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Predicting Girder End Twist in Skewed Straight Steel Girder Bridges

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Abstract

Girder end twist in straight skewed steel girder bridges presents significant challenges during bridge erection. The amount of twist at the end of a skewed girder is difficult to predict yet must be accounted for in erection planning to facilitate the fit-up of end cross frames and to achieve a vertical web under the specified loading condition. Through the use of large scale laboratory experiments this paper investigates the sources of end twist including skew and stability effects. The causes of end twist restraint are considered including the stiffness of the end cross frames and tipping restraint provided by the bearing.

1. Introduction

The existence of girder end twist in straight skewed steel girder bridges (shown in Fig. 1) was debated for a significant period of time (Ude, 2009), however recent field, laboratory, and finite element modeling have documented the deformational behavior related to the skewed geometry, (Colletti, Chavel, & Gatti, 2009), (Ude, 2009). While these studies provided insight into the behavior, the sources of girder end twist and restraint in skewed steel girder bridges have yet to be fully investigated in the laboratory.

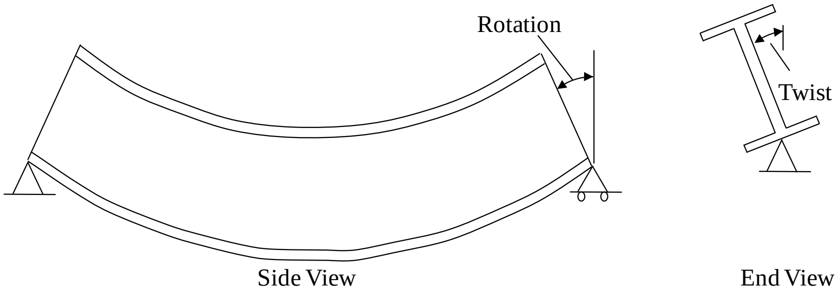

Figure 1: Girder Rotation and End Twist

Provided the end restraint is approximately 20 times the torsional stiffness of the girder, the impact of end twist on the girder buckling strength is relatively small for typical span to depth

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ratios of 20 to 30 (Quadrato, Helwig, Engelhardt, & Frank, 2010). Still, girder end twist plays a significant role in the fit-up of end cross frames and the position of the web under construction loading. Predicting the amount of end twist in a girder is necessary for the proper fabrication of the cross frames to ensure proper installation during erection and to achieve acceptable web plumbness in the final bridge.

Predicting girder end twist in straight skewed steel girder bridges is complicated because there are two sources of twist and two possible sources of restraint. One source of twist is due to the skewed effects (Colletti, Chavel, & Gatti, 2009), and the other is due to the stability forces (Bose, 1982). Additionally there are two possible sources of end twist restraint. One is the cross frame that limits the twist of adjacent girders, and the second is the restraint to tipping provided by the bearing. The interaction of these sources of twist and restraint make it difficult to accurately predict girder end twist.

The Texas Department of Transportation (TxDoT) sponsored a study at The University of Texas at Austin focused on understanding the impact of torsional bracing connection details on the stability behavior of straight bridge girders with skewed supports. The study consisted of full-scale experiments conducted at Ferguson Structural Engineering Laboratory that compared the girder buckling behavior of different bracing details. The two details that were considered consisted of a bent plate connection detail that is frequently used in skewed bridges with a newly proposed split (round) pipe detail. The resulting test data is analyzed in this a paper and a method to isolate the individual sources of twist and its restraint in the laboratory experiments is presented. Additionally, observations are made about the sources of skewed girder end twist and its restraint. The two large scale specimens that are the subject of this study are described below.

2. Test Specimens

Both specimens consisted of three W30x90 standard steel shapes spanning 56ʹ with 9ʹ spacing on a 53.13˚ skew, as depicted in Figs. 2 and 3, with one specimen using the split pipe end cross frame connection and the other using the bent plate cross frame connection detail.

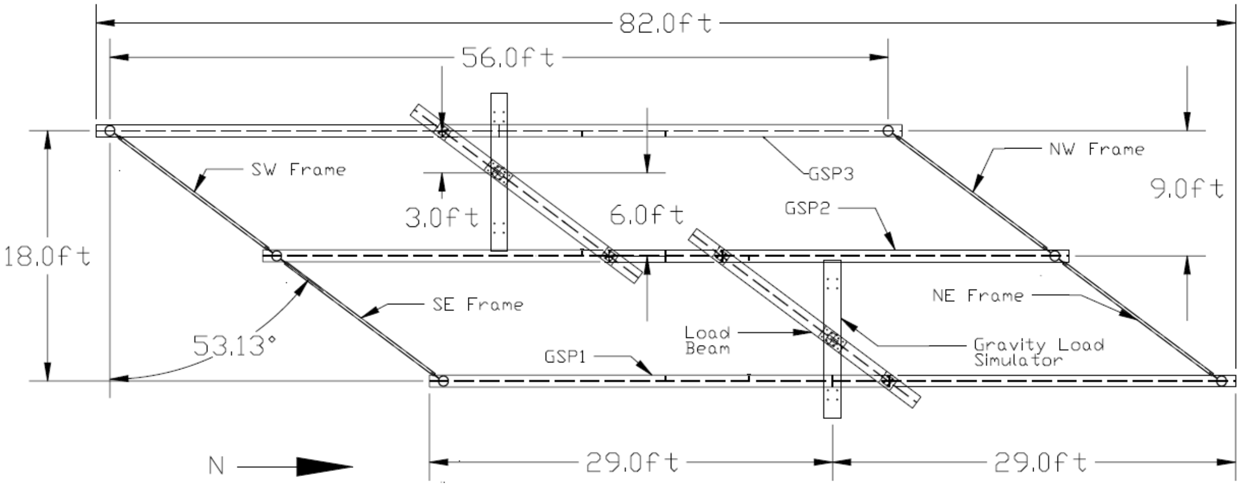

Figure 2: Large Scale Test Set Up

Figure 3: Large Scale Test Set Up (looking south)

The details of the split pipe and bent plate connections are discussed in (Quadrato, Helwig, Engelhardt, & Frank, 2010). Based on laboratory validated, finite element modeling of such cross frames in the previously mentioned reference, the split pipe detail provided a cross frame and connection nearly three times as stiff as the bent plate detail at the 53˚ skew angle and thus provides an indication of the impact of cross frame stiffness on the girder end twist.

The impact of tipping restraint was analyzed by providing two different types of bearing pads for each of the two specimens. The first set of bearing pads was commercially fabricated and sized in accordance with the TxDoT standard bearing EE1 (3.5" x 9" x 15" with 50 durometer rubber) and the second set of bearings was manufactured to the same standard without the TxDoT specified seven steel shims. Both bearings were compression tested in the lab with the unshimmed bearings having a compressive stiffness of 22 k/in and the shimmed bearings having a 178 k/in stiffness. Therefore the unshimmed bearing pads provided negligible tipping restraint, while the shimmed bearing pads provided a very stiff source for tipping restraint.

3. Test Results

The results for the girder end twist for the north and south ends of the center girder are show in Figs. 4 and 5. These graphs do not flatten out from the buckling since they show the twist at the supports where the girders are braced. The twists therefore represent the deformations due to axial shortening in the members of the cross frame. Fig. 4 shows the results for both specimens with the unshimmed bearings while Fig. 5 shows the results for both shimmed bearing specimens. The positive sign convention is defined as a clockwise rotation looking north in all figures.

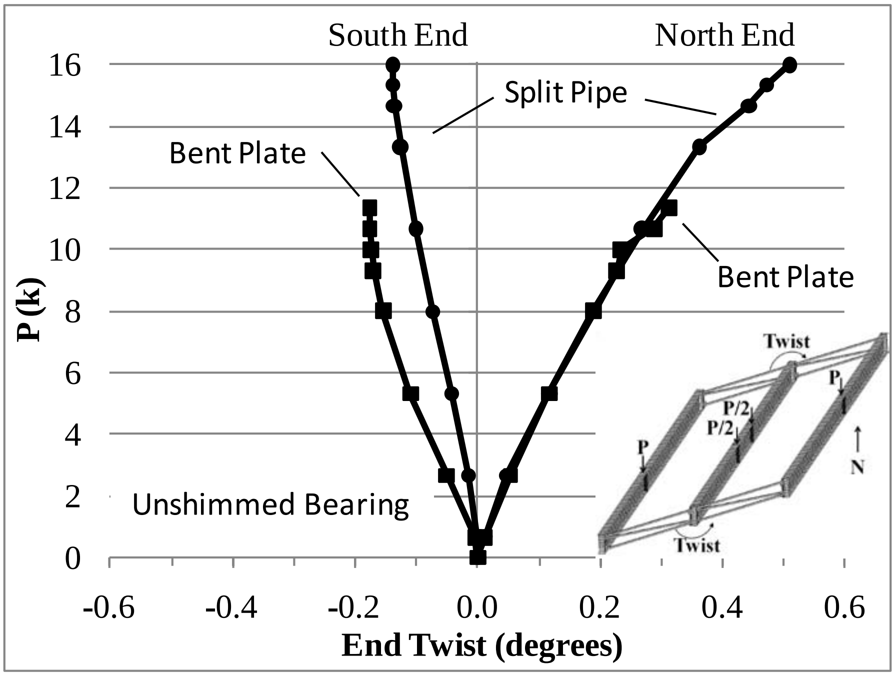

Figure 4: Unshimmed Bearing Specimen Girder End Twist

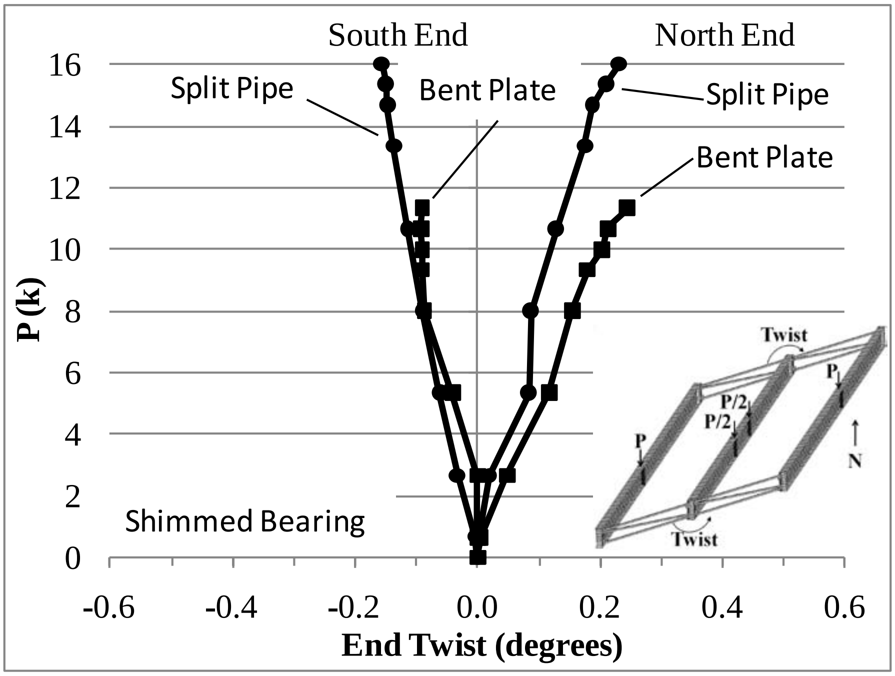

Figure 5: Shimmed Bearing Specimen Girder End Twist

Several observations can be made based upon a comparison of the test results. First, the northern ends of all specimens twisted more than the southern ends primarily due to the initial imperfections that caused a positive twist during buckling. Therefore the twist due to the stability forces on the north end was positive and added to the twist from the effects of skew.

Conversely, on the southern end, the twist due to the stability forces works opposite to the skew induced twist. This is most dramatically seen as the specimens approach their buckling loads (approximately 9k for the bent plate specimen and 14k for the split pipe specimen). While on the southern side the twist due to stability restrains the rate of change of twist to near zero, on the northern end the twist increases dramatically as the onset of significant buckling occurs. Finally, comparing the results from the rubber bearing tests to the shimmed bearing tests shows clearly that the stiffer shimmed bearing provided more tipping restraint that resulted in smaller end rotations. For both bearings the twists at the South end were smaller than at the North end. To more fully understand the end twist behavior, each component of the total end twist must be isolated and examined.

4. Sources and Restraints of Girder End Twist

The components that make up the overall twist at the northern and southern ends of the center girder are given in Eqs. 1 and 2.

$$\varphi_{north} = \varphi_{stability} + \varphi_{skew} - \varphi_{tip\ restraint\ north} \tag{1}$$

$$\varphi_{south} = \varphi_{stability} - \varphi_{skew} - \varphi_{tip\ restraint\ south} \tag{2}$$

Where φ_{north} and φ_{south} are the total twist on the northern and southern girder ends respectively, $\varphi_{stability}$ is the twist due to stability effects, φ_{skew} is the twist due to skew effects, and $\varphi_{tip\ restraint}$ is the twist prevented due to the tip restraint provided by the shimmed bearings.

Using Eqs. 1 and 2 and the laboratory test results, each component of girder end twist may be isolated and examined. The sections below describe this process.

4.1 Tipping Restraint

The twist prevented by the tipping restraint provided by the bearings may be directly derived from the laboratory data. The unshimmed bearings were very flexible relative to the shimmed bearing and provided a minimal amount of tipping restraint. Therefore, the total support twist of the shimmed bearing specimens was subtracted from the support twist measured with the unshimmed bearing specimens. The resulting difference in the twist between the two bearings provided an indication of the tipping restraint by providing a relatively stiff bearing. A plot showing the differential twist between the two bearing types is shown in Fig. 6. Several interesting facets of the system behavior can be seen in the figure. First, the bent plate specimen and split pipe specimens behaved very differently. On the southern end, where the combined sources of twist are smaller, the more flexible bent plate specimen mobilized the bearing pad tip restraint while the stiffer split pipe specimen did not. However on the northern end, where the combined sources of twist are greater, the split pipe specimen mobilized the bearing pad tipping restraint while the bent plate specimen did not. This indicates that the degree of tipping restraint provided by the bearing is dependent on both the stiffness of the cross frame as well as the degree of tipping moment generated by the skew and stability forces.

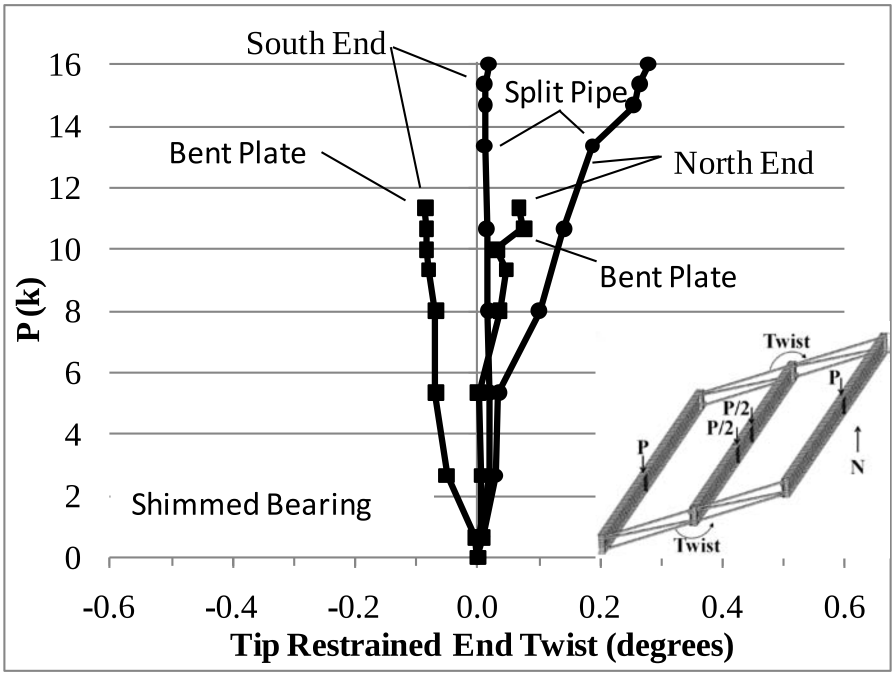

Figure 6: Tip Restraint Provided by Shimmed Bearings

4.2 Girder End Twist Due to Skew Effects

Since the specimen and loading are symmetric, the twist due to skew is equal but opposite on opposing ends, and the twist due to stability is equal in magnitude and direction on both girder ends. Using these facts and subtracting Eq. 2 from Eq. 1 results in the following expression:

$$\varphi_{skew} = \frac{\varphi_{north} - \varphi_{south}}{2} + \frac{\varphi_{tip\ restraint\ north} - \varphi_{tip\ restraint\ south}}{2} \tag{3}$$

Since the total end twist on each girder end is known from the laboratory results and the twist prevented by the tipping restraint has been found in the previous section, the twist due to skew from Eq. 3 may be found.

To verify the accuracy of this result, the analytic solution for girder end twist caused by the skew effect may be used. The analytic solution, as described by Ude (Ude, 2009), relates the end twist to the vertical deflection at mid-span for a simply supported skewed girder exposed to a distributed load. Following the same procedure, the derivation of the two symmetric point load case on the test specimen center girder is shown below. The derivation begins with the equations for the mid-span deflection and end rotation due to two point loads given in Eqns. 4 and 5.

$$\Delta_{\text{mid-span}} = \frac{Pa}{48EI}(3L^2 - 4a^2) \tag{4}$$

$$\theta_{end} = \frac{Pa(L-a)}{4EI} \tag{5}$$

Where $\Delta_{mid\text{-}span}$ is the girder mid-span vertical deflection, P is the applied point load, a is the distance from support to the first load, E is the modulus of elasticity, I is the moment of inertia, L is the girder length between supports, and θ_{end} is the girder end rotation in the plane of the web.

Solving for *P* in Eq. 4 and substituting into Eq. 5 produces the following expression:

$$\theta_{end} = 12\Delta_{mid-span}\left(\frac{L-a}{3L^2-4a^2}\right) \tag{6}$$

Using the vector relationship between the girder end rotation and twist depicted in Fig. 7 yields the trigonometric relationship between girder end twist and rotation given in Eq. 7.

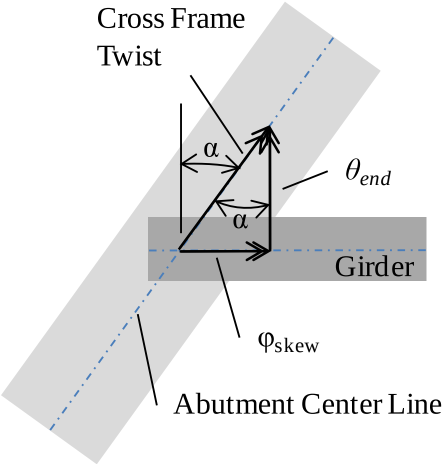

Figure 7: Vector Relationship Between Girder End Rotation and End Twist

$$\varphi_{skew} = \theta_{end}\tan\alpha \tag{7}$$

Where α is the bridge skew angle. Substituting Eq. 6 into Eq. 7 gives the following expression for the twist due to the skew effects in terms of the vertical deflection:

$$\varphi_{skew} = 12\Delta_{mid-span}\left(\frac{L-a}{3L^2-4a^2}\right)\tan\alpha \tag{8}$$

A comparison of the analytic solution predicted by Eq. 8 and the experimental results derived from Eq. 3 is shown in Figs. 8 and 9 for the respective cases of the bent plate unshimmed bearing and the split pipe shimmed bearing specimens.

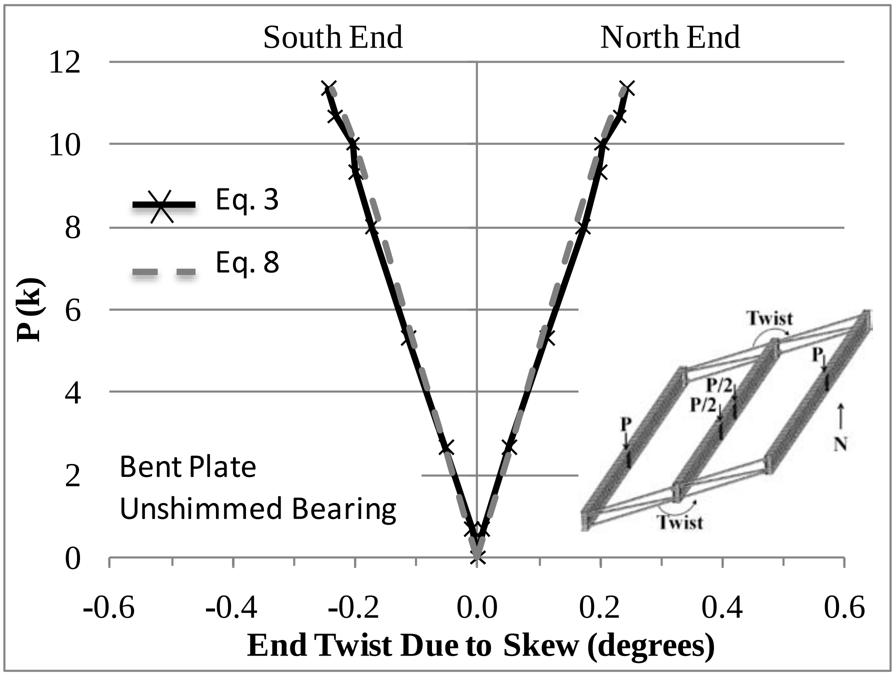

Figure 8: Bent Plate Unshimmed Bearing Specimen End Twist Due to Skew

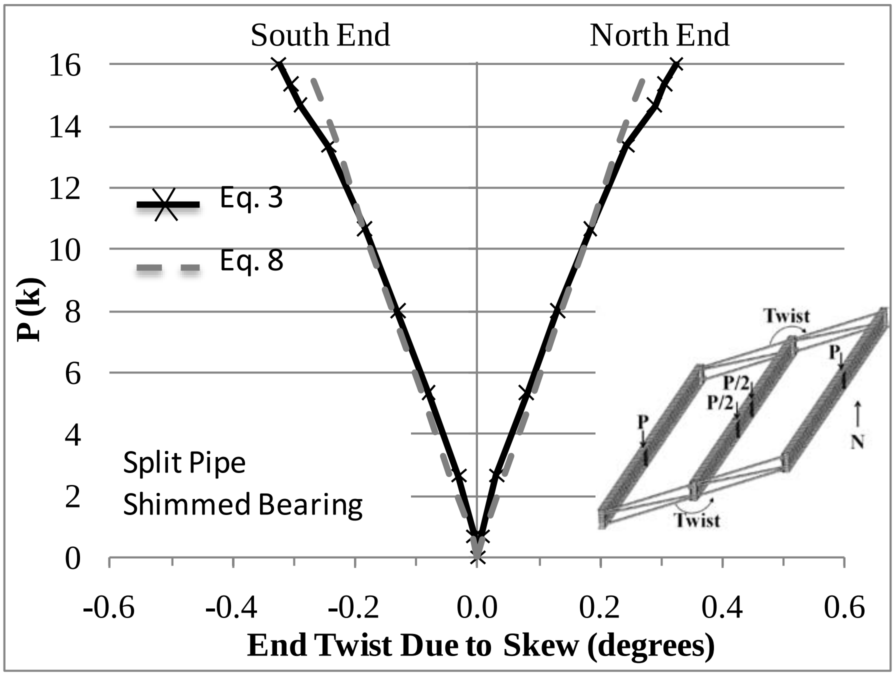

Figure 9: Split Pipe Shimmed Bearing Specimen End Twist Due to Skew

From Figs. 8 and 9 it can be seen that the analytical and laboratory results had very good agreement. Similar agreement was found for the bent plate with shimmed bearings specimen and the split pipe with unshimmed bearings specimen. Additionally, as would be expected, Figs. 8 and 9 confirm that the twist due to skew is symmetric. Additionally, these results strongly suggest that the method of determining the amount of tipping restraint provided by the bearing has reasonable accuracy since the twist due to skew predicted by Eq. 3 for the shimmed bearing specimen depends on the restraint provided by the bearing.

If the bent plate and split pipe specimens end twist due to skew are compared, it can be seen that the stiffer split pipe cross frame connection has less end twist due to skew than the more flexible bent plate connection. This result is shown in Fig. 10. The reason is because the split pipe specimen deflects less vertically at its mid-span then the bent plate specimen. This result is confirmed by the analytical solution given in Eqn. 8 which depends only on the girder mid-span deflection. This is most likely due to the stiffer split pipe cross frame not allowing as much rotation at the girder ends as the more flexible bent plate cross frame. This effect was also noticed in finite element solutions on similar geometries.

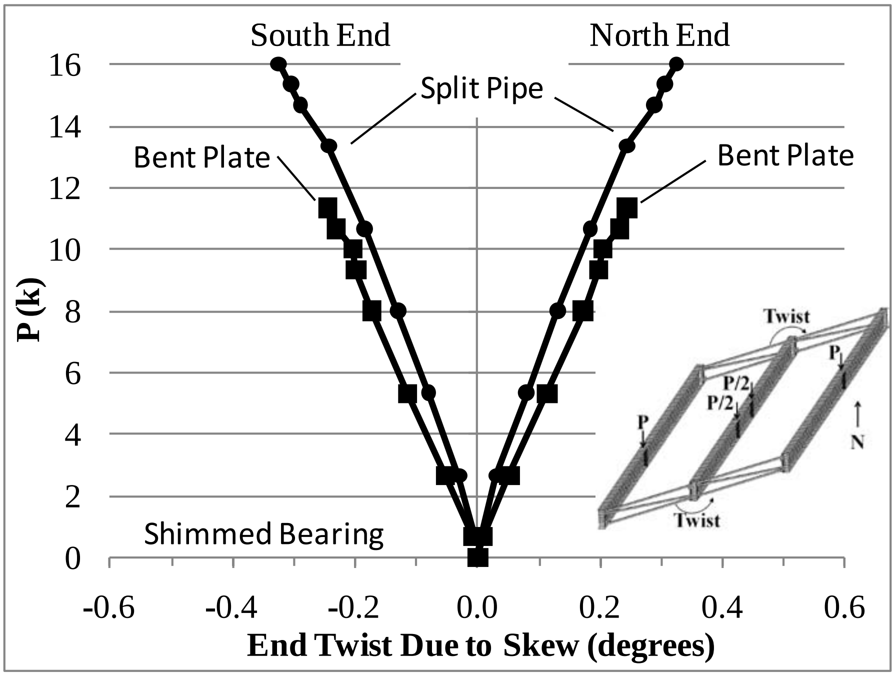

Figure 10: Split Pipe and Bent Plate Shimmed Bearing End Twist Due to Skew

4.3 Girder End Twist Due to Stability Effects

With the tipping restraint and twist from the skew effects isolated, the twist due to the stability effects is the final component to be addressed. This twist can be isolated by solving Eqns. 1 and 3 for $\varphi_{stability}$ and substituting in the known quantities found in the previous sections. The results for the end twist due to stability for the split pipe and bent plate specimens using this method are shown in Figs. 11 and 12, respectively. The plots show that, as expected, the twist due to stability is the same in direction and magnitude on the northern and southern girder ends due to the half-sine mode shape.

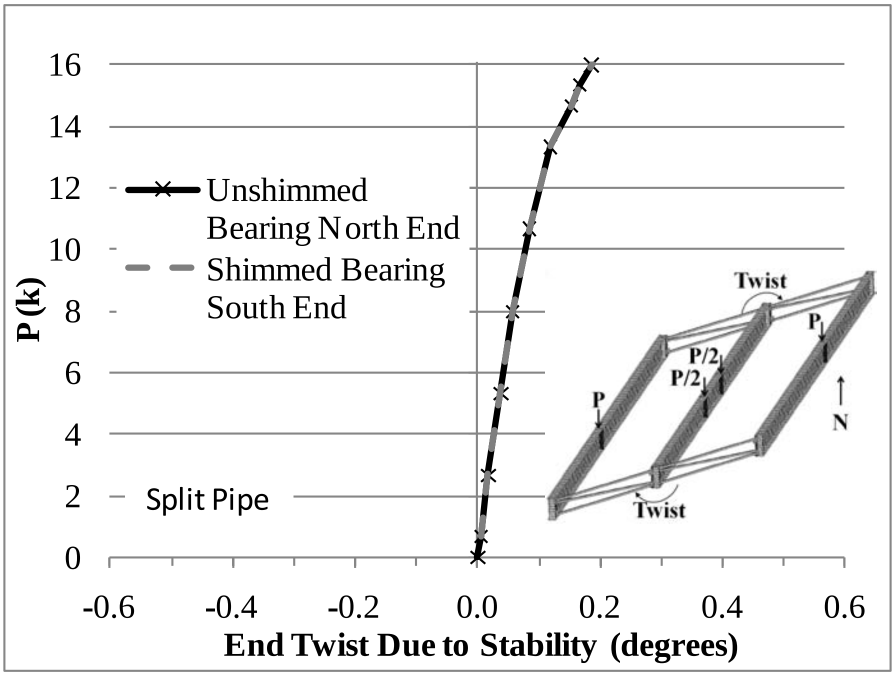

Figure 11: Split Pipe Specimen End Twist Due to Stability

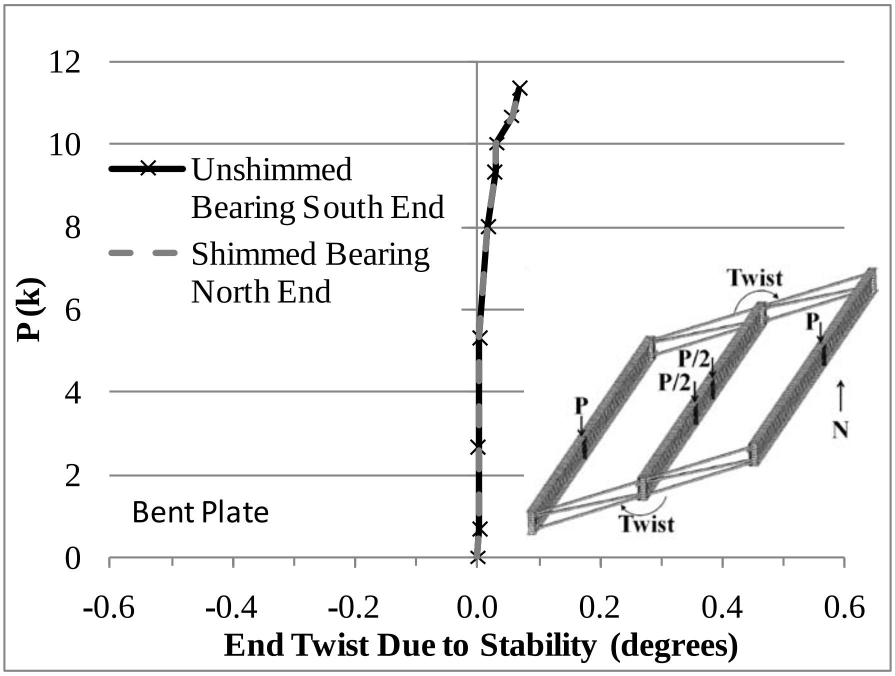

Figure 12: Bent Plate Specimen End Twist Due to Stability

A comparison of the split pipe and bent plate specimen shows that the split pipe specimen has a slightly larger end twist due to stability effects than the bent plate specimen. This can be seen from Fig. 13 where the scale of the horizontal axis has been changed to show the small difference in twist between the two unshimmed specimens. A similar small difference was also found between the shimmed bearing specimens. While this small difference may seem to indicate that the pipe stiffener system is more flexible in terms of controlling end twist due to stability, the mid-span twist in the pipe stiffener specimens was considerably smaller than that of the bent plate specimens as seen in Figure 14 (similar results were seen with the shimmed bearing specimens as well). Therefore future tests and finite element modeling will be required to determine if this is a consistent result based on the system behavior, or an artifact of this particular test.

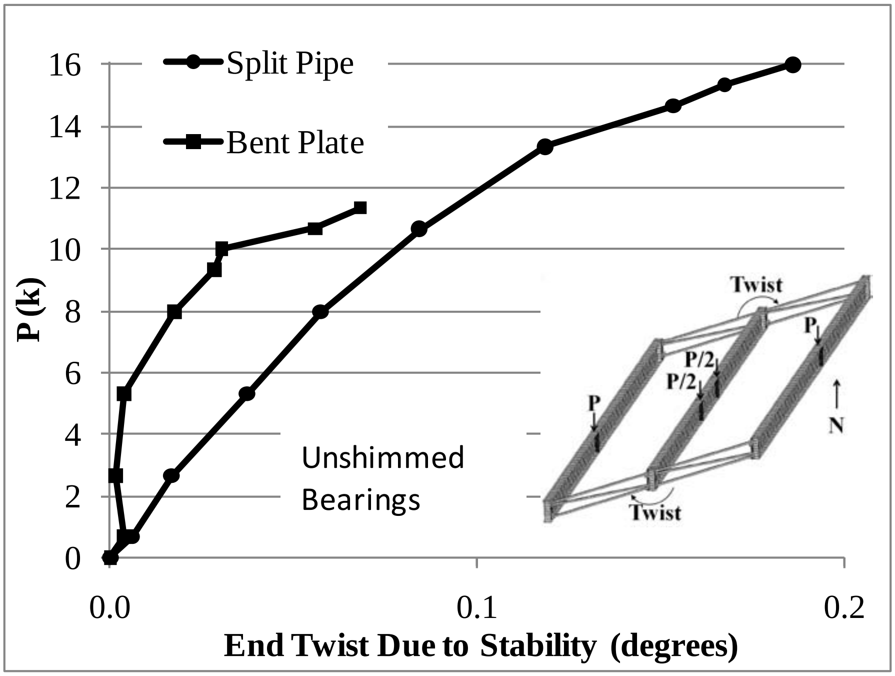

Figure 13: Split Pipe to Bent Plate Specimen End Twist Due to Stability

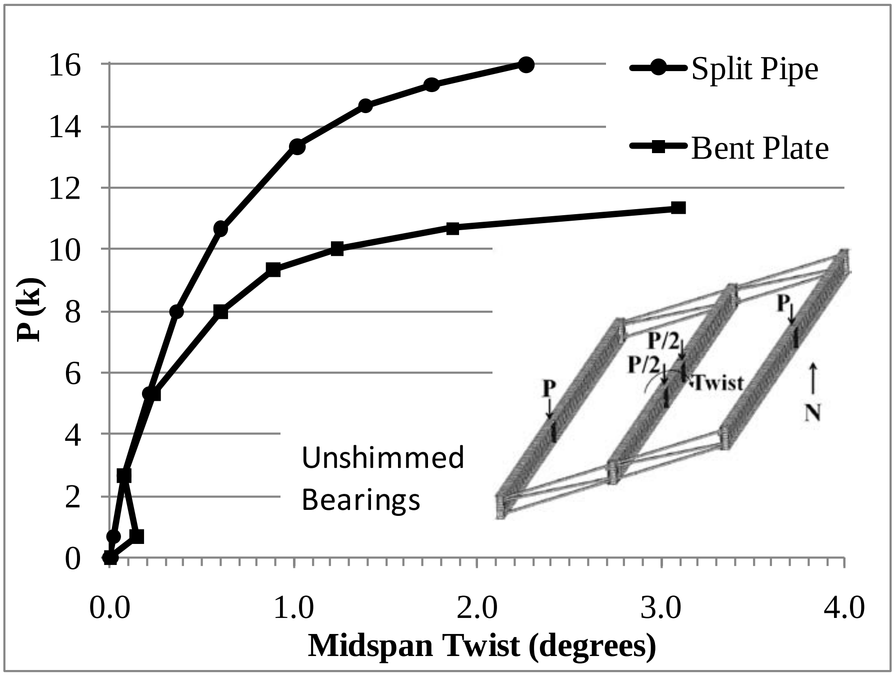

Figure 14: Split Pipe to Bent Plate Specimen Mid-span Twist

5. Conclusions and Future Work

Several preliminary conclusions can be drawn from this initial work. First, the analytic equation used to predict end twist due to the bridge skew angle appears to accurately predict end twist. However, if the twist due to the stability forces is neglected, the end twist estimate may significantly differ from the actual amount of twist. While the stability forces at the 53˚ skew angle are only about 20% of the total twist, at smaller skew angles they will be a much larger portion of the overall twist. This presents a significant challenge since it is often difficult to predict which direction a girder is going to buckle and therefore which direction the twist due to stability will act. In the laboratory study, the direction of buckling was easily measured, but in the field, knowing the direction the girder will buckle becomes much more problematic.

The data shows the relation between tipping restraint, cross frame stiffness, and the amount of twist caused by the skew and stability forces. The data indicates that the amount of tipping restraint provided by the bearing may be dependent on the relative stiffness of the cross frame to the bearing and the amount of twist applied by the skew and stability forces. If the cross frame is stiff enough relative to the bearing, the cross frame appears to restrain twist without requiring tipping restraint from the bearing. Conversely if the cross frame is not stiff enough to mobilize the bearing tipping restraint, then the cross frame will be the only source of restraint and the girder will tilt up on the bearing without compressing it. This appears to be a very complicated behavior and will require additional study to confirm and further define.

Finally, the procedures used in this study seem to be an accurate way to separate the sources of twist and restraint in a straight skewed steel girder bridge. However, these conclusions are only preliminary and the result of one series of tests. Currently there is another series of tests being performed at the University of Texas Ferguson Structural Engineering Laboratory using a specimen with a smaller skew angle. When these results are available these procedures will be further validated. Additionally, parametric studies are planned to extend these laboratory results and procedures to a wider array of geometries.

Acknowledgments

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