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# IMPROVED CROSS FRAME CONNECTION DETAILS FOR STEEL BRIDGES WITH SKEWED SUPPORTS

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**Abstract**. *Cross-frames are essential to straight steel girder bridge system stability during construction. However, due to fabrication complexities, these braces often make up a large percentage of the bridge cost and when they transmit live load forces, they can produce fatigue cracks at their connections to the girders. At the abutments of skewed bridges current detailing specifications require the cross frames to be parallel to the skew angle. Many jurisdictions currently use a bent plate to connect the skewed end cross frames to the girders. A Texas Department of Transportation sponsored research study is underway at The University of Texas to investigate the bent plate connection's impact on girder stability and develop alternative connection details for skewed steel bridge end cross frames. A connection candidate being investigated consists of using a round half-pipe stiffener to connect the girder to the cross frame. This paper investigates the pipe stiffener's impact on girder buckling strength.*

## 1 INTRODUCTION

A major skewed steel bridge issue is the differential deflections that occur along a contiguous line of intermediate cross frames as trucks pass over the bridge. When these differential deflections occur, the cross frames become part of the live load structural system and help carry the live loading between the girders. This in turn can lead to fatigue cracking at the girder to cross frame welds – especially near the skewed abutments where the differential deflections are the greatest.

One way to mitigate the differential deflections and associated fatigue cracking is to position the first intermediate cross frame line farther away from the skewed abutment. This will lessen the differential deflections along the first and subsequent cross frame lines. However, to ensure elastic stability during placement of the concrete slab over the longer unbraced length, a source of stability must be found to compensate for the longer unbraced girder length during concrete deck placement. One solution is to provide warping restraint to the girder flanges at the skewed end cross frame connection.

Current end cross-frame detailing specifications require the end cross frame to be placed parallel to the skewed support, and hence at an angle to the girders [1]. To provide access for welding during fabrication and erection, plates, bent to match the skew angle, are often used to connect the cross-frames to the girder. Such a connection provides little if any warping restraint. However, if a pipe, welded to the girder web and both flanges, is used to connect the end cross frames then significant warping restraint will be provided to the girders [2]. Such a connection is shown in Figure 1.

The attractiveness of the half-pipe stiffener detail lies in its fabrication and structural advantages. Besides offering warping restraint, the pipe stiffener connection accommodates any skew angle and can standardize the cross frame connection in any bridge orientation. Finally, the pipe stiffener offers the possibility of a more rigid connection increasing the end cross frame stiffness and its ability to prevent girder end twist during slab placement.

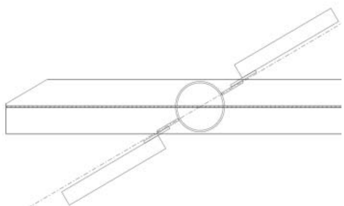

Figure 1: Pipe stiffener skewed end frame connection.

## 2 LABORATORY TESTING AND FINITE ELEMENT MODEL VALIDATION

Previous analytic studies have shown significant increases in buckling strength when warp restraining devices are used to connect a girder's top and bottom flange [3], [4]. During this study, laboratory tests were conducted to confirm these analytic results for a pipe stiffener. A finite element model was then created and validated with the laboratory results.

### 2.1 Laboratory Testing

A series of twin girder buckling tests were conducted at Ferguson Structural Engineering Laboratory at The University of Texas at Austin to confirm the analytical results in the literature. Pipe stiffened and plate stiffened 17m long W760x134 rolled girders were tested using a gravity load simulator to deliver a concentrated load at the mid-span of each girder. The ends of the girders were supported with a simple support and lateral restraints were used to prevent twist at the ends of the girders. A picture of a typical test is shown in Figure 2.

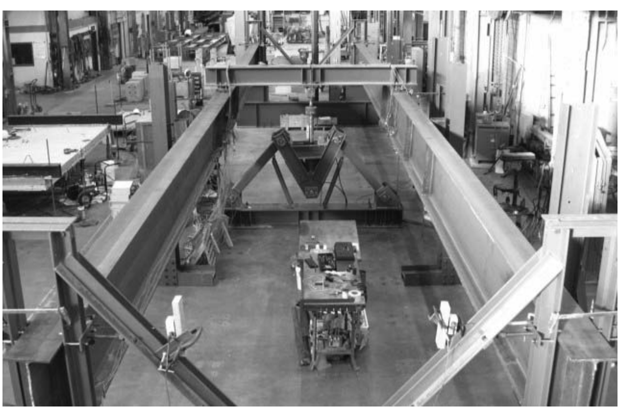

Figure 2: Plate stiffened twin girder buckling test.

Comparisons for the results from the plate and pipe stiffened girders are shown in Figure 3. Shown in the figure are the results for the mid-span top flange lateral displacement of each girder type. From the figure it can be seen that the warping restraint provided by the pipe stiffener increases the buckling capacity of the girder by about 50%. This finding is consistent with the previously mentioned analytical results.

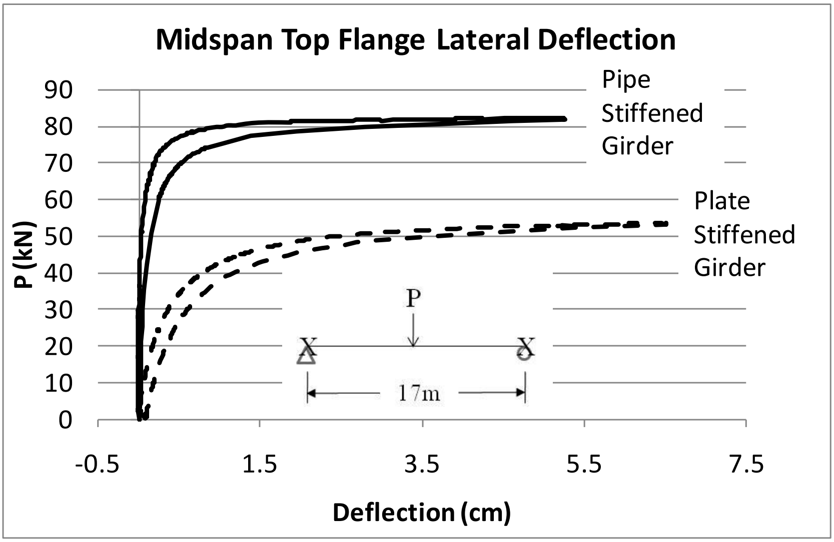


Figure 3: Pipe and plate stiffened girder buckling test laboratory results.

**2.2 Finite Element Model Validation**

In order to extend these results to other girder geometries, a finite element model of a pipe stiffened girder was created. The model was built in the three dimensional finite element modeling program ANSYS 11.0 using eight node shell elements. A picture of the pipe stiffened girder model is shown in Figure 4.

Figure 4: Pipe stiffened girder finite element model (elements shown).

A nonlinear geometric analysis of the model was run to compare with the laboratory results for the pipe stiffened girder. The analysis included the girder's initial imperfection and self weight. A graph of the results of the mid-span top flange lateral deflection comparison is shown in Figure 5. From the figure it can be seen that the model is conservative by about 2% at the maximum applied load. The main sources of conservatism are due to several assumptions made during modeling. First, it was assumed that the lateral stops at the end of the girder provide no warping restraint. Second, only a modest increase in the cross sectional torsional constant was made to account for the size of the W760x134 rolled shape fillet, while the fillet size at the girder ends were slightly larger than the average values given by the Steel Construction Manual [5]. Finally, the cross section geometry was assumed to be constant throughout its length. Despite these conservative assumptions and expected conservative result, the graph shows reasonable agreement between the specimen and model.

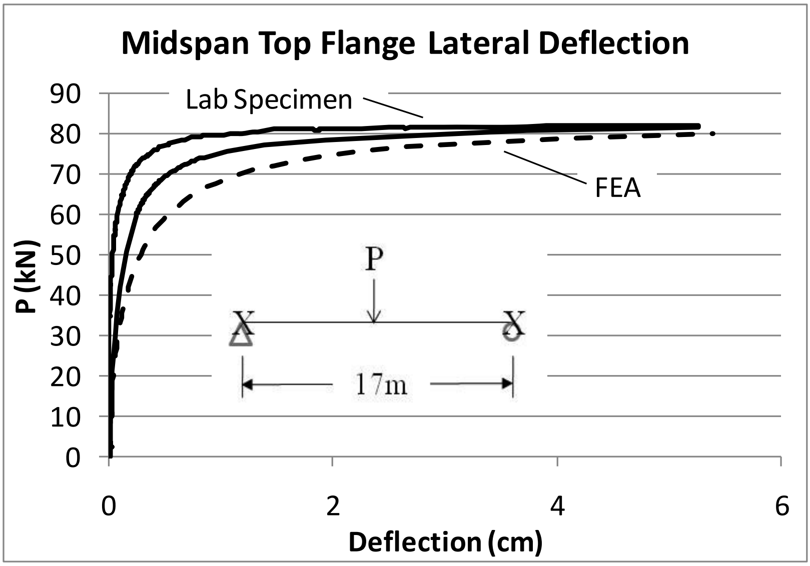


Figure 5: Lab specimen to FEA comparison for mid-span top flange lateral deflection

## 3 DESIGN EQUATION DEVELOPMENT

### 3.1 Background

The basic elastic buckling strength of bridge girder subject to uniform moment is defined by Equation 1 [6].

$$M_o = \pi / L_b \sqrt{EI_y GJ + \pi^2 E^2 C_w I_y / L_b^2} \tag{1}$$

where

E = Young's modulus
$I_y$ = weak axis moment of inertia
$L_b$ = unbraced length
G = shear modulus
J = torsion constant
$C_w$ = warping constant
$L_g$ = total girder length

Two of the assumptions in Equation 1 are that the ends of the girder do not twist and are free to warp. However, due to flexible cross frame connections and skewed abutments neither of these assumptions is necessarily accurate at the end of skewed bridge girders. Previous research on the impact of end connections on girder twist has shown that most supports are much more torsionally stiff than the girder cross section, so any restraint provided by the end frame will more than adequately resist the loss of strength due to twist [7]-[9], and therefore the no-twist assumption can be used with little impact on the buckling strength of bridge girders.

However, as has been shown through the previously mentioned laboratory results and analytical studies, warping restraint can significantly improve the girder buckling strength. Typically warping restraint has been treated as an all or nothing proposition where accounting for its impact on buckling strength means either considering no warping restraint or infinite warping restraint [2]. But, the use of a closed pipe section to restrain warping by bracing one flange against the other does not provide such a clear boundary condition.

An accurate numeric integration technique to predict the buckling capacity of a girder with warping restraint provided by a pipe stiffener has been developed [3]; however, this highly iterative method does not lend itself to routine design practice. Additionally, while the impacts of warping restraint of adjacent girder sections on the critical sections have been researched and a simplified analysis procedure has been found [2], this technique does not apply to warping restraint provided to the end of girders. Fortunately, by relying on basic column buckling theory and the side-sway inhibited alignment chart [5], a simplified method can be used to aid in girder design where pipe stiffeners provide warping restraint to the girder ends.

### 3.2 Pipe Stiffener Design Methodology

An examination of Equation 1 shows that the terms under the radical define both components of the girder's resistance to lateral torsional buckling. The first term is the uniform (St. Venant) torsional resistance and the second term is the torsional warping resistance. Therefore, the warping resistance provided by a pipe stiffener could be incorporated into the second term as an effective torsional length factor ($K_z$) as shown in Equation 2. Such a method has previously been employed to calculate the impact of warping restraint provided by adjacent unbraced girder lengths [2].

$$M_o = C_b \pi / L_b \sqrt{E I_y G J + \pi^2 E^2 C_w I_y / (K_z L_b)^2} \tag{2}$$

where

$C_b$ = moment gradient coefficient
$K_z$ = effective length factor for torsion

The critical parameter in determining $K_z$ for a pipe stiffener lies in the relative rotational stiffness of the girder's compression flange about its strong axis ($2EI_f/L$ where $I_f$ is the flange's strong axis moment of inertia) to the torsional stiffness of the pipe ($GJ/L$). If the torsional stiffness of the pipe is much greater than that of the girder flange then $K_z$ will approach 0.5 (torsionally fixed). Likewise if the pipe's stiffness is much smaller than the flange's stiffness then $K_z$ will approach 1.0 (torsionally free). This is analogous to a sidesway inhibited column where the torsional stiffness of the pipe is considered as the flexural stiffness of a girder framing into the end of a column. Approaching the problem in this way allows the sidesway inhibited alignment chart for columns to be used to select an appropriate $K_z$, where the relative rotational stiffness of the girder flange to the torsional stiffness of the pipe is used to calculate $G_A$ or $G_B$ at the girder's pipe stiffened end.

In order to use the alignment chart, the chart's assumption that the stiffening girders bend in single curvature in the formulation of the chart's G-value must be considered in terms of the pipe stiffener. If the pipe is much stiffer than the girder flanges, then as the flanges attempt to warp in opposite directions they will be rigidly held in position by the pipe. This condition would result in multiplying the assumed stiffening girder or analogous pipe stiffness by three in the equation for G used in the chart. As the torsional stiffness of the pipe drops relative to the flexural stiffness of the girder flanges, then this multiplier drops to one. Using this logic for pipe stiffeners G may be defined as in Equation 3.

$$G = \frac{\left(EI / L_b\right)_{flange}}{m\left(GJ / L\right)_{pipe}} \tag{3}$$

where

I = flange strong axis moment of inertia
m = pipe stiffness multiplier based on relative stiffness of pipe to flange ($1 \le m \le 3$)
L = pipe length

The difficulty in assessing the value of m comes from the indeterminate nature of the pipe boundary conditions. Since the boundary conditions depend on the relative torsional stiffness of the pipe to the flexural stiffness of the flange and in turn the flexural stiffness of the flange depends on the torsional stiffness of the pipe there is no simple solution to define m. Therefore, a parametric study using the 3-D finite element modeling program ANSYS and the previously described pipe stiffened girder model was used to establish values of m for corresponding ratios of the pipe torsional stiffness to the girder flange flexural stiffness.

### 3.3 Parametric Study to Determine m

The cross sections used in the parametric study to determine m are shown in Figure 6.

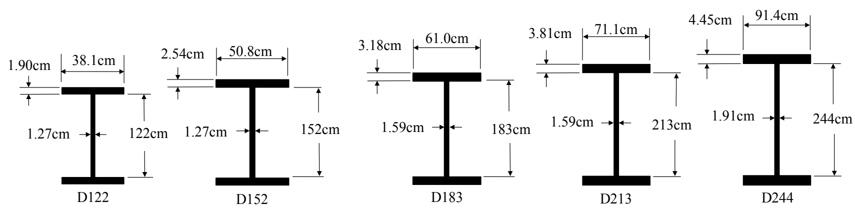


Figure 6: Cross sections used in parametric study.

Each cross section was analyzed via eigenvalue analysis with simple supports and no end twist using span to depth ratios of 10 to 40 in increments of 5. Uniform moment, mid-span concentrated load, and uniform loading were considered for each cross section and span to depth ratio. Each case was run with and without a pipe stiffener. Pipe diameters were varied from one half the flange width to two inches less than the flange width. All pipes used had a 1.27cm wall thickness. Based on the parametric studies, the values of m in Table 1 were selected.

Table 1: m values from parametric study.

| m | $(GJ/L)_{pipe}/(EI/L_b)_{flange}$ |
|---|---|
| 1.0 | < 4 |
| 1.5 | 4 - 6 |
| 3 | > 6 |

### 3.4 Analytic Equation Results

A comparison between the analytic solution given by Equation 2 and the finite element analysis for two of the cross sections, load cases, and pipe sizes are given in Figure 7 and Figure 8. The pipe stiffened girder critical loads have been normalized by the values for the critical loads for the non-pipe stiffened section and all span (L) to depth (D) ratios investigated are shown in the graphs.

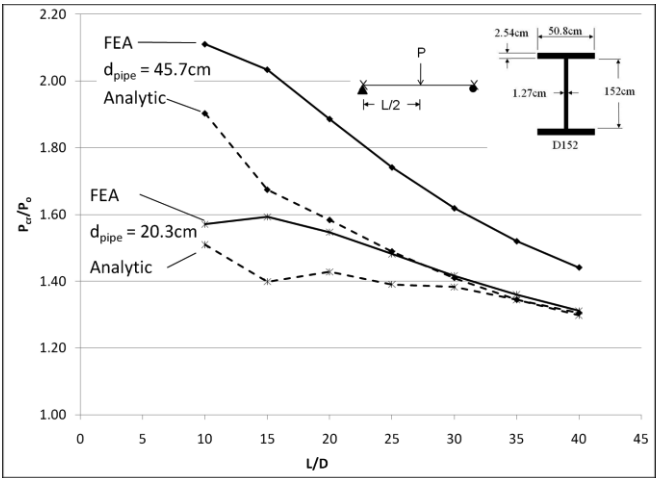


Figure 7: D152 analytic to FEA pipe stiffener comparison (point load).

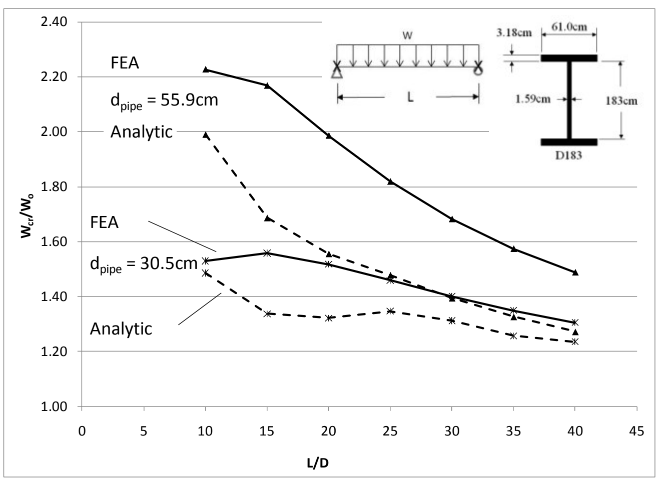


Figure 8: D183 analytic to FEA pipe stiffener comparison (distributed load).

From the graphs the increase in buckling capacity due to the pipe stiffener is evident. Additionally it can be seen that the analytic solution using Equation 2 is conservative with respect to the FEA solution. The majority of this conservatism comes from Equation 2 only accounting for the additional warping restraint provided by the pipe stiffeners. Additionally, the uniform (St. Venant) stiffness has also been increased and is not accounted for in Equation 2. It is conservative to neglect this effect and this leads to underestimating the FEA buckling strength by around 20% for the largest pipe diameters.

## 4 CONCLUSION AND FUTURE WORK

The laboratory tests and finite element modeling results in this study confirm that the warping restraint provided by a pipe stiffener installed at the ends of simply supported girder substantially increases the girder's elastic buckling capacity. Therefore, a pipe stiffener cross frame connection is a good candidate to increase the unbraced length at the end spans of a skewed steel bridge and allow the first row of intermediate cross frames to be moved farther from the abutment. By doing so, the differential deflections along the cross frame lines will be decreased, therefore mitigating fatigue related cracking at the cross frame connections.

In addition to the warp restraint it provides, the half pipe stiffener allows a cross frame connection at almost any skew angle and can also serve as an integral bearing stiffener. Therefore it can be used to standardize connections for a wide variety of bridge skew angles. Additionally, in fatigue tests performed at Ferguson Structural Engineering Laboratory, the pipe stiffener performs at least as well as the plate stiffener. While this may not be a concern at the abutment, should the pipe stiffener be used in the negative moment region at an intermediate support, its connection to the tension flange will be exposed to fatigue.

Finally, a simplified method to calculate the increase in buckling capacity due to the warping restraint provided by the pipe stiffener has been proposed. This method, based on the no-sway alignment chart in the Steel Construction Manual [5], gives designers a simple and conservative tool to calculate the increase in unbraced length due to the pipe stiffener.

Further tests are underway at Ferguson Structural Laboratories to compare the commonly used bent plate connection and the pipe stiffener connections. These tests consist of a series of three girder tests with end and intermediate cross frames with 53° and 24° skew angles. These results will be used to quantify the stiffness of the two connections and further validate the finite element modeling of the connections and cross frames used in skewed steel bridges.

## REFERENCES

[1] AASHTO/NSBA Steel Bridge Collaboration. *Guidelines for Design for Constructibility.* AASHTO, 2003.

[2] Structural Stability Research Council. *Guide to Stability Design Criteria for Metal Structrues.* Edited by T.V. Galambos. New York: John Wiley & Sons, 1988.

[3] Ojalvo, M., and R.S. Chambers. "Effects of Warping Restraints on I-Beam Buckling." *ASCE Journal of the Structural Division* 103, no. ST12 (1977): 2351-2360.

[4] Hunt, Fred A. "The Suppression of Warping in Thin-Walled Beams." *M.S. Thesis Submitted to The Ohio State University.* 1973.

[5] American Institute of Steel Construction. *Steel Construction Manual.* Chicago: American Institute of Steel Construction, 2005.

[6] Timoshenko, Stephen P., and James M. Gere. *Theory of Elastic Stability.* New York: McGraw-Hill, 1961.

[7] Schmidt, Lewis C. "Restraints Against Elastic Lateral Buckling." *Journal of the Engineering Mechanics Division*, December 1965: 1-10.

[8] Flint, A.R. "The Influence of Restraints on the Stability of Beams." *The Structural Engineer*, 1951: 235-246.

[9] Bose, B. "The Influence of Torsional Restraint Stiffness at Supports on the Buckling Strength of Beams." *The Structural Engineer*, December 1982: 69-75.