GIRDER END TWIST PREDICTION FOR STRAIGHT SKEWED STEEL GIRDER BRIDGES

DR. CRAIG QUADRATO

WEIHUA WANG

DR. TODD HELWIG

BIOGRAPHY

Craig Quadrato is an Academy Professor at the United States Military Academy. He earned his Ph.D. in Structural Engineering at The University of Texas at Austin in 2010. He earned his M.S. degree in structural engineering from Stanford University in 2001 and a B.S. in civil engineering from The United States Military Academy in 1991.

Weihua Wang is a graduate research assistant at the University of Texas at Austin. He earned his M.S in civil engineering from the University of Akron in 2004 and B.S. in structural engineering from Zhejiang University in 1999.

Dr. Todd Helwig earned his Ph.D. in structural engineering from The University of Texas at Austin in 1994. After teaching at the University of Houston for 11 years, he joined The University of Texas at Austin engineering faculty in 2005.

SUMMARY

Girder end twist in straight skewed steel girder bridges presents significant challenges during bridge erection. The amount of twist at the end of a girder in a skewed bridge is difficult to predict yet must be accounted for in erection planning to facilitate end cross frame fit-up and to achieve a vertical web under the specified loading condition. Currently girder end twist is predicted solely by the vertical deflection of the girders. However, at least two other parameters may have a significant impact on girder end twist - the tip restraint provided by the bearing and the twist induced by the stability effects.

This paper assesses the impacts of the bearing tip restraint and stability effects on the prediction of girder end twist via a series parametric studies conducted with a 3-D finite element model validated with large scale laboratory tests conducted at The University of Texas at Austin. These parametric studies will be used to assess when tip restraint and stability forces should be considered for accurate girder end twist prediction.

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Introduction

Accurately predicting how much girder end twist is induced during deck placement is required in order to ensure girder webs at the abutment end up in the planned post deck placement configuration. However, accurately predicting girder end twist for skewed straight steel girder bridges during deck placement can be problematic due to the multiple sources of twist and restraint for the girder end. While not necessarily a strength concern, as long as the end cross frames or diaphragms possess adequate stiffness, inaccurately predicting end twist can cause inefficiencies during erection and result in the girder not sitting flat on the bearing after deck placement. Recently a simple method of superimposing these girder end twist sources and restraint was proposed and is defined by the equation below (1).

$$\varphi_{end} = \varphi_{stability} \pm \varphi_{skew} - \varphi_{restraint} \quad (1)$$

where

φ_{end} = total girder end twist

$\varphi_{stability}$ = girder end twist due to stability forces

φ_{skew} = girder end twist due to skew

$\varphi_{restraint}$ = girder end twist restraint due to bearing pad

Using a series of laboratory tests sponsored by The Texas Department of Transportation (TxDOT) and conducted at The University of Texas Ferguson Structural Engineering Laboratory, the validity of this equation has been investigated for one set of laboratory data (1). However, in order to extend these results for a wider range of girder geometries as well as cross frame and bearing pad stiffnesses, an additional series of laboratory tests has been conducted and a finite element analysis (FEA) model has been developed and validated, and is now being used to conduct parametric studies. This paper describes the laboratory testing, FEA model validation and initial parametric study results.

Laboratory Tests

Two series of laboratory tests were used to validate Equation (1). The first used three W30x90 simply supported girders with a 56' span, 53° skew, and 9' girder spacing (Figure 1). The cross frames were single diagonal cross frames using HSS 2.5x2.5x0.233 members connected to the girders using a split pipe connection. The cross frames are completely described in References (1) and (2). The second specimen used the same parameters except had a 24° skew.

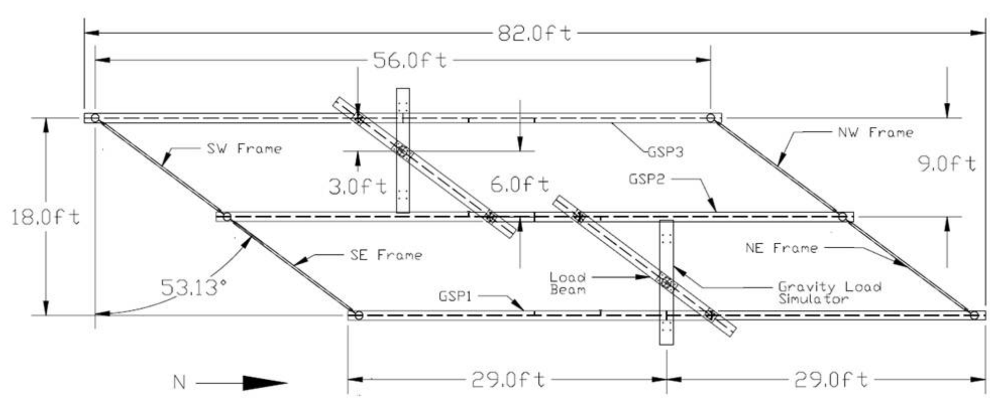

Figure 1. 53° Skew Test Specimen

Both specimens were tested using two sets of bearings. The first had no metal shims and 50 durometer rubber to give a total compressive stiffness of 22 k/in. The second bearing was the same as the first except seven metal shims were added to give a total compressive stiffness of 178 k/in.

As the specimens were loaded with point loads oriented parallel to the skew angle, the girder end twist was measured with tilt sensors accurate to 0.03°. The results for the unshimmed and shimmed bearing specimens are shown Figures 2 and 3 respectively (in all figures clockwise looking north is positive and all results are for the center girder).

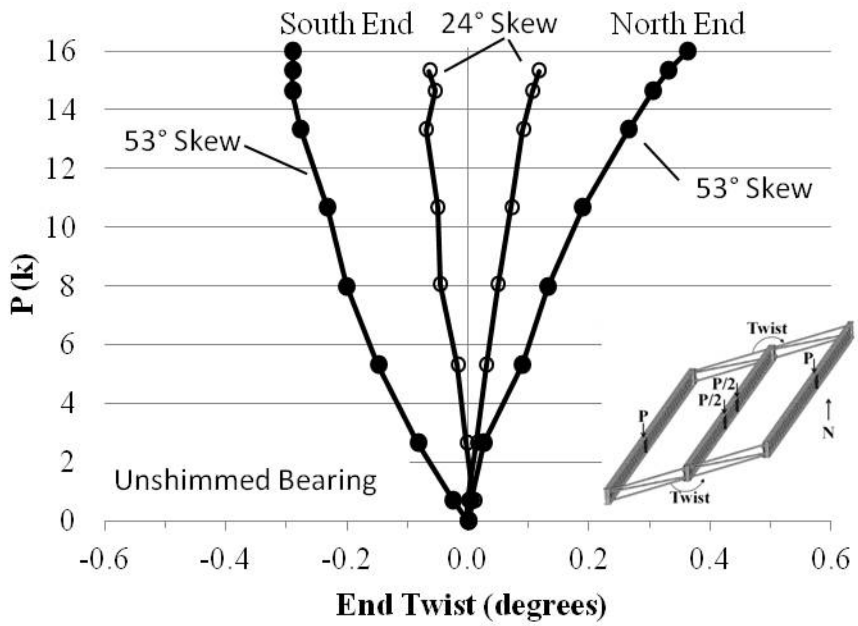

Figure 2. Unshimmed Bearing Specimen Test Results

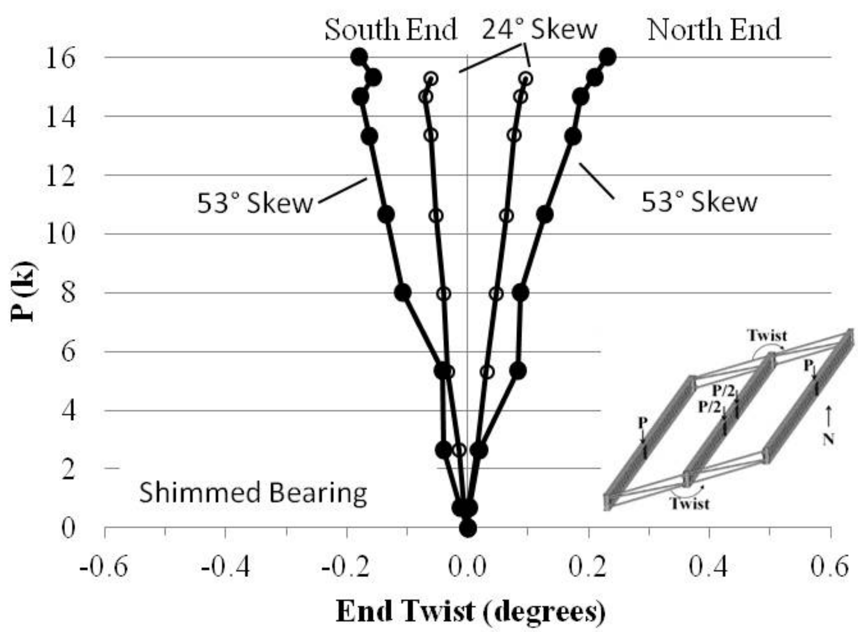

Figure 3. Shimmed Bearing Specimen Test Results

Several conclusions can be drawn by comparing the laboratory results. First as skew increases, the amount of end twist increases as expected (1) (3) (4). Additionally, by comparing Figures 2 and 3, the impact of the bearing pad can also be seen. The presence of a stiff bearing pad mitigates the amount of end twist noticeably at the 53° skew. However, the impact of the bearing pad at the smaller 24° skew appears to have little significance.

To isolate the sources of twist and restraint, Equation (1) can be applied to the total twist as outlined in Reference (1) and each component plotted to determine its importance. The results are plotted in Figures 4, 5, and 6 for the shimmed bearing pad specimens.

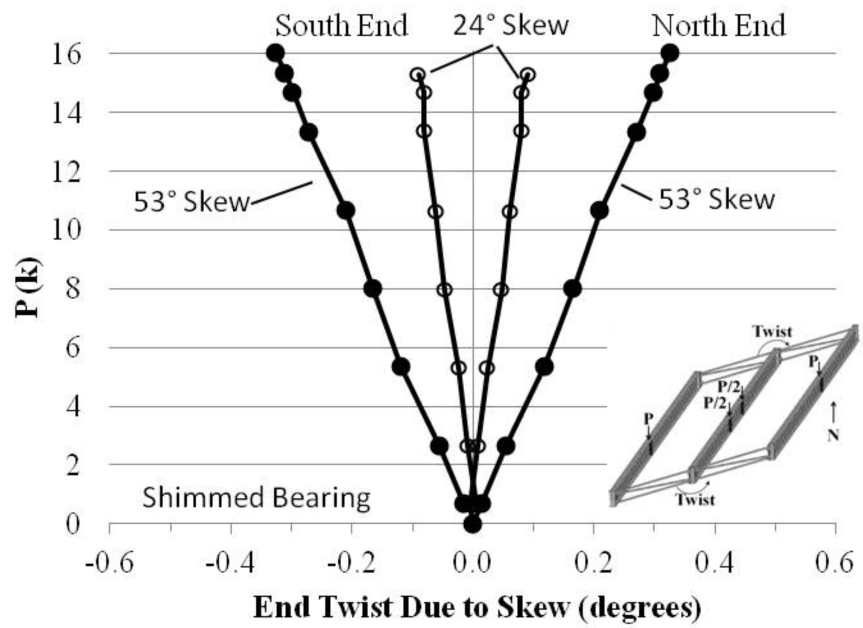

Figure 4. Shimmed Bearing Specimen Skew End Twist

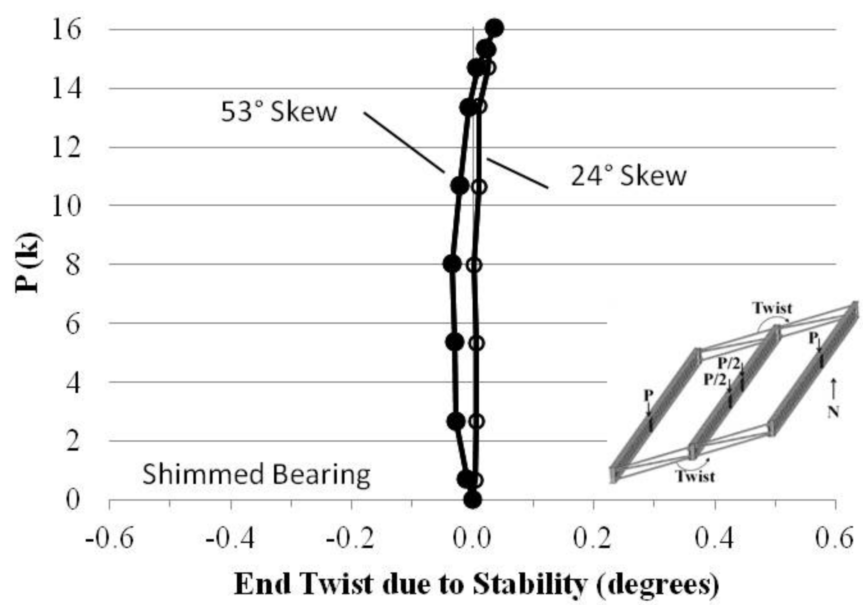

Figure 5. Shimmed Bearing Specimen Stability End Twist

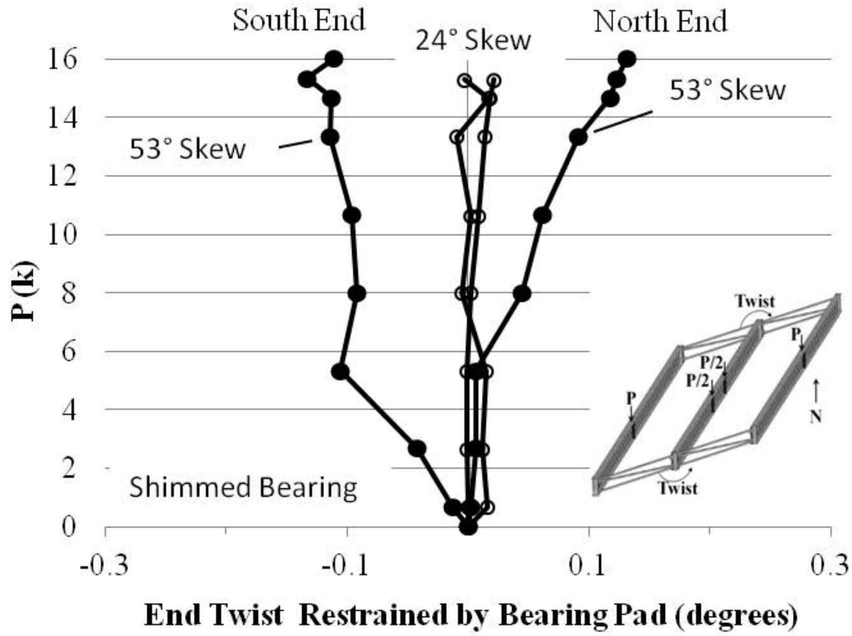

Figure 6. Shimmed Bearing Specimen Bearing Pad Restrained End Twist

The figures show some clear results. First, the impact of the stability force on end twist is very minor until the onset of significant buckling occurs (about 14 k for these specimens). Second, neglecting the impact of the bearing pad on end twist at the 53° skew may lead to significant error in predicting end twist even at loads approaching only 50% of the critical buckling load. As an example consider the south end of the 53° skew shimmed bearing pad specimen at 8 kips of load. If only skew is considered, as is done in current practice (4), the total end twist will be calculated as 0.2° when in reality to total twist is only 0.1° due to the restraint provided by the bearing pad resulting in a 100% error in prediction.

Finally, as shown in Figure 7, the end twist due to skew from Equation (1) shows good agreement with the analytical solution derived for the lab test in Reference (1) and shown in Equation (2). Similar good agreement was found at the 53° skew and is reported in Reference (1).

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

where

$\Delta_{mid\text{-}span}$ = mid-span vertical deflection

L = span

a = distance between loads

α = skew angle

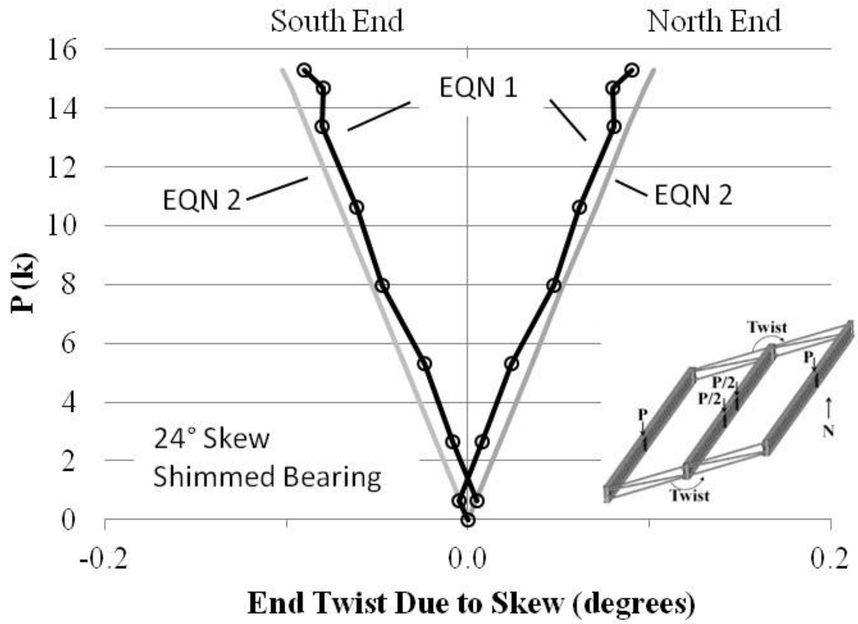

Figure 7. Analytic Comparison for 24° Skew Shimmed Bearing Specimen

Finite Element Modeling

In order to conduct parametric studies to investigate the relationship between skew angle and the twist restraint provided by the bearing pad as well as the impact of cross frame stiffness on end twist, a finite element model was developed. The primary purposes were to discover at what skew angle the bearing pad significantly contributed to restraining girder end twist and to determine the impact of cross frame stiffness on end twist.

The finite element modeling techniques used were similar to that of related girder buckling studies (1), (2), (5), (6) and used 8-node shell elements to create the plates and tubes for the girders and cross frames and the three dimensional finite element modeling program ANSYS version 11.0. The bearing pads were modeled using compression only elements with three translational degrees of freedom at each end. Each bearing pad element was assigned a modulus derived from the bearing pad's stiffness, and each element's area and length. The finite element model is shown in Figure 8 and Figure 9 shows the bearing pad elements used at the end of each specimen as well as the pipe stiffener end frame connection.

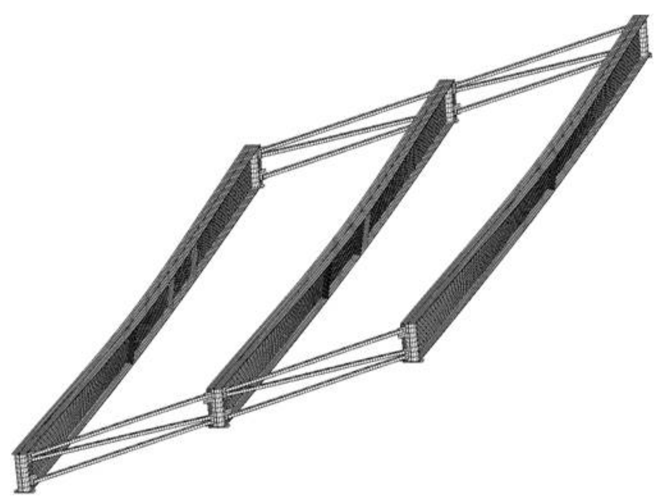

Figure 8. 53° Skew Finite Element Model (Elements and Deflected Shape Shown)

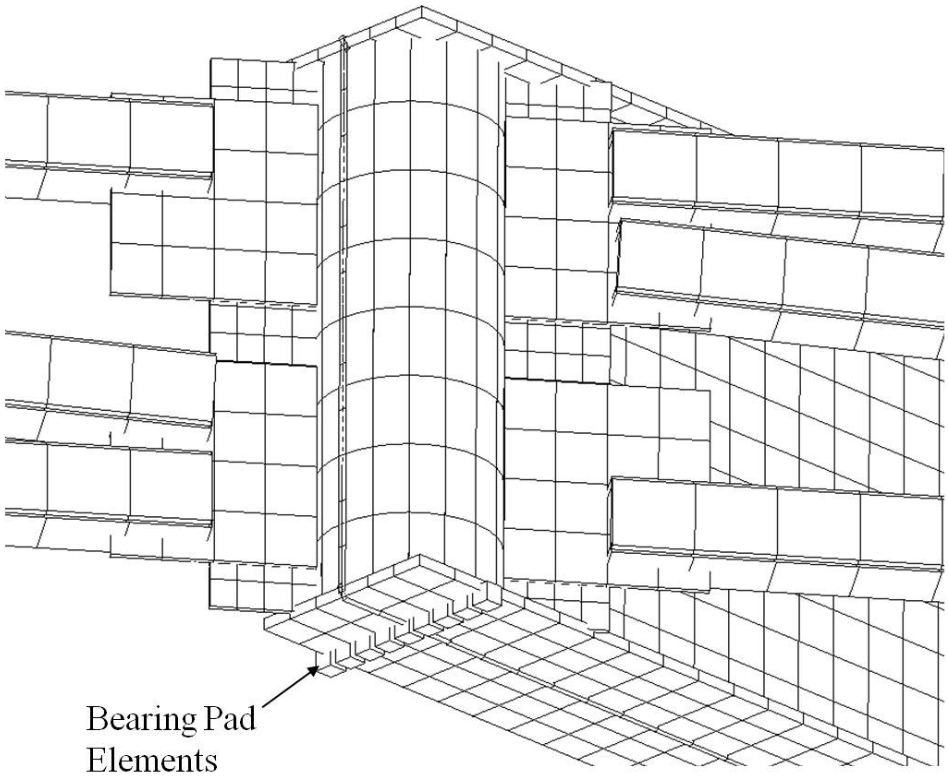

Figure 9. Bearing Pad Elements and Cross Frame Connection (Elements Shown)

Figures 10 and 11 show the model validation for the 53° and 24° skew specimens, respectively. From the figures it can be seen that the model is in very good agreement with the laboratory end twist data. Similar good agreement was found in the unshimmed bearing pad specimens.

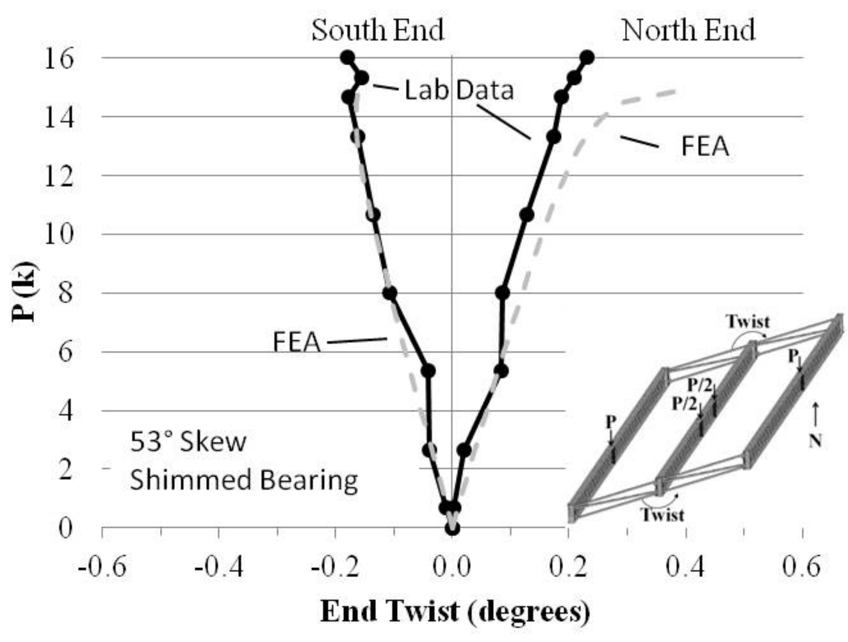

Figure 10. 53° Skew FEA and Lab Data Comparison

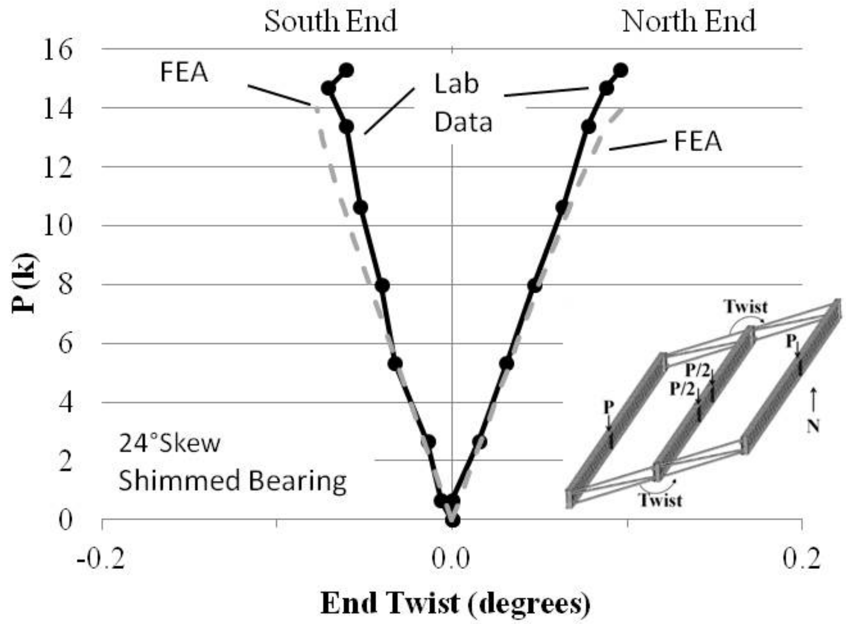

Figure 11. 24° Skew FEA and Lab Data Comparison

Parametric Study Results

In order to assess the impact of skew angle on the bearing pad restraint, two additional skew values of 35° and 45° were analyzed using the validated finite element model. Both the unshimmed and shimmed bearing models were run at each skew to determine the restraint provided by the shimmed bearing. The results for 8 kips of total load on each girder is plotted versus skew in Figure 12.

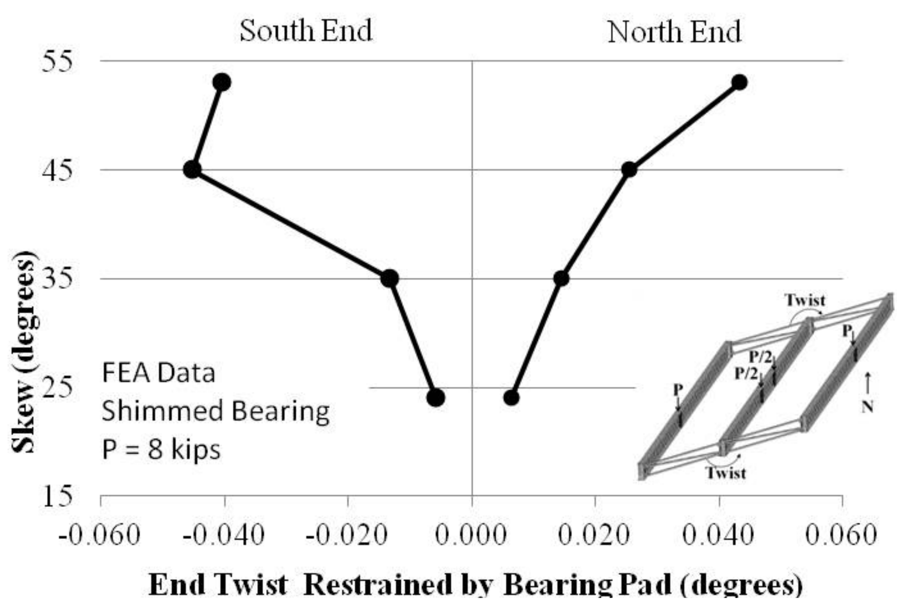

Figure 12. FEA and Lab Data Comparison

From Figure 12 it can be seen that at the lower skew angles (35° and below) the difference in resistance provided by the bearing pad is nearly symmetric with respect to the north and south girder ends which is expected since the end twist due to skew is symmetric. However, as the skew angle approaches and exceeds 45°, the restraint provided by the bearing pad begins to show the effects of the end twist due to stability (the end twist due to stability adds to the end twist due to skew on the north end and subtracts from the end twist due to skew on the south end), this result suggests that the end twist due to stability becomes a more important factor as the skew angle increases. This observation is confirmed directly by plotting the end twist due to stability calculated using Equation (1) for each skew angle as shown in Figure 13.

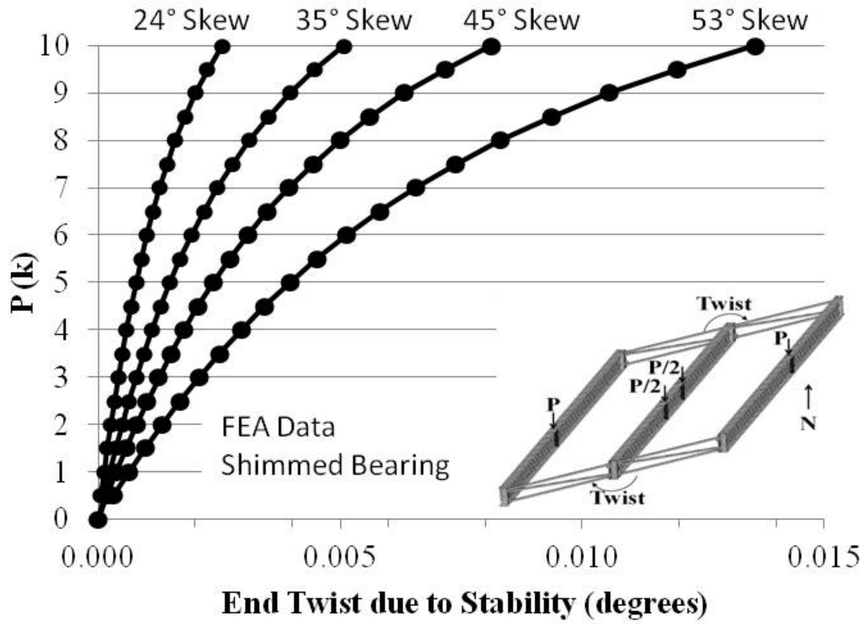

Figure 13. End Twist Due to Stability for each skew angle.

The primary cause for this variation in end twist due to stability with respect to skew angle is the change in effective cross frame stiffness with increasing skew. As the skew angle increases, the effective stiffness of the cross frame decreases (5). This in turn allows more twist due to stability as the skew angle increases causing the bearing pad to have to restrain less total twist on the southern end of the girder and more total twist on the northern end of the girder.

Even with this variation in end twist restrained by the bearing pad, the amount of twist restrained by the bearing pad is significant at 35° skew and above. Ignoring the contribution to twist restraint due to the bearing pad at this skew and above will result in significant error when trying to predict girder end twist.

To investigate the impact of cross frame stiffness on end twist, another parametric study was conducted. For this study the 53° skew angle model was used with the three different cross frame stiffnesses: cross frame 1 with 32,000 in-k/rad (value used in all preceding models), cross frame 2 with 55,900 in-k/rad, and cross frame 3 with 97,400 in-k/rad. The cross frame stiffnesses were varied by changing the area of the cross frame members and calculated using the method given in Reference (5). A plot of the girder end twist for each cross frame stiffness is shown in Figure 14.

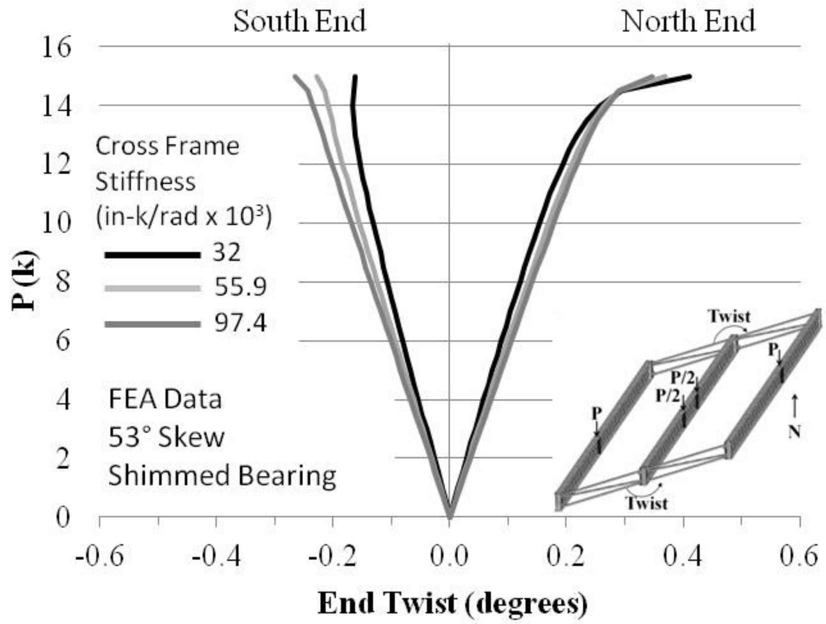

Figure 14. End Twist for Variable Cross Frame Stiffnesses

From Figure 14, it can be seen that the total end twist variation with cross frame stiffness makes sense on the southern end if the cross frame stiffness is considered with respect to the end twist for stability. On the south end, the end twist actually increases slightly as the cross frame stiffness increases. This is because the cross frame restricts the twist due to stability, so, on the southern end, this would increase the total twist since the twist due to skew is partially offset by the twist due to stability. However, we would expect that the same hold true on the northern end. So that as the cross frame becomes stiffer the end twist would decrease due to the restraint of the end twist due to stability. But, as shown in Figure 14, this does not occur and the more flexible cross frame instead has just slightly less end twist until the onset of significant buckling.

The reason for this apparent contradiction is that not only does the cross frame restrain end twist due to stability, it also causes the end twist due to skew, and both components are impacted by the finite stiffness of the cross frame. As the cross frames become stiffer, the end twist due to skew will approach the analytical solution that assumes the cross frame members are infinitely stiff (3) (8). Evidence of this can be seen in Figure 7 where Equation (2), with its assumption of infinitely rigid cross frames, predicts slightly more end twist due to skew than Equation (1) which is based on the finite cross frame stiffness from the laboratory tests. Additional evidence of this can be seen by plotting the difference between the end twist for cross frames 1 and 2 and cross frames 1 and 3 as shown in Figure 15. From the figure it can clearly be seen that prior to significant buckling, the stiffer cross frames increase the end twist due to skew. After significant buckling begins, the girder begins to tilt up on the bearing pad (as verified the finite element model) and the cross frame then begins to aid in resisting the overturning moment, and its net effect is then to resist rather than add to the total end twist. This effect is seen in Figure 15 as the plots of difference in end twist due to skew change direction as significant buckling occurs.

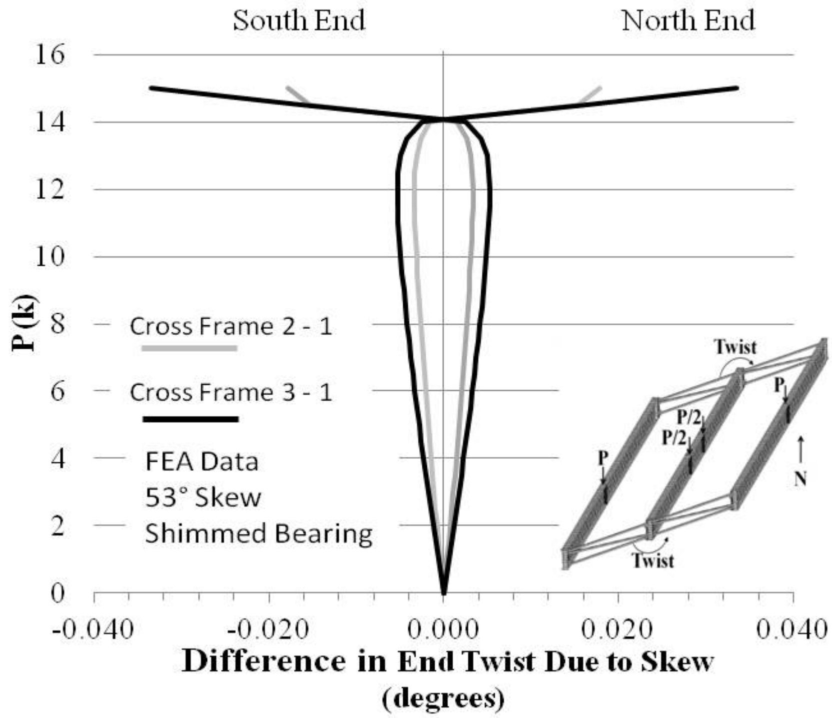

Figure 15. Difference in End Twist Due to Skew for Variable Cross Frame Stiffnesses

Considering this Figure 14 makes more sense. On the southern end the stiffer the cross frames cause more twist due to skew and less twist due to stability resulting in the stiffer cross frame causing more total twist. While on the northern end, the stiffer cross frame causes more end twist due to skew but also restrains some of the end twist due to stability resulting in slightly more end twist for the northern end.

Finally, the effect of cross frame stiffness on the end twist due to stability may be directly observed in Figure 16. In the figure it can be seen that the end twist due to stability is impacted as expected by the cross frame stiffness. As the cross frame gets stiffer, the end twist due to stability decreases since the stiffer cross frame better restrains the twist. But, the difference in twist due to stability with respect to cross frame stiffness is very small until the onset of significant buckling.

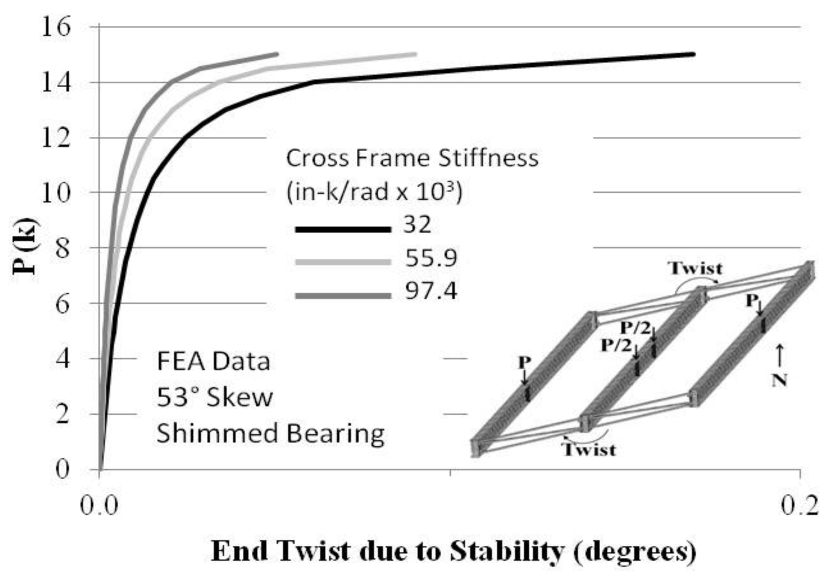

Figure 16. End Twist Due to Stability Forces for Variable Cross Frame Stiffnesses

The preceding analysis leads to an important conclusion. Although the cross frame stiffness is not explicitly accounted for in Equation (1), its effects are represented in the end twist due to stability and the end twist due to skew. But, for this analysis assuming the cross frame is rigid therefore resulting in slightly more end twist due to skew, and less end twist due to stability will lead to only a relatively small error for normal loading (about 75% of the critical buckling load and below).

Conclusions and Future Work

This paper has shown that neglecting the impact of the bearing pad restraint can lead to significant error when calculating end twist of straight skewed steel girders, while assuming the cross frame is infinitely stiff does not if the girders total load does not exceed about 75% of the critical buckling load. Additionally, the results show that the stiffness of the end cross frames has an effect on the end twist due to skew as well as the end twist due to stability that become significant portions of the total end twist as significant buckling occurs.

While the above conclusions may be correct for the specimens studied, further study is required prior to a generalized statement about the impacts of neglecting the contribution of the bearing pad and cross frame in calculating end twist due to skew. Parametric studies are currently underway to apply these concepts to different girder geometries to validate that the conclusions hold for a wider range of specimens. Additionally, further study is required to determine if there is a minimum end cross frame stiffness that is required to minimize the impact of the end twist due to stability. Finally, as a part of calculating the minimum cross frame stiffness, the cross frame connection, especially if a relatively flexible connection such as a bent plate is used, should be included in the cross frame stiffness.

References

(1) Quadrato, C. E., Wang, W., Helwig, T. A., Engelhardt, M. D., & Frank, K. F. (2011). Predicting End Twist in Skewed Straight Steel Girder Bridges. *Proceedings for the Annual Stability Conference.* Pittsburg: Structrual Stability Research Council.

(2) Quadrato, C., Frank, K., Helwig, T., & Engelhardt, M. (2010). Improved Cross-Frame Connection Details for Steel Bridges with Skewed Supports. *Transportation Research Record Journal of the Transportaion Research Board* , 29-35.

(3) Colletti, D., Chavel, B., & Gatti, W. (2009). The Problems of Skew. *The Proceedings of the World Steel Bridge Symposium.* San Antonio: National Steel Bridge Alliance.

(4) Ude, T. (2009). Field Study of Skewed I-Girders During Construction. *Proceedings of the World Steel Bridge Symposium.* San Antonio: National Steel Bridge Alliance.

(5) Wang, L., & Helwig, T. A. (2008). Stability Bracing Requirements for Steel Bridge Girders with Skewed Supports. *Journal of Bridge Engineering , 13* (2), 149-157.

(6) Whisenhunt, T. W. (2004). Measurement and Finite Element Modeling of the Non-Composite Deflections of Steel Plate Girder Bridges. *M.S. Thesis Submitted to North Carolina State University* . Raleigh, NC.

(7) Yura, J. (2001). Fundamentals of Beam Bracing. *Engineering Journal* , 11-26.

(8) Beckman, F., & Medlock, R. D. (2005). Skewed Bridges and Girder Movements Due to Rotations and Differential Deflections. *Proceedings of the World Steel Bridge Symposium.* Orlando: National Steel Bridge Alliance.