2024}$	$\beta_{br,eff,FEA}$	$\frac{\beta_g}{\beta_{T,ideal}}$
( $S$ )	( $W_g$ )	( $L$ )	( $n_c$ )	( $L_b$ )	$\left(\frac{kip - in}{rad}\right)$	$\left(\frac{kip - in}{rad}\right)$	
80'	320'	160'	3	40'	12,702,000	64,000	200
40'	160'	160'	3	40'	3,175,000	64,000	50
80'	320'	150'	5	25'	10,278,000	229,000	45
40'	160'	150'	5	25'	2,569,000	228,000	11

As stated previously, when  $\beta_g$  is suitably large to be treated as infinitely stiff,  $\beta_{br}$  can be directly related to  $\beta_{T,ideal}$ . This is due to the expression for springs in series, Eq. 2, which dictates that the  $\beta_T$  is equal to  $\beta_{br}$  when the other terms drop out. A summary of these developments is given in Fig. 7.



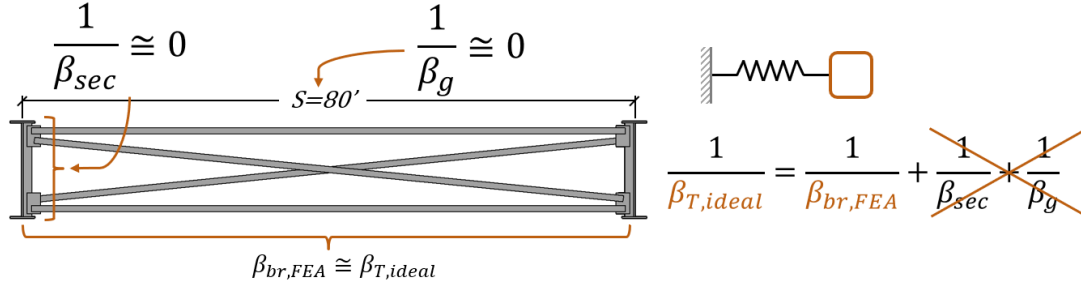


Figure 7: Idealized system isolating the effects of a single stiffness component such that  $\beta_{T,ideal}$  can be obtained

By relating  $\beta_{T,ideal}$  directly with  $\beta_{br}$ , the independence, or lack thereof, of cross-frame line behavior could be determined. If cross-frame lines acted independently, layouts would exhibit no effect on the brace stiffness requirements of the girders. Thus, the  $\beta_{br}$  requirement would solely be based on the girder geometry and the applied moment. Based on conventional understanding, the provided  $\beta_{br}$  is dependent on the position, member sizes, and number of cross-frames in a cross-frame line. Henceforth, cross-frames lines with the same number of cross-frames, member sizes, and cross-frame positioning are referred to as equivalent stiffness cross-frame lines.

Based on recent research on the in-plane girder stiffness (Fish et al. 2024), a factor was developed to account for an increase in  $\beta_{br}$  due to multiple in-line cross-frames,  $C_{nc}$ . Due to the accuracy of the new factor and corresponding expression, the brace stiffness of conventional systems can be used to determine the  $\beta_{T,ideal}$  of a stiffness-isolated girder system. Using finite element analyses, the  $\beta_{br}$  can be related directly to the area property of the truss elements.

The first step in determining the impact of lean-on struts on bracing behavior is to determine the minimum brace area corresponding to buckling between the brace points in the stiffness isolated conventional system. The minimum brace area corresponds to  $\beta_{T,ideal}$  and can be used as a point of reference. To buckle between the brace points, a girder must have all brace points (cross-frame lines) achieve sufficient stiffness. Once  $\beta_{T,ideal}$  is determined, the system can be reanalyzed with some of the conventional cross-frame lines replaced by equivalent stiffness cross-frame lines with lean-on struts. As the girder cross-section and moment are unchanged, the ideal stiffness and thus brace stiffness requirement are the same. The minimum brace area of these new cross-frame lines can then be determined, equated to  $\beta_{T,ideal}$ , and used to verify the design equations and behavior of lean-on systems.

Various layouts were tested utilizing equivalent stiffness cross-frame lines after collecting the corresponding  $\beta_{T,ideal}$  from a conventional bridge system. The layouts shown in Fig. 8 correspond to the layouts tested for a 5-girder system. The aim of these layouts was to determine the effects of cross-frame number and position on the effective brace stiffness of a cross-frame line with lean-on.

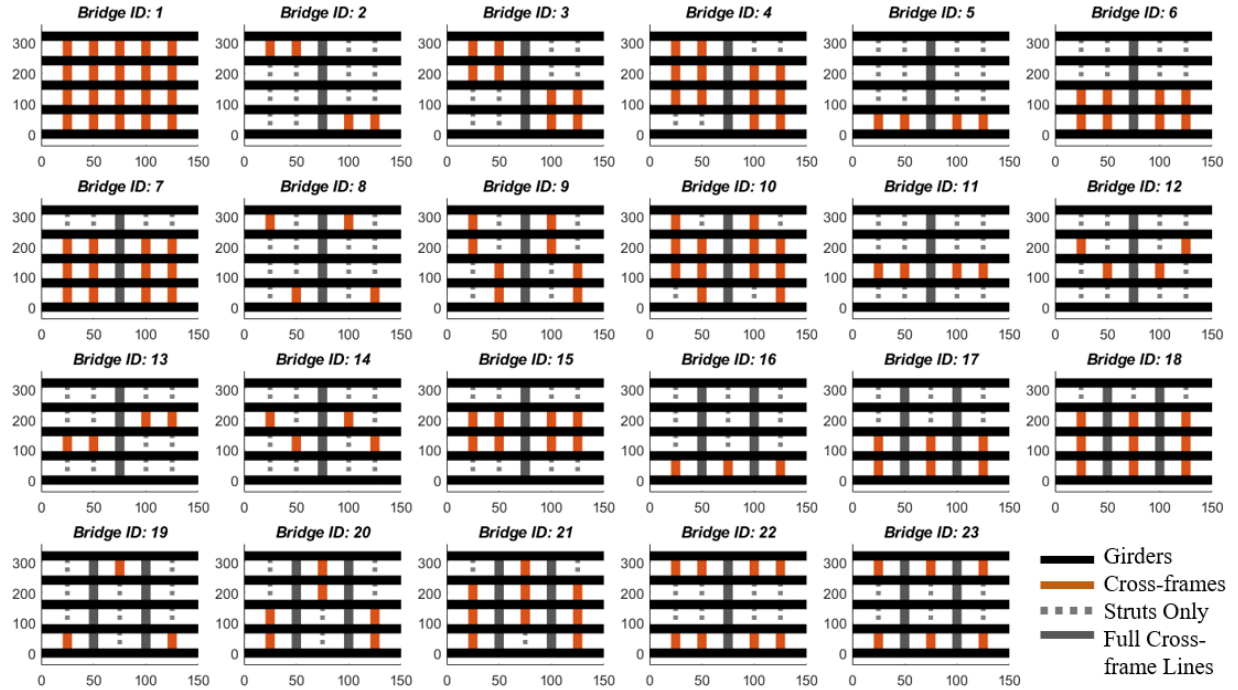


Figure 8: Girder layouts used in the layout effect parametric study

A summary of the layouts used in the study is provided in Table 2 and comprises the results of 135 bridge systems. The systems tested can be subdivided into systems with only internal cross-frames (reference bridge 11 in Fig. 8) and systems with cross-frames extending from the exterior (reference bridges 2 to 4 in Fig. 8).

# of Girders	# of Layouts Total	# of Layouts with only Internal Cross-frames	# of Layouts with Cross-frames Extending from the Exterior
7	52	24	28
6	37	14	23
5	23	5	18
4	16	1	15
3	7	0	7

The data in Table 3 provides typical examples of the results obtained from the eigenvalue buckling analyses of these isolated systems. Overall, the results demonstrate that different permutations of the orientation of the same cross-frame line altered the minimum required brace area needed to obtain buckling between the brace points ( $\beta_{T,ideal}$ ). In general, the orientation of the equivalent stiffness cross-frame lines produced up to a 30% variation in the minimum brace area. This indicates that the effective brace stiffness of a cross-frame line is dependent on the layout of the system as well as the number, size, and position of the cross-frames in that cross-frame line.

Exterior Cross-frame Layout	$\frac{A_{br,lean}}{A_{br,lean,min}}$	Interior Cross-frame Layout	$\frac{A_{br,lean}}{A_{br,lean,min}}$
	1.02		1.18
	1.20		1.17
	1.07		1.00
	1.20		1.07
	1.00		

Using the examples in Table 3 for reference, the lean-on cross-frame lines performed best when the distribution of cross-frames was equal and opposite about the axes of symmetry of the bridge. Additionally, cross-frames in adjacent cross-frame lines in direct contact increased the efficiency of the braces. This led to the categorization of two layout effects which aided in the development of design recommendations:

- Global layout effect
- Local layout effect

The global layout effect is categorized based on the global distribution of the cross-frames, as illustrated in Fig. 9. The distribution should be centered about the axes of symmetry of the bridge system, aiming for opposite sections of the bridge to have equal cross-frame distributions. Biases in the distribution lead to lower stiffness and a reduction in the maximum moment capacity.

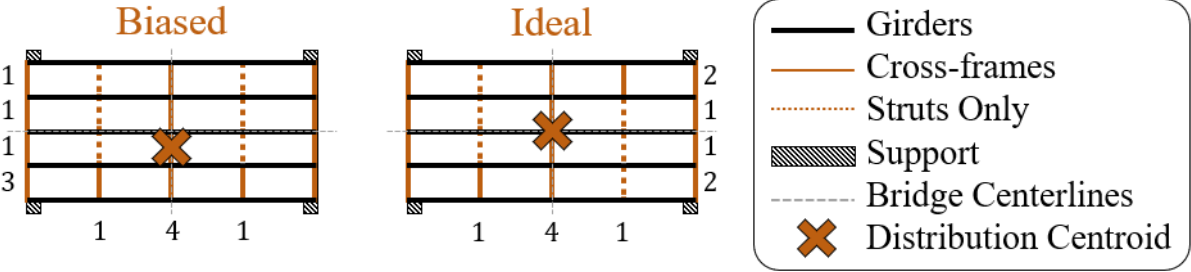


Figure 9: Illustration covering the source of the global layout effect

The local layout effect is categorized based on the interaction between adjacent cross-frame lines and is highlighted in Fig. 10. Cross-frames of adjacent cross-frame lines in the same bay provide greater stiffness than cross-frames in different bays. Failure to link corresponding cross-frame lines lowers the maximum moment capacity and alters displacement distributions (maximum displacement is no longer about a critical geometric imperfection). This layout effect can cause amplified differential displacements and brace stresses in systems with geometric imperfections.

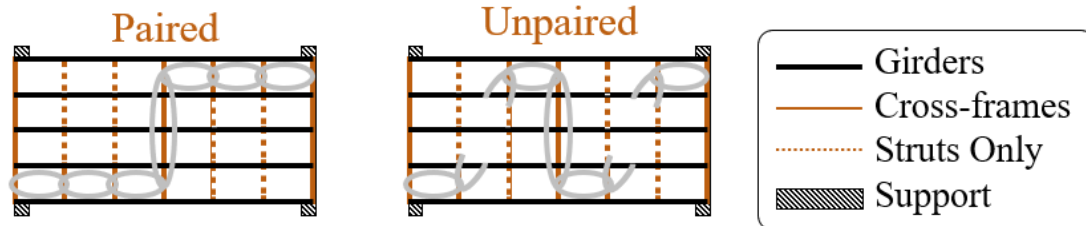


Figure 10: Illustration covering the source of the local layout effect

The layout effects can be further highlighted by examining the displacements and member stresses of bridge systems with poor local and global layouts at the ideal stiffness. Local layout effects are demonstrated with Bridge 8 and global layout effects with Bridge 19 in Fig. 11. Both reduce the maximum moment capacity (maximum load proportionality factor, LPF), but local effects specifically can cause a drastic increase in the member stresses and changes in the final displaced shape.

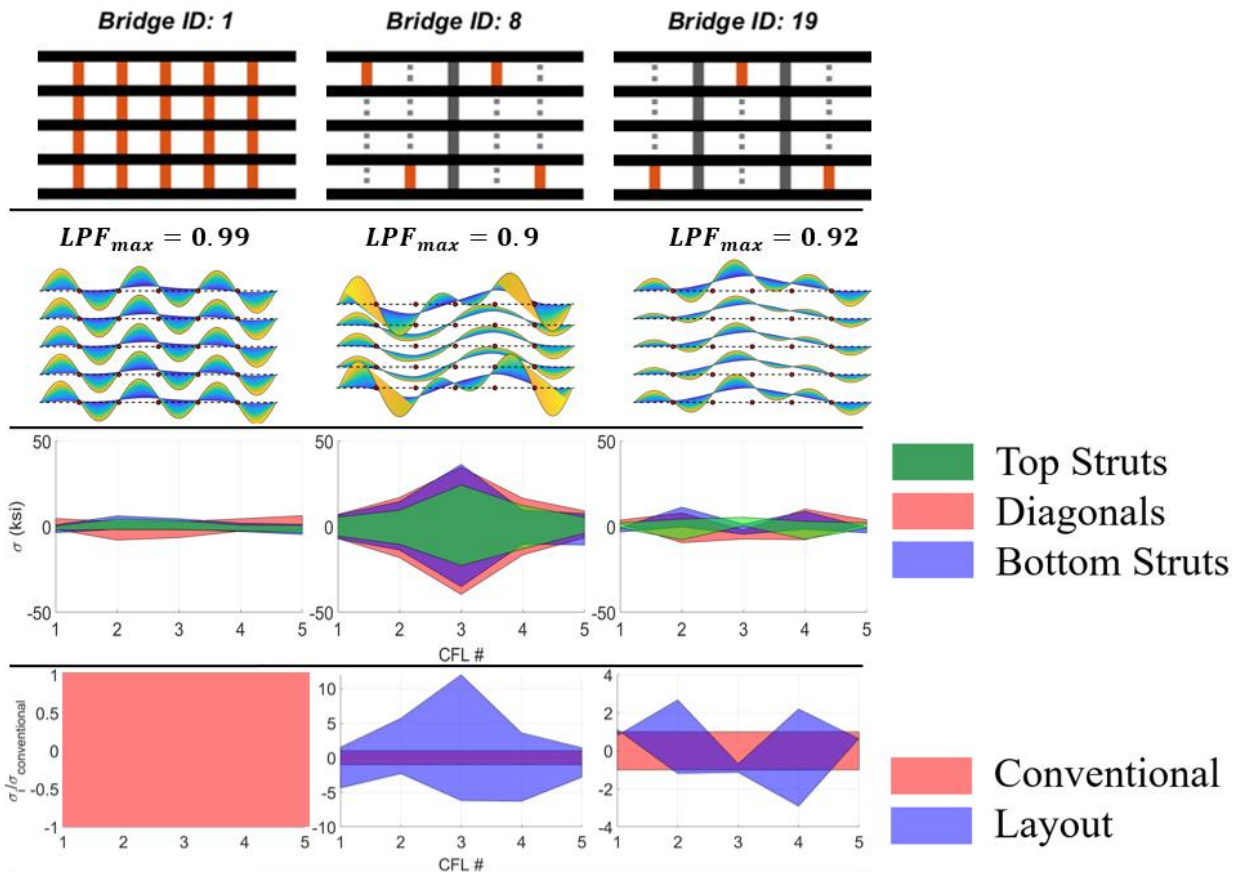


Figure 11: Maximum layout brace stress envelope for multiple layouts

In addition to the layout effects, adjacent leaning girders also had a substantial effect on the performance of layouts. This is best highlighted by the systems with cross-frames extending from the exterior. The impact of not only the global cross-frame distribution, but of the number of adjacent leaning girders on the total diagonal brace volume requirement is shown in Fig. 12. As the plot demonstrates, a biased distribution with the most adjacent leaning girders possible will have a brace volume requirement nearly 4 times greater than that of a conventional system.

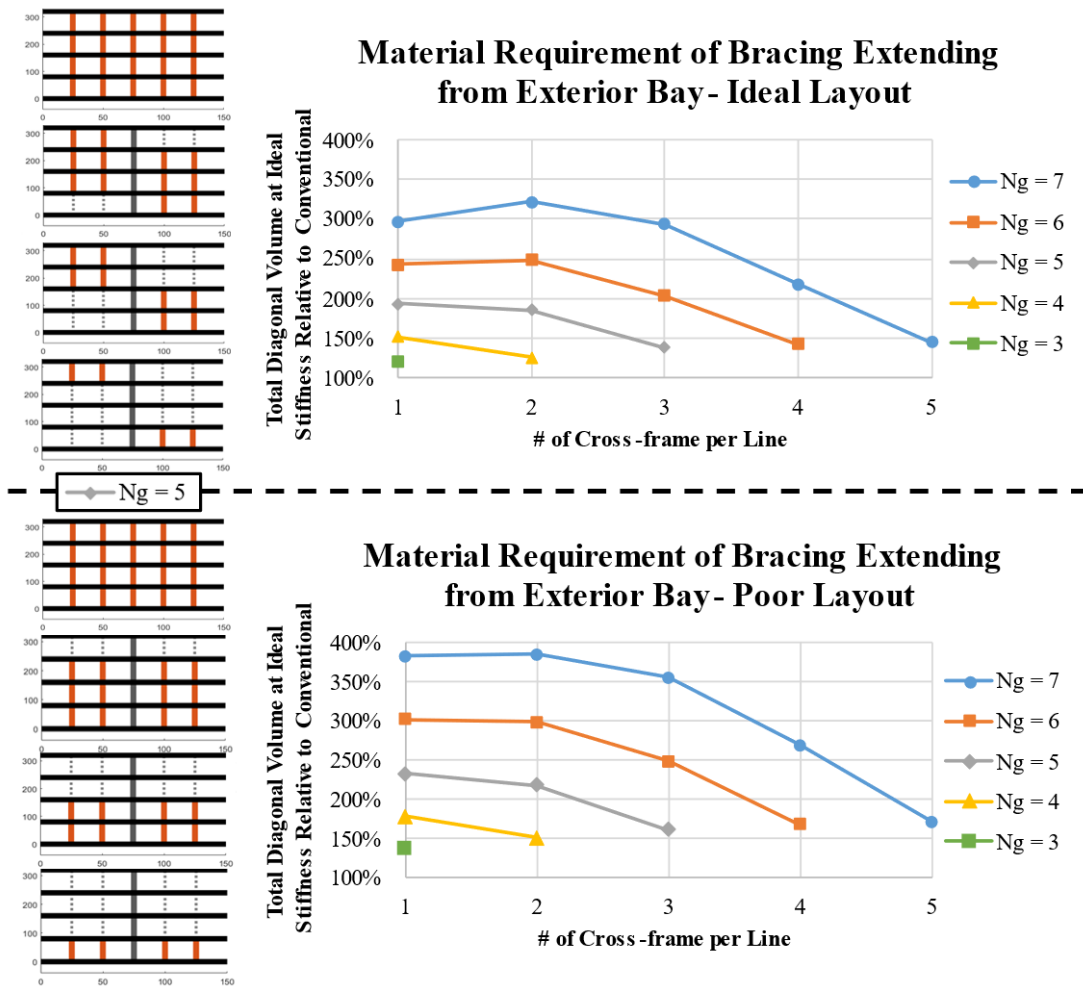


Figure 12: Global layout effect and number of adjacent leaning girders on bracing material requirements

Thus, minimizing the number of adjacent leaning girders by using cross-frame lines, such as the ones illustrated in Fig. 13, is key to improving cross-frame line performance. The cross-frame lines in Fig. 13 reached the ideal stiffness within 20% of the material used in the conventional cross-frame line.

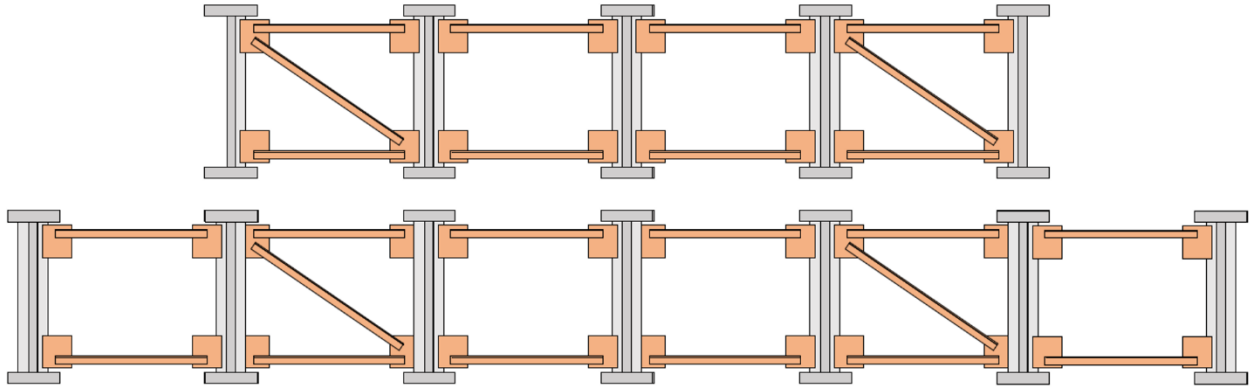


Figure 13: Effective lean-on cross-frame line for reducing brace area requirements

The study emphasizes the need to link corresponding cross-frame lines, distribute cross-frames about the axes of symmetry, and minimize the number of adjacent leaning girders. The identified layout effects will need to be considered when designing layouts to prevent reductions in moment capacity, brace efficiency, and susceptibility to critical geometric imperfections.

## 5. Conclusions and Future Work

The research paper provides an overview of the effects of lean-on layouts on brace stiffness and considered a wide array of lean-on layouts with an isolated brace stiffness to determine the direct effects of individual layouts on brace stiffness. Overall, the results highlight two unique behaviors related to the layout: global and local layout effects. The global layout effect was based upon the distribution of the cross-frames throughout the system whereas the local layout effect was dependent on the linkage of adjacent cross-frame lines. Both effects had implications such as reducing system capacity and causing susceptibility to imperfections. Additionally, adjacent leaning girders were shown to cause reductions in brace efficiency.

Future work will involve better quantifying the effects of leaning girders on layout efficiency and the effects of layout on the in-plane girder stiffness. In addition, layout effects on skew systems will be explored.

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## References

- AASHTO. (2020). "LRFD bridge design specifications." Washington DC: AASHTO, 9.
- AISC. (2017). "Specification for structural steel buildings." *ANSI/AISC 360*, Chicago: AISC.
- Fish, D., Bjelland, A., Helwig, T.A., Engelhardt, M, Park, S. (2024). "Torsional Beam Bracing Design for Straight I-shaped Girder Systems." Unpublished.
- Han, L., Helwig, T.A. (2020). "Elastic Global Lateral-Torsional Buckling of Straight I-Shaped Girder Systems." *Journal of Structural Engineering*, ASCE, 146(4) 10 (pages).
- Helwig, T.A., Wang, L. (2003). "Cross-Frame and Diaphragm Behavior for Steel Bridges with Skewed Supports." *Research Report 1772-1*, Report for Texas Department of Transportation.
- Liang, C., Reichenbach, M., Helwig, T.A., Engelhardt, M.D., and Yura, J. (2022). "Effects of Shear on the Elastic Lateral Torsional Buckling of Doubly-Symmetric I-Beams." *ASCE Journal of Structural Engineering*, 148(3) (14 pages).
- Prado, E. and White, D. (2015). "Assessment of Basic Steel I-Section Beam Bracing Requirements by Test Simulation." *Report to the Metal Building Manufacturers Association*.
- Reichenbach, M., White, J., Park, S., Zecchin, E., Moore, M., Liu, Y., Liang, C., Kovesdi, B., Helwig, T.A., Engelhardt, M.D., Connor, R., and Grubb, M. (2021). "Proposed Modification to AASHTO Cross-Frame Analysis and Design, NCHRP Research Report 962." 156 (pages).
- Timoshenko, S.P., Gere., J.M. (1961). "Theory of elastic stability." McGraw Hill, NY.
- Wang, L., Helwig, T.A. (2005). "Critical Imperfections for Beam Bracing Systems." *Journal of Structural Engineering*, ASCE, 131(6) 933-940.
- Winter, G. (1960). "Lateral Bracing of Columns and Beams." *ASCE Transactions*, 125 809-25.
- Yangqing, L., Helwig, T.A. (2020). "Torsional Brace Strength Requirements for Steel I-Girder Systems." *Journal of Structural Engineering*, ASCE, 146(1) 10 (pages).
- Yura, J.A., Philip, B., Raju, S., Webb, S. (1992). "Bracing of steel beams in bridges." *Research Rep. No. 1239-4F*, Austin, TX: Center for Transportation Research, University of Texas at Austin.
- Yura, J.A. (2001). "Fundamentals of beam bracing." *Engineering Journal*, American Institute of Steel Construction, 38(1) 11-26.