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Skewed Cross Frame Connection Stiffness

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Skewed Cross Frame Connection Stiffness

by

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Thesis

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Dedication

To Dad, Mom, and Christy whose love and support is priceless.

To Grandmom: May the high ball be great in Heaven.

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December 1, 2009

Skewed Cross Frame Connection Stiffness

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The University of Texas at Austin, 2009
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Cross frames and diaphragms are essential to the stability of straight steel girder bridge systems as they help to resist lateral torsional buckling during construction and horizontal loading conditions. In skewed bridge systems, cross frames are often oriented parallel to the supports and hence, at an angle to the girder. To facilitate construction fit-up, plates, bent to match the skew angle, form the cross frame to stiffener connection. While the bent plate connection is a simple solution, it could introduce undesirable flexibility into the system, potentially compromising the effective brace stiffness. A proposed detail utilizing half pipe stiffeners may provide enhanced structural performance, while possibly reducing overall fabrication costs. Field and laboratory tests to determine the stiffness of both connection types are presented in the thesis.

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CHAPTER 1

Introduction

1.1 PROBLEM STATEMENT

The critical stage for the stability of steel girder bridges often occurs during early stages of construction either before or during placement of the concrete bridge deck. The primary source of stability of the girders is provided by cross frames that are spaced along the length of the bridge. The cross frames brace the girders against lateral torsional buckling under gravity loads and also assist in resisting lateral wind loads. However, due to complex fabrication requirements and construction fit-up difficulties, these braces often represent a significant percentage to the overall bridge cost. Moreover, service fatigue issues can significantly add to the life-cycle cost of the structure, especially in bridges with skewed supports such as the one depicted in Figure 1.1. In Figure 1.1, the symbol α denotes the skew angle. Differential deflections between adjacent girders at the ends of the cross frames can lead to large live load induced forces in the braces.

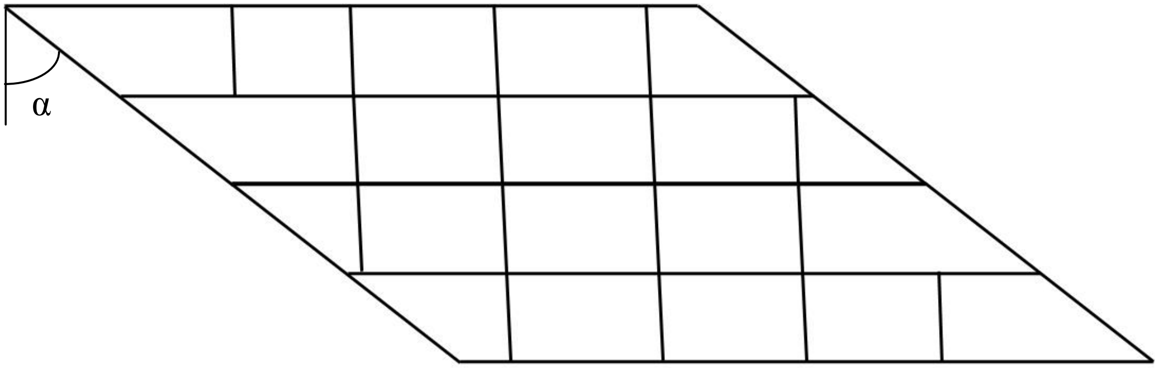


Figure 1.1 Skewed Bridge with Perpendicular Bracing Layout

When constructing bridges with support skew, interior cross frames are typically oriented in one of two ways: parallel to the supports for skew angles less than 20 degrees, or perpendicular to the girder web for skew angles greater than 20 degrees [AASHTO 2007]. In either case, the end cross frames are usually parallel to the supports, requiring the cross frame to be connected to the girder at the skew angle. To simplify the connection between the brace and the girder, a bent connection plate is often used. This connection plate is typically formed by cold bending to the desired skew angle, and is then used in conjunction with struts and diagonals to form the cross frame system. The left portion of Figure 1.2 shows a schematic layout of the bent plate connection. The right portion of the figure is a photo of a bent plate cross frame to girder connection taken on a bridge during construction. In both the sketch and the photo, the view is looking down at the top flange of the girder.

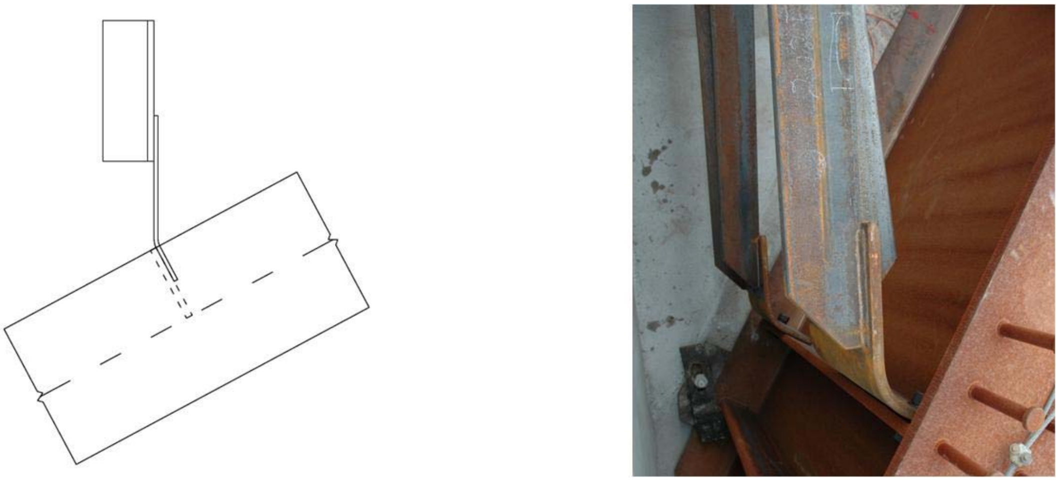


Figure 1.2 Bent Plate Detail

The primary concern with the bent plate is the flexibility of the connection, and the consequent loss of bracing stiffness. For braces to be effective in controlling the stability of bridge girders, they must satisfy both strength and stiffness criteria. The overall stiffness of a cross frame is controlled by the most flexible component [Yura 2001]. Therefore, using a flexible bent plate connection between the cross frame and the girder may significantly reduce the overall stiffness of the cross frame. This, in turn, can adversely affect the safety of a bridge during construction, or increase the cost of construction by requiring the use of additional cross frames.

While bent plate connections are often used in steel bridges with skewed supports, a review of the literature suggests little previous research has been conducted to examine the impact of the bent plate on the effectiveness of cross frames. An example of the potential problems associated with the use of the bent plate connection is the large deflections that occurred during girder erection on the Churchman Road Bridge in Delaware featured in Figure 1.3 [Winterling 2007]. Although the bridge had a skew angle of approximately 60 degrees, all of the intermediate cross frames were oriented parallel to the skew angle and incorporated the bent plate connection detail. Because of the flexibility in the bent plate connection, the girders displaced laterally several inches under only the steel self weight and required substantial retrofits to improve the behavior of the bridge. Overall, additional research is needed to better characterize the stiffness of the bent plate connection detail, and to better define where the use of the bent plate detail may lead to problems during construction.

Figure 1.3 Churchman Road Bridge over Interstate 95 in Christiana, Delaware

1.2 SCOPE OF STUDY

The research presented in this thesis is part of the on-going Research Project 0-5701, “Cross Frame and Diaphragm Layout and Connection Details”, sponsored by the Texas Department of Transportation (TxDOT). The primary goal of the study is to investigate the behavior of the bent plate connection through field investigation, laboratory tests, and finite element analyses. Another goal of the investigation is to develop improved connection details for cases in which the bent plate connection may have poor behavior. A likely detail that shows promise is the use of a round pipe stiffener, the geometry of which allows perpendicular welded connections between the cross frame connection plate and the stiffener. The investigation includes field monitoring, laboratory testing, and computational studies. Key overall elements of Research Project 0-5701 are described below.

A field investigation was conducted on a steel bridge with a support skew of approximately 60 degrees located in Lubbock, TX. In this bridge, the end cross frames were located parallel to the support, and connected to the girders using a bent plate connection (see photo in Figure 1.2). Forces in the end cross frame members were measured during the placement of the concrete deck and under a controlled live load test. Data from this test was used to improve the overall understanding of the cross frame response and to help validate finite element models.

The project also includes three different series of laboratory tests. Small scale tests were conducted to examine the stiffness of the bent plate connection and the proposed half pipe connection. The investigation also includes fatigue tests that are being conducted to examine the performance of the half pipe stiffener compared with a conventional stiffener used with the bent plate connection under cyclic loads similar to the conditions a bridge will experience due to truck traffic. Lastly, large scale girder buckling tests will be conducted to study system performance with these two cross frame to girder connection details in two and three girder configurations.

In addition to the field and laboratory investigations, extensive parametric finite element analyses are being conducted to improve the understanding of skewed bridge behavior. The parametric investigations will provide valuable insight into the problem so that a rational design philosophy can be developed. Guidelines will be developed as to when the bent plate connection provides and does not provide a safe and effective bracing system, as well as the benefits of the half pipe stiffener and how to properly size and detail this connection.

As noted above, the research presented in this thesis is part of TxDOT Research Project 0-5701, “Cross Frame and Diaphragm Layout and Connection Details.” Work is still in progress on this project, and it is anticipated that an additional MS thesis and a PhD dissertation will be published in later stages of the project.

1.3 THESIS OUTLINE

This thesis consists of six chapters, with a major focus on results from field observations and laboratory experiments. Following this introductory chapter, Chapter 2 provides background information relevant to the research, including a description of the potential problems with the bent plate connection. It will seek to evaluate the bent plate’s effectiveness using basic stability principles, as well as to discuss problems observed during construction, based on information found in the literature review. Information on the design of cross frames for skewed bridges based on code provisions and standard practices is presented, and standard details for bridge designs utilizing bent plates will be shown. Through an understanding of the background, the major research objectives of this thesis will be described.

A discussion of the advantages of a proposed half pipe stiffener solution is provided in Chapter 3. Attention is given to previous research on related uses along with availability of pipe sizes, and material specification information. To close the chapter, experiences and concerns of various fabricators on the half pipe stiffener are presented.

A summary of the results pertinent to the bent plate detail from the field investigations is given in Chapter 4. An end cross frame utilizing bent plate connections was instrumented and data was collected during the casting of the concrete deck and under a controlled live load testing program after bridge construction was completed.

A review of the small scale laboratory experiments conducted to determine the behavior and stiffness of the bent plate connection and the alternate connection using the half pipe stiffener is provided in Chapter 5. The chapter presents an overview of the design and fabrication of the test setup and the test specimens. The instrumentation of the specimens is described and some important aspects of the testing frame are discussed.

Test results are presented examining the effect of skew angle, bend radius, and bolted/welded construction options. Results from tests on the half pipe stiffener are then presented and discussed and a comparison of the behavior of the two connections is made.

Finally, a summary of the research conducted on the bent plate and half pipe stiffener details is provided in Chapter 6. Future work as part of TxDOT project 0-5701 is discussed and preliminary recommendations will be made.

CHAPTER 2

Background

2.1 INTRODUCTION

In order to better understand the effect the bent plate connection may have on the stability of skewed steel bridges, it is important to review background information regarding this detail. This chapter provides a description of skewed bridge systems, and highlights cross frame layouts. Basic bracing principles are reviewed, with the emphasis on the effect of connection stiffness on the effectiveness of cross frames in bracing girders. Next, a case study on a skewed bridge using the bent plate detail is presented. Major construction problems were encountered in the bridge as a result of the flexibility in the connection plates of the braces, thereby requiring costly retrofits. Recommendations from the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications [2007] are cited, along with information pertaining to the cold bending of the plates. Standard details used by TxDOT for skewed cross frames are also presented. The chapter concludes with a discussion on research needs on the bent plate connection and the major objectives of the research presented in this thesis.

2.2 SKEWED BRIDGE CHARACTERISTICS

Skewed bridges are frequently required when the underlying roadway or terrain necessitates the bridge superstructure to rest on supports not perpendicular to the girder lines. The angle of skew, as designated throughout this thesis and represented by the symbol α in Figure 1.1, refers to the relative angle from a normal perpendicular bridge, or 0 degree skew. A photo of a steel bridge with supports skewed approximately 60 degrees is shown in Figure 2.1. When the skew angle exceeds 20 degrees, the AASHTO specification requires the interior cross frames to be oriented normal to the girders. This requirement is to prevent the use of excessively long brace members as well as ineffective braces as a result of large angular offsets in the connections. The bridge in Figure 2.1 utilized intermediate bracing lines that were perpendicular to the longitudinal axis of the girders and also made use of a cross frame layout that is referred to as “lean-on bracing”, which will be discussed later in this section.

Figure 2.1 Skewed Steel Bridge

2.2.1 Cross Frames

Cross frames provide lateral stability to the bridge superstructure, especially during construction. Their main function is to improve the lateral torsional buckling capacity of the girders and resist lateral forces from sources such as wind. They serve to prevent girders from buckling during erection, but are most important during the placement of the concrete deck when the full weight of the wet concrete acts on the non-composite girder section.

There are many different types of cross frames used in bridge construction. The X-type and K-type cross frames, as portrayed in Figure 2.2, are relatively common systems.

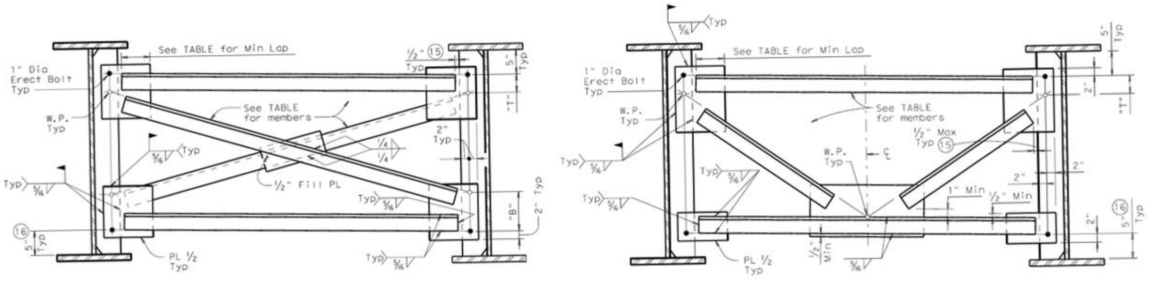


Figure 2.2 (a) X-type Cross Frame and (b) K-type Cross Frame [TxDOT 2008]

Alternatively partial depth diaphragms can be used, typically constructed from wide flange shapes. These diaphragms rely upon their bending stiffness to resist torsion between adjacent girders. This detail is restricted to girders with less than 54 in depths in Texas with an example given in Figure 2.3 [TxDOT 2008].

While these typical cross frames usually provide very stiff bracing systems for bridge girders, some unique issues and problems arise in bridges with skewed supports, particularly when the cross frames are placed parallel to the skew. Some of these issues and problems are discussed in the following sections.

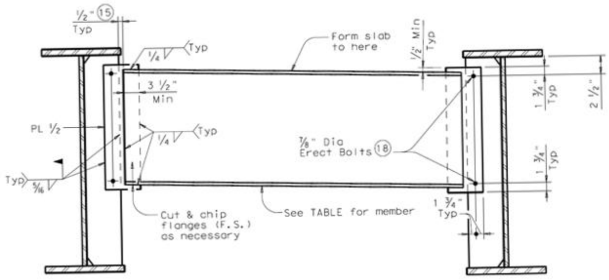


Figure 2.3 Partial Depth Diaphragm Detail [TxDOT 2008]

2.2.2 Bent Plate Connection

When cross frames are placed parallel to the skew (i.e. the cross-frames are at a skew to the girders), the connection between the cross frame and the girder web must be made at an angle. Although it is possible to angle the web stiffener to match the skew angle, many states have adopted the bent plate connection as depicted in Figure 2.4.

While the bent plate simplifies fabrication for the cross frame connection, the detail introduces an eccentricity into the connection that can reduce the effectiveness of the b due to excessive flexibility in the connection. The stability implications of the bent plate will be further discussed later in this chapter.

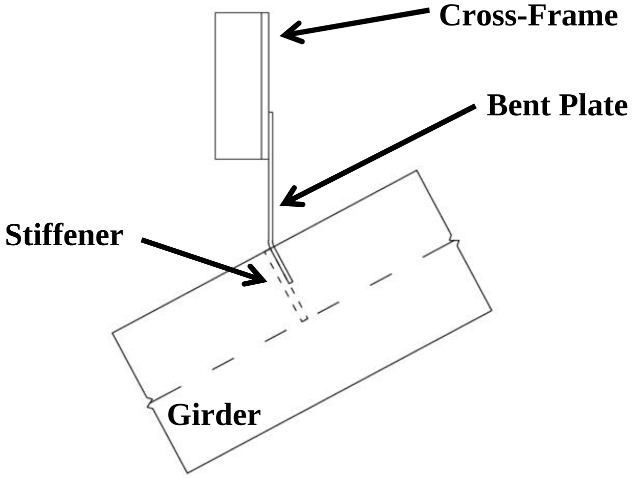
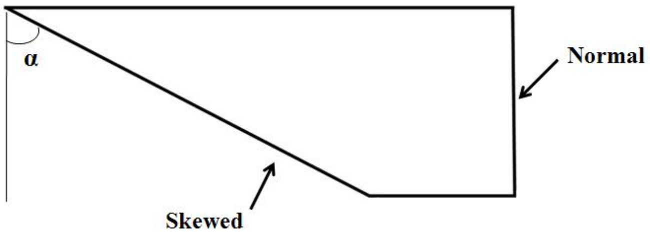


Figure 2.4 Bent Plate Connection

2.2.3 Brace Length

Another problem inherent to bridges with skewed supports is longer brace lengths compared to cross frames normal to the girders. Consider the geometry of a normal cross frame versus that of a skewed cross frame given in Figure 2.5.



<u>Normal Cross Frame</u>

Brace Length = Girder Spacing

Brace Length = 8 ft

<u>Skewed Cross Frame</u>

Brace Length = Girder Spacing / cos α

Brace Length = 8 ft / cos 60° = 16 ft

Figure 2.5 Cross Frame Geometry

For the given scenario of a 60 degree skew angle, the length of a skewed brace is twice the length of a normal brace. As will be discussed later this chapter, AASHTO makes recommendations when to use normal cross frames rather than skewed ones to avoid excessive lengths, however skewed braces are usually used along abutment and interior support lines.

2.2.4 Girder Rotations

Skewed bridges usually experience an increase in girder rotations compared to non-skewed bridges. Due to initial imperfections, the bridge girder system will tend to buckle in one direction. However, the skewed supports also cause a rotation, magnifying the stability induced deformations experienced along one support line while reducing those at another. A simple case for a single span twin girder system is illustrated in Figure 2.6. Data confirming this type of response is presented in Chapter 4.

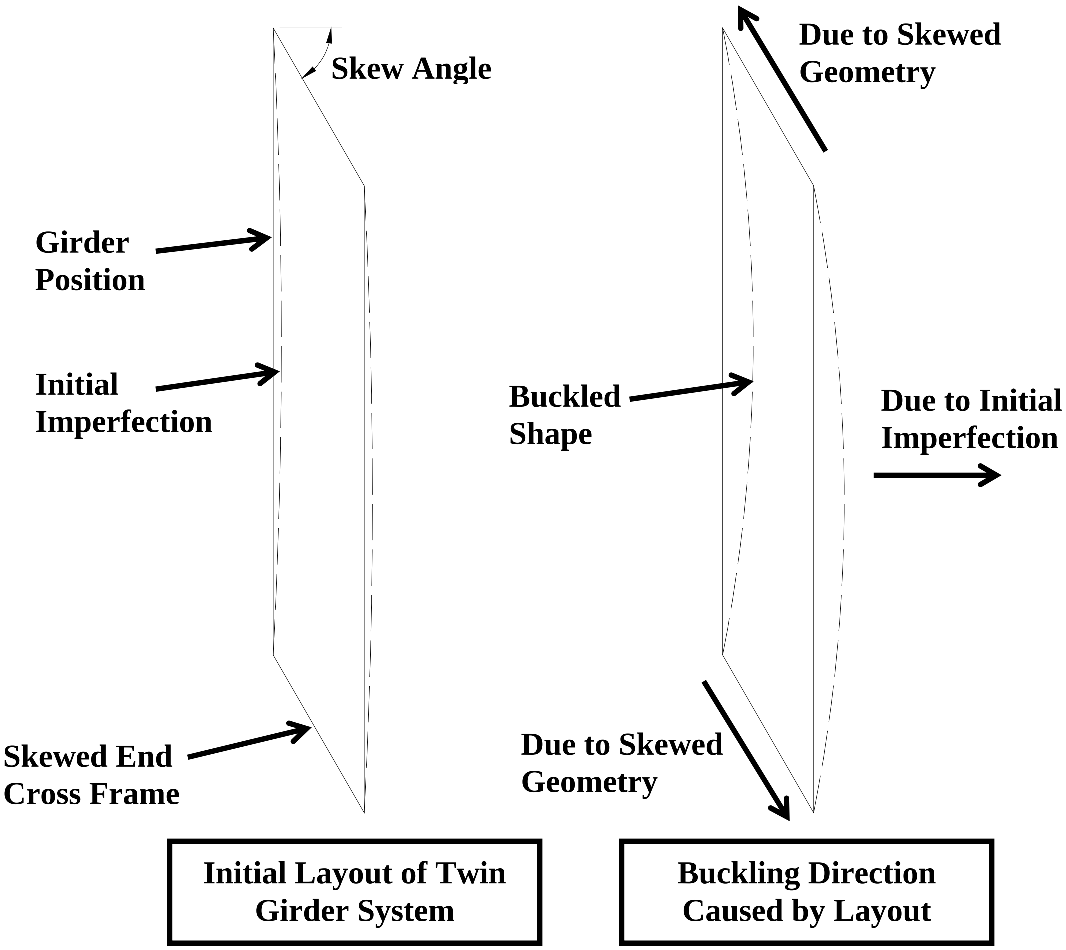


Figure 2.6 Skewed Support Effect on System Buckling Direction

Research conducted by Beckmann and Medlock identified a major problem with skewed bridges as the relative displacement of the top flange to bottom flange both laterally and longitudinally as a result of the skew [2005]. In turn, this affects the positioning of the various components when dead and live loads are applied, potentially causing the webs and stiffeners to be out-of-plumb if the deformation is not accounted for during fabrication.

2.2.5 Potential Fatigue Problems

Bridges with skewed supports and cross frames normal to the girders are prone to service fatigue problems as large live load induced forces can be present in the cross frames. These forces can lead to cracking at the cross frame connections, requiring costly retrofits and potentially increased inspection frequency. The forces develop largely from differential deflections between adjacent girders, specifically under truck loading [Helwig 2005].

Consider the line of cross frames indicated in Figure 2.7. When loads are applied on the superstructure, deflections along this line will vary significantly. For instance, at Girder 1, the deflection will be minimal because of its close proximity to the support. The deflection at Girder 6, however, will be much larger as these cross frames are near midspan of the girder. The differential vertical deflections can lead to large forces in the cross frames along this line, which in turn can lead to large live load stresses induced in the connections to the girder. To mitigate the problem, lean-on bracing concepts can be used. Lean-on bracing allows for an individual cross frame to be proportioned such that it provides bracing to other girders [Helwig 2005]. Effective bracing in beams can be provided by preventing either lateral movement of the compression flange or twist of the girder system. Cross frames are categorized as torsional braces since they control the twist of the girders. In the case where a full cross frame is not utilized, the top and bottom struts control girder twist by leaning the girder on the other cross frames in the bracing line. The struts help to alleviate forces by allowing relative vertical deflection to occur [Helwig 2005]. The callouts in Figure 2.7 (marked with #3) indicate the locations of full depth cross frames, while the unmarked lines represent strut-only details. Field test information shows this layout to be effective at reducing forces in the members and controlling twist of the structure [Fasl 2009].

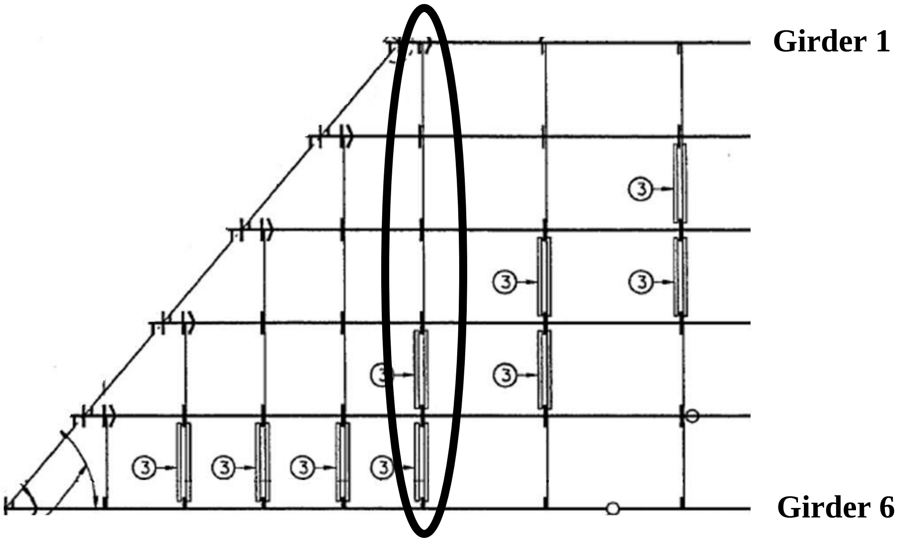


Figure 2.7 Cross Frame Layouts Leading to Differential Deflection Issues

Another method to reduce service loads experienced by the cross frames is to stagger their layout such that the cross frames' centers align parallel to the skew, but they remain normal relative to the girders (Figure 2.8). However, a study by Berglund and Schultz revealed that web gap distortion increases when the cross frames are situated in this manner [2006]. This is primarily a function of the magnitude of differential deflection, which was found to increase with the skew angle. While not directly covered in this thesis, later stages of TxDOT project 0-5701 will examine the behavior of such staggered layouts and their effect on girder buckling behavior.

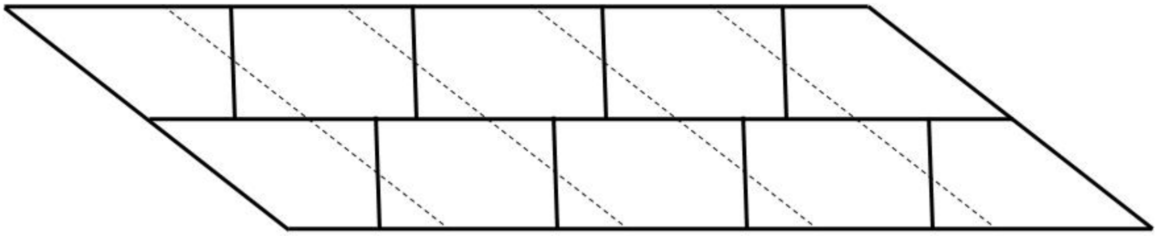


Figure 2.8 Staggered Cross Frame Layout

In terms of cross frame forces, research by Bishara and Elmir suggests the skew angle effect can be neglected for bridges with skew angles less than 20 degrees [1990]. For skew angles larger than 20 degrees, the cross frame forces increase as the skew increases when cross-frames are normal to the girders. The forces in the end cross frames are not dependent on the size of the intermediate braces, as changes in their size did not affect reported forces at the end cross frames.

2.3 STABILITY REQUIREMENTS

Beams subject to flexure are subject to two basic types of instability: local buckling and lateral torsional buckling. Local buckling in the flange or web depends primarily on the width-thickness ratios of these cross-section elements. Lateral torsional buckling, on the other hand, is a failure mode involving both lateral movement and twist of the beam cross-section and is controlled by the use of bracing. To qualitatively understand this type of buckling, consider the notion that the compression portion of the beam's cross-section has a tendency to buckle laterally, just as in a column. Meanwhile, regions in tension tend to stay straight. These counteracting behaviors introduce a twist on the girder, which will be resisted by the section's torsional rigidity [Winter 1958]. As the moment becomes larger, the beam will continue to buckle, resulting in the displacement shown in Figure 2.9.

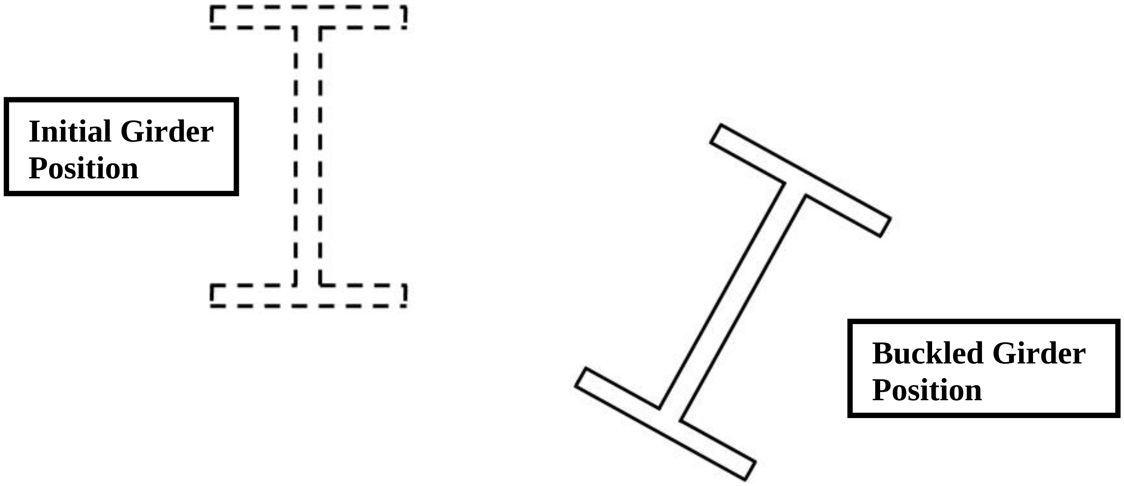
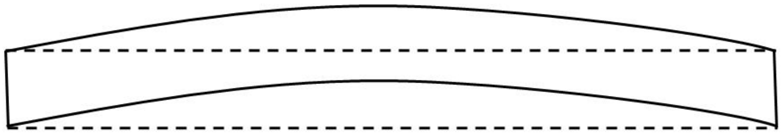
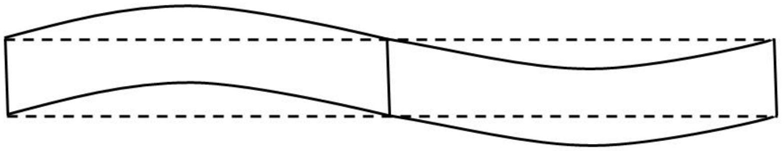


Figure 2.9 Lateral Torsional Buckling

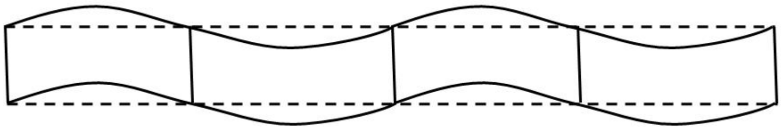
As the unbraced length increases, lateral torsional buckling becomes more critical and often governs the girder's flexural strength. As previously discussed, braces help to increase the global buckling resistance. The buckled shape of a member between braces is generally a half sine wave, as represented in Figure 2.10. Effective braces positioned along the length of the girder force the member to buckle between brace points. Each different buckled shape of a member is referred to as a buckling mode. Reducing the spacing between brace points in the girder results in a significant increase in the buckling capacity.



(c) No Intermediate Brace



(b) One Intermediate Brace



(a) Three Intermediate Braces

Figure 2.10 Buckled Shapes for Different Number of Intermediate Braces

An important concept to understand is “the efficiency of bracing depends not only on its strength but also on its rigidity” [Winter 1958]. For instance, Winter [1958] showed the impact of brace stiffness on the buckling load of columns.

The term effective brace also applies to beams when considering the buckled shapes of bridge systems. For instance, if a brace does not supply the required strength or stiffness at a brace location, lower modes of buckling can occur as depicted in Figure 2.11. In bridges, these braces are the cross frames or diaphragms installed along the length of the girders. Often, the strength of these braces is quite substantial, easily handling the loads that develop. However, when girder spacing is increased, the length of the members constituting the braces increases, thereby resulting in a reduction in the brace stiffness.

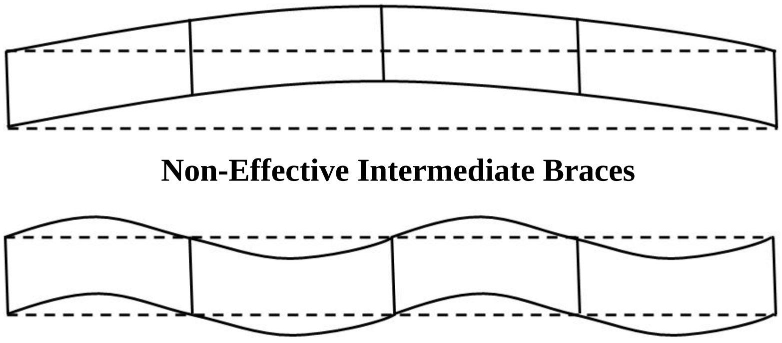


Figure 2.11 Difference in Brace Effectiveness

Timoshenko [Timoshenko and Gere 1961] developed Equation (2.1) for the elastic critical buckling moment for a simply supported beam subjected to uniform moment.

$$M_0 = \pi/L_b\sqrt{EI_yGJ + \pi^2E^2C_wI_y/L_b^2} \tag{2.1}$$

where,

M_0 = *Critical Unbraced Buckling Moment*
L_b = *Length of Beam between Braces*
E = *Elastic Modulus*
I_y = *Moment of Inertia of the Section (weak axis)*
G = *Shear Modulus*
J = *Torsional Constant*
C_w = *Warping Constant*

This calculation can be used in conjunction with the equations given below to determine the buckling moment for braced beams, with the beams continuously restrained by torsional bracing [Yura 2001].

$$M_{cr} = \sqrt{C_{bu}^2M_o^2 + \frac{C_{bb}^2\bar{\beta}_TEI_{eff}}{C_T}} \leq M_y \text{ or } M_{bp} \tag{2.2}$$

where,

$$\bar{\beta}_T = \frac{n\beta_T}{L_b} \tag{2.3}$$

M_{cr} = Critical Braced Buckling Moment
C_{bu} = Moment Gradient Coefficient for Unbraced Beam
C_{bu} = Moment Gradient Coefficient for Effectively Braced Beam
$\bar{\beta}_T$ = Attached Torsional Brace Stiffness (in-kip/rad per inch length)
I_{eff} = Effective Moment of Inertia
C_T = Top Flange Loading Modification Factor
M_y = Yield Moment of Cross Section
M_{bp} = Buckling Moment between the Braces
n = Number of Intermediate Cross Frames
β_T = Effective Brace Stiffness

In the calculation of Equations (2.1) and (2.2), it is suggested modifiers be used to account for other factors, such as non-uniform bending and load height effects. The fifth edition of the Guide to Stability Design Criteria for Metal Structures [SSRC 1998] summarizes the application of these modifiers and includes a number of informative examples.

It is important to use an accurate estimate of the brace system stiffness when calculating Equation (2.3), because as $\bar{\beta}_T$ decreases, the critical buckling moment decreases. In order to calculate the effective brace stiffness, β_T, Equation (2.4) can be utilized, with the formulation modified from the original to include the effects of the brace stiffness, cross-sectional distortion, the in-plane stiffness of the girder, and also connection flexibility [Yura 2001].

$$\frac{1}{\beta_T} = \frac{1}{\beta_{web}} + \frac{1}{\beta_{brace}} + \frac{1}{\beta_{girder}} + \frac{1}{\beta_{connection}} \tag{2.4}$$

where,

β_{web} = Stiffness of the Web Cross-Section
β_{brace} = Stiffness of the Attached Brace
β_{girder} = Stiffness of the Girder System
$\beta_{connection}$ = Stiffness of the Cross Frame Connection

There are numerous equations in the literature to help calculate the first three stiffness components to this equation [Yura 2001, Wang and Helwig 2008]. Wang and Helwig particularly focused on the effect of skew angle on the stiffness of the brace. Since braces at skewed supports are significantly longer than their perpendicular counterparts, their stiffness decreases rapidly with the cosine squared of the skew angle [Wang and Helwig 2008].

One of the consequences of Equation (2.4) is the effective brace stiffness will always be less than the stiffness of the least stiff component. Therefore, a flexible connection can significantly reduce the effectiveness of an otherwise stiff cross frame. In the case of skewed cross frames with bent plate connections, the flexibility of the bent plate connection can adversely affect the effective stiffness of the cross frame. The research conducted in this thesis, and in TxDOT project 0-5701, is geared towards quantifying the stiffness of the bent plate connection and determining its overall impact through field and laboratory tests.

2.4 CASE STUDY: CHURCHMAN ROAD BRIDGE

When performing the literature review, there was very little information found specifically pertaining to the bent plate connection and there appears to be little or no research to support the development of design guidelines for this connection. In the past, designers have generally relied upon previous successful use of this detail and experience-based “rules of thumb” for designing the connection. However, there is at least one known case of problem in a skewed steel bridge with cross frames connected with the bent plate detail. These problems arose at the Churchman Road Bridge in Delaware. The following provides an overview of the problem and solution for the Churchman Road Bridge, as presented in a thesis by Winterling [2007].

The Churchman Road Bridge is a four span continuous plate girder bridge situated outside of Newark, Delaware, crossing Interstate 95 in Christiana, Delaware. It has three spans at 199.25 ft and one span of 175 ft and was completed in 2006. Its cross-section consists of eight girders, equally spaced at 8.33 ft center to center. It was constructed using high performance steel, Grade 70W, at a skew angle of 63 degrees. The intermediate cross frame lines were initially constructed parallel to the skewed supports, making the bridge torsionally flexible and insufficiently braced to support the concrete deck placement [Winterling 2007].

The original cross frames constructed along the skew angle, were K-type cross frames with two diagonal angles, a bottom strut angle, and a top chord consisting of a W-section. All bottom chords were L8x8x1 members with the diagonals being L5x5x7/8 or L5x5x1 angles. The top chords were W16x45, W10x33, or W6x15. The member sizes used in the cross frames varied along the length of the bridge corresponding to the required strength [Winterling 2007]. An example cross frame detail is shown in Figure 2.12. Note that the cross frames were connected to the girders using a bent plate detail.

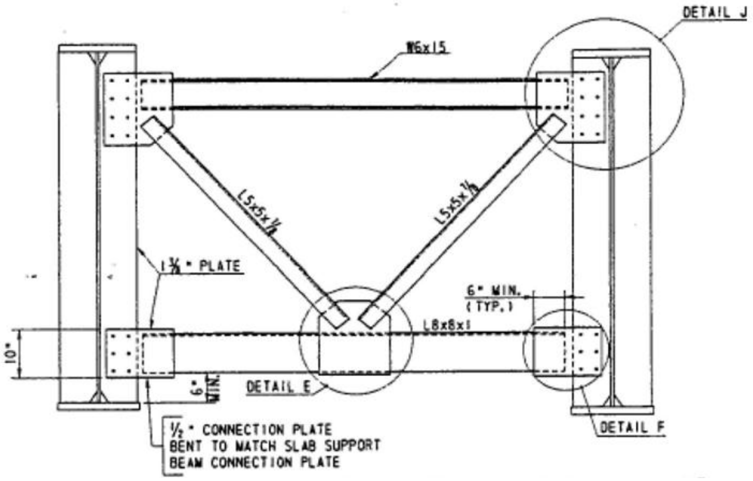


Figure 2.12 Typical Cross Frame Detail [Winterling 2007]

The bent plates were 5/8 in thick connecting to the 1/2 in stiffeners with between 6 and 8 bolts as shown in Figure 2.12. Figure 2.13 shows additional details of the cross frame to web stiffener connection, and Figure 2.14 shows the installed connection.

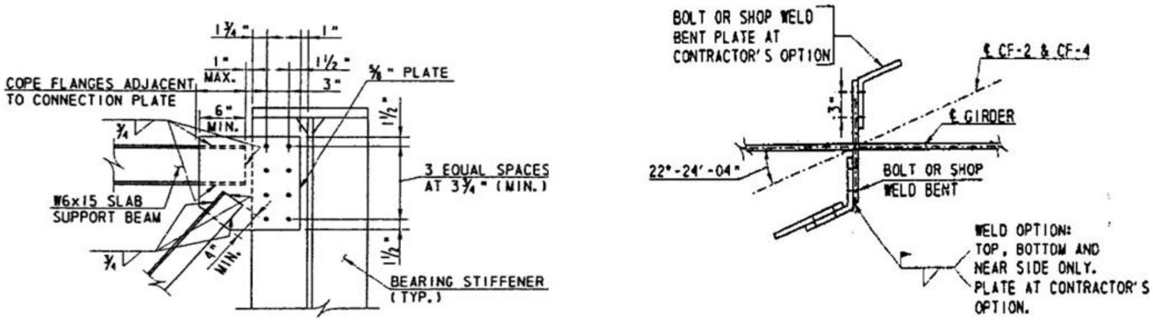


Figure 2.13 Cross Frame to Web Stiffener Details (a) Elevation View (b) Plan View [Winterling 2007]

Figure 2.14 Installed Bent Plate Connection

After erection of the steel girders was completed, temporary supports were removed. Upon introduction of the full dead weight of the steel to the erected bridge skeleton, the girders rotated out of plane approximately 3 degrees. Additionally, the dead load caused cross frames, previously not fully bolted into position, to move relative to their connections, leaving gaps up to 3 in between the bent plates and the stiffeners to which they were partially connected. When attempting to realign the bent plates with the connection, yielding of the plates occurred, causing further stability concerns [Winterling 2007].

The ensuing investigation determined through analysis that the bridge would not have been adequate to resist the load required by the concrete deck placement. It was predicted a hinge would form in the bent plate as it fully yields, transferring the load to the stiffener-web weld. A second hinge would form at this location creating a mechanism [Winterling 2007].

By creating a finite element model in the software STAAD, the stiffener and bent plate were modeled, and subjected to the forces anticipated during the concrete deck pour. The bent plate was modeled as a kinked plate, with two separate plates joined along the bend radius. Finite element analyses concluded the stiffener would in fact yield prior to the bent plate as its thickness was less. The critical location was found to be at the stiffener to web interface in the vicinity of the bent plate connection [Winterling 2007]. One factor not considered in this conclusion is the introduction of yielding in the plates due to the construction fit-up that would need to take place on the rotated girder geometry. Analysis suggested the bridge was incapable of supporting the weight of the wet concrete during deck placement, and consequently a retrofit of the structure was necessary [Winterling 2007].

To retrofit the structure, hydraulic jacks were used to straighten the girders into their intended position. New cross frames were then installed normal to the girders rather than parallel to the skew. The new cross frames were also K-type, with L3x3x3/8 angles for the bottom struts and diagonals and L4x4x3/8 angles for the top chords. The retrofit of the bridge was quite expensive as stiffeners needed to be welded in the field for each of the 145 new perpendicular cross frames. Moreover, the current erected position would not allow whole cross frames to be lifted into place by crane. Therefore, the four individual components of each brace were installed by hand, bolting each to the connection plate bolted to the stiffener. Overall, this process set back construction over two months, delaying the completion of the project and creating significant expense [Winterling 2007].

The situation at the Churchman Road Bridge illustrates the necessity for research into the behavior of the bent plate connection in skewed steel bridges. While the bridge did not meet AASHTO's current specification in terms of when skewed cross frames are allowed (see next section), it demonstrates the problems that can arise when constructing these types of bridges. In addition, a comparison between the skewed cross frames and the normal cross frames reveals a significant decrease in member sizes in the normal cross frames. This illustrates the significance of connection flexibility. While the members of the skewed braces were relatively large for cross frame construction, they were ineffective in bracing the girders due flexibility of the cross frame to girder connections. As noted earlier, the effect of connection flexibility needs to be considered in the calculation of effective brace stiffness to ensure safe structures.

2.5 CURRENT SPECIFICATIONS

At the present, AASHTO estimates two-thirds of all bridges in the United States are skewed [2007]. It is stated that,

> While the skew generally tends to decrease extreme force effects, it produces negative moments at corners, torsional moments in the end zones, substantial redistribution of reaction forces, and a number of other structural phenomena that should be considered in design [AASHTO 2007].

AASHTO also provides a few design rules specific to skewed bridges, such as separate load distribution factors [2007]. However, much of the specification indicates the engineer should consider the effects of the skew in the design of the bridge, but does not give detailed guidance, especially pertaining to the design of the cross frames and cross frame to girder connections.

2.5.1 Cross Frames

Currently, the AASHTO LRFD Bridge Design Specifications [2007] allows intermediate bracing to be oriented parallel to the abutments for skew angles less than 20 degrees (Figure 2.15). For larger skew angles, the intermediate cross frames must be perpendicular to the girders, but cross frames at supports are still situated parallel to the skew (Figure 2.16). For this case, normal cross frames are also permitted in a staggered pattern such that the center of the cross frames line up parallel to the skew (Figure 2.8).

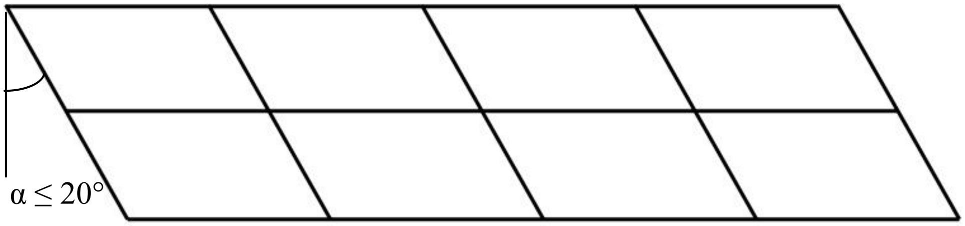


Figure 2.15 Example Bracing Layout for Bridge with Less Than 20° Skew Angle

Figure 2.16 Example Bracing Layout for Bridge with Greater Than 20° Skew Angle

Furthermore, in previous editions of the specification, AASHTO required an arbitrary minimum spacing of 25 ft for cross frames. AASHTO now recommends a "rational analysis" be performed to determine the intermediate cross frame spacing which "will result in the elimination of fatigue-prone attachment details" [2007]. The specification further requires the investigation for spacing of cross frames and diaphragms to included but not be limited to [AASHTO 2007]:

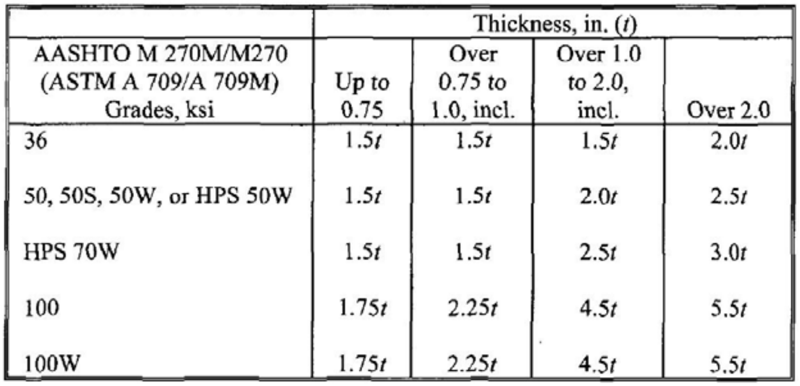
- Resistance of lateral wind loads
- Stability of the bottom flange in all cases when in compression
- Stability of top flange in compression prior to curing of the concrete deck
- Consideration of any flange lateral bending effects
- Distribution of dead and live load forces

While AASHTO does not provide the engineer with specific recommendations as to what constitutes a "rational analysis", elimination of the 25 ft spacing requirement allows for larger unbraced lengths and a decrease in the number of cross frames than in the past.

2.5.2 Bent Plate Connection

Even though the topic of skewed cross frames is considered in the AASHTO 2007 Specifications, there is no mention of the bent plate detail often used to connect these cross frames to the girders. However, guidelines were provided in the 2004 AASHTO Bridge Construction Specifications on bending plates. AASHTO [2004] lists the minimum cold bend radii of the plates (Table 2.1).

Table 2.1 Minimum Cold Bending Radii [AASHTO 2004]



	Thickness, in. (*t*)			
AASHTO M 270M/M270 (ASTM A 709/A 709M) Grades, ksi	Up to 0.75	Over 0.75 to 1.0, incl.	Over 1.0 to 2.0, incl.	Over 2.0
36	1.5*t*	1.5*t*	1.5*t*	2.0*t*
50, 50S, 50W, or HPS 50W	1.5*t*	1.5*t*	2.0*t*	2.5*t*
HPS 70W	1.5*t*	1.5*t*	2.5*t*	3.0*t*
100	1.75*t*	2.25*t*	4.5*t*	5.5*t*
100W	1.75*t*	2.25*t*	4.5*t*	5.5*t*

It is further recommended the bend line be oriented perpendicular to the direction of rolling. Otherwise, it is suggested the radii listed in Table 2.1 be multiplied by 1.5. If a smaller bend is required, hot bending is necessary in accordance with the specification and approval of the engineer of record.

The AASHTO/NSBA Steel Bridge Collaboration confirm these bending radii to thickness ratios, with the absence of Grades 100/100W steel, in their Guidelines for Design for Constructability [2002]. It is also suggested the material be rejected if it contains “non-specified kinks or sharp bends, cracks, large dents, or visible reduction of section (necking)” [AASHTO/NSBA 2002]. AASHTO/NSBA also recommends the maximum radius possible be used as well as ensuring the dies are smooth.

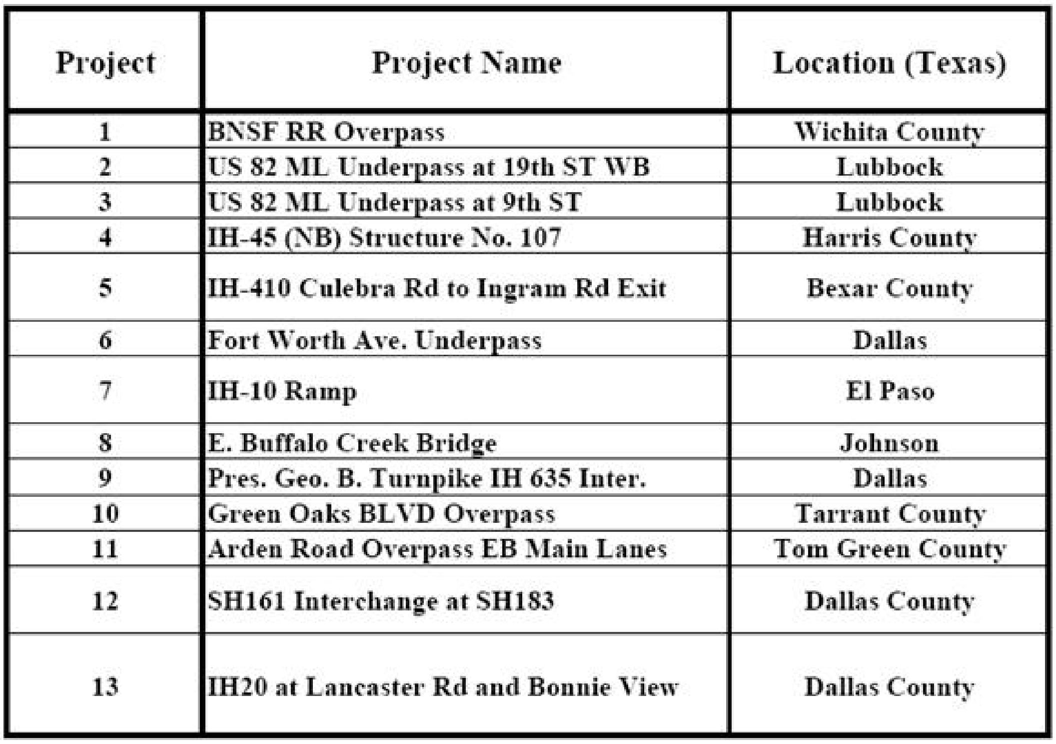
TxDOT research project 0-4624 investigated the "Performance and Effects of Punched Holes and Cold Bending on Steel Bridge Fabrication" [RTI 2006]. The bend radii suggested by this research is 5 times the thickness rather than 1.5 as required by AASHTO (for plates up to 1 in of Grades 36, 50, and 70 steel). The project also discovered heat assisted bending significantly reduces the ductility and fracture toughness of the plate. If heat is used, temperatures should be less than 1200 degrees Fahrenheit and the plate should be heated uniformly through the thickness. In addition, the bending force should be applied slowly to minimize severe local distortions and to prevent cracking from occurring [RTI 2006].

2.6 TXDOT STANDARD DETAILS

The bent plate detail is commonly used in Texas for skewed connections between cross frames and girders. Field welding of connections of cross frames and diaphragms to the girders is preferred over fully bolted connections due to potential difficulties in maintaining erection tolerances when bolted connections are used [Texas Steel Quality Council 2007]. The cross frames are typically connected with erection bolts and then welded prior to placement of the concrete bridge deck. Texas also allows the spacing of cross frames to exceed 25 ft provided a rational analysis is performed to justify the spacing. For the cross frame members, single equal leg angles are typical with commonly used sizes being L3.5x3.5x3/8, L4x4x3/8, and L5x5x1/2 [Texas Steel Quality Council 2007].

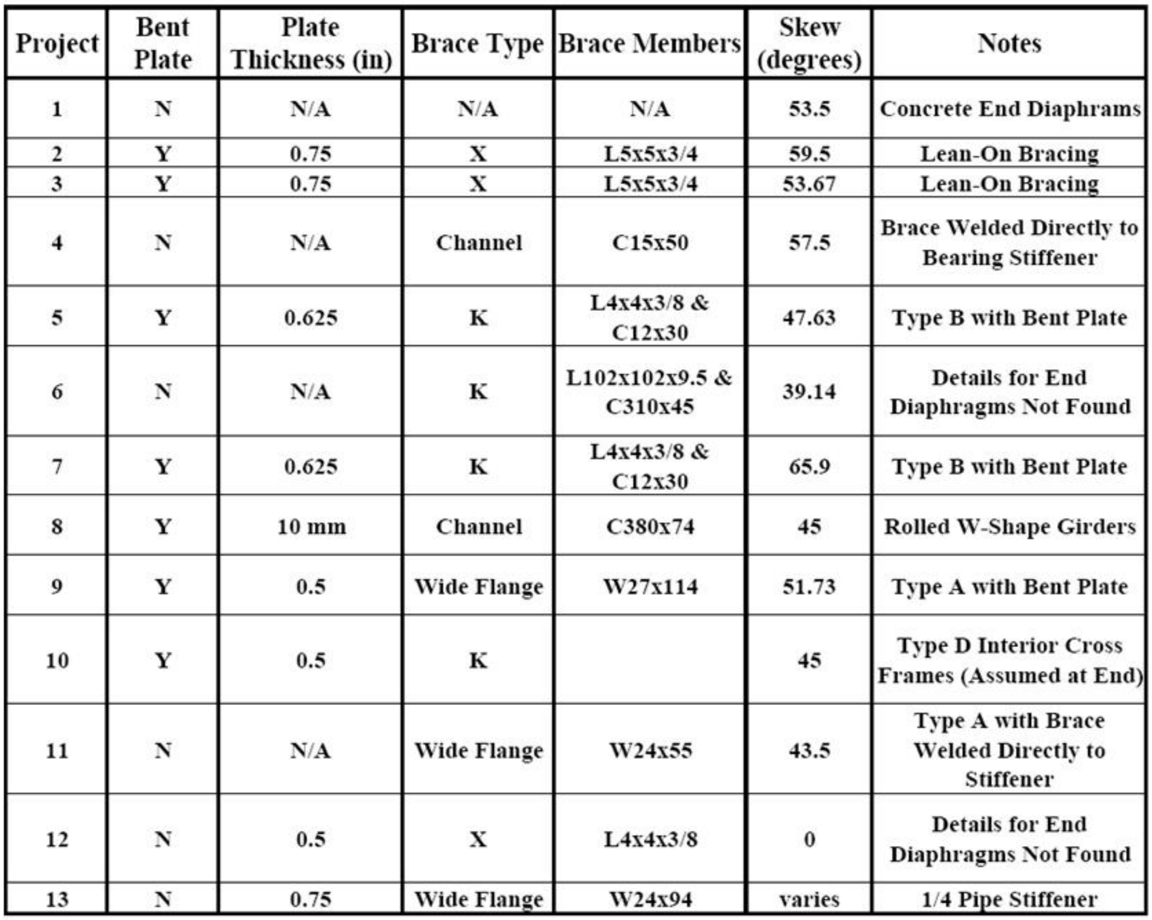
Construction plans for a series of bridges with skewed supports in Texas was obtained by the research team, with skew angles ranging from 39 to 60 degrees. Seven of the thirteen bridges utilized bent plates to connect cross frames to the girders, with the thickness of the bent plates ranging from 1/2 in to 3/4 in. Most cross frames were constructed using angle members. Some braces also had channel members, while others consisted solely of a channel or wide flange diaphragm. The bridges that did not use the bent plate connection either directly welded the braces to skewed stiffeners (two bridges), or it was not evident from the drawings what system was used (two bridges). One bridge used concrete end diaphragms and another used a quarter pipe stiffener (will be discussed in detail in the next chapter). Table 2.2 and Table 2.3 summarize the various plans reviewed and the cross-frame and diaphragm details.

Table 2.2 Plans Reviewed



Project	Project Name	Location (Texas)
1	BNSF RR Overpass	Wichita County
2	US 82 ML Underpass at 19th ST WB	Lubbock
3	US 82 ML Underpass at 9th ST	Lubbock
4	IH-45 (NB) Structure No. 107	Harris County
5	IH-410 Culebra Rd to Ingram Rd Exit	Bexar County
6	Fort Worth Ave. Underpass	Dallas
7	IH-10 Ramp	El Paso
8	E. Buffalo Creek Bridge	Johnson
9	Pres. Geo. B. Turnpike IH 635 Inter.	Dallas
10	Green Oaks BLVD Overpass	Tarrant County
11	Arden Road Overpass EB Main Lanes	Tom Green County
12	SH161 Interchange at SH183	Dallas County
13	IH20 at Lancaster Rd and Bonnie View	Dallas County

Table 2.3 Brace Connection Details



Project	Bent Plate	Plate Thickness (in)	Brace Type	Brace Members	Skew (degrees)	Notes
1	N	N/A	N/A	N/A	53.5	Concrete End Diaphrams
2	Y	0.75	X	L5x5x3/4	59.5	Lean-On Bracing
3	Y	0.75	X	L5x5x3/4	53.67	Lean-On Bracing
4	N	N/A	Channel	C15x50	57.5	Brace Welded Directly to Bearing Stiffener
5	Y	0.625	K	L4x4x3/8 & C12x30	47.63	Type B with Bent Plate
6	N	N/A	K	L102x102x9.5 & C310x45	39.14	Details for End Diaphragms Not Found
7	Y	0.625	K	L4x4x3/8 & C12x30	65.9	Type B with Bent Plate
8	Y	10 mm	Channel	C380x74	45	Rolled W-Shape Girders
9	Y	0.5	Wide Flange	W27x114	51.73	Type A with Bent Plate
10	Y	0.5	K		45	Type D Interior Cross Frames (Assumed at End)
11	N	N/A	Wide Flange	W24x55	43.5	Type A with Brace Welded Directly to Stiffener
12	N	0.5	X	L4x4x3/8	0	Details for End Diaphragms Not Found
13	N	0.75	Wide Flange	W24x94	varies	1/4 Pipe Stiffener

An example of the bent plate detail for these bridge plans is shown in a plan view in Figure 2.17. Note that the stiffeners used to attach the cross frames are separate from the bearing stiffener at the support. The skewed cross frames are oriented so the line of action in the cross frames intersects the centerline of the girder at the bearing stiffener.

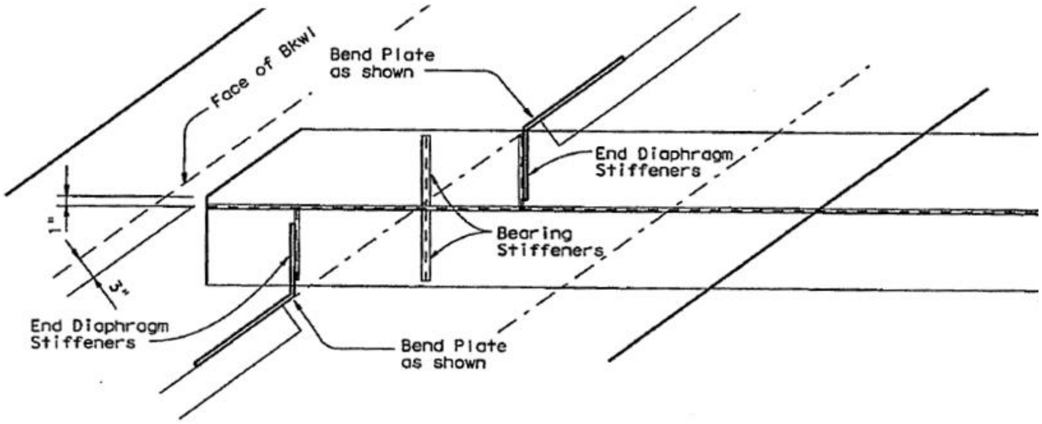


Figure 2.17 TxDOT Plan View of Bent Plate Connection

2.7 RESEARCH NEEDS AND OBJECTIVES

As previously discussed, a review of the literature revealed no past research on the behavior of the bent plate detail and the influence that this connection detail has on the stability of steel girders in skewed bridge. The AASHTO LRFD Specification [2007] does not provide information on the basis of this detail, nor does it give guidance on how to proportion the detail for effective bracing. However, as illustrated by the construction problems encountered at the Churchman Road Bridge in Delaware, the bent plate detail can have a significant impact on the stability and safety of a skewed steel bridge. Consequently, research is needed to better understand the behavior of the bent plate detail, to quantify the stiffness of this connection detail, and to examine the effect of the flexibility of this connection on the overall stiffness of the cross frame system.

With these research needs in mind, the objectives of the research described in this thesis are as follows:

- Examine the demand on the bent plate connection in a typical skewed steel bridge,
- Understand the fabrication process of the bent plate,
- Study the structural behavior of the bent plate connection,
- Quantify the stiffness of the bent plate connection,

- Investigate the effect of varying certain parameters on the stiffness of the bent plate connection, including skew angle, bend radius, and bolted/welded construction,
- Investigate the half pipe stiffener connection as a possible alternative to the bent plate connection for increased stiffness and better structural performance,
- Compare the proposed alternative connection to the bent plate connection.

CHAPTER 3

Proposed Alternative Cross Frame Connection

3.1 INTRODUCTION

As discussed in Chapter 2, the flexibility of the bent plate connection can adversely affect the stability of steel bridges by reducing the effectiveness of cross frames for bracing girders. A detail for connecting skewed cross frames to girders that may potentially offer better performance than the bent plate is the use of a half pipe stiffener. The half pipe stiffener will lead to significant increases in the connection stiffness between the brace and the girders and also allow perpendicular intersections in the welded connections for any skew angle. In addition to stiffer connections there are additional structural benefits to using the pipe stiffener that may reduce the number of braces required in the congested regions around the supports of the bridge. In this chapter, the proposed half-pipe connection detail is described. Background information on similar details is discussed, both from previous research and from field applications. A discussion on material availability, properties for structural steel pipe, and fabricator feedback on this new detail complete the chapter.

3.2 HALF PIPE STIFFENER DETAIL

When dealing with skewed steel bridges, many geometrical and behavioral difficulties are encountered as a result of the skew angle. As was described in Chapter 2, the bent plate connection is often used to facilitate connection of the cross frames, which on a skew, intersect the web cross-section at an angle. However, a proposed detail is to replace the conventional single plate cross frame stiffener with a half pipe stiffener, which potentially provides an overall stiffer connection. The total stiffness of torsional bracing systems such as cross frames are a function the stiffness of several components including the stiffness of the brace, the in-plane stiffness of the girder, the effect of cross sectional distortion, and the stiffness of the connection. As outlined in the last chapter, the total system stiffness is smaller than the smallest component. With a highly flexible connection, such as can be found in some bent plate connections, the connection stiffness may be the limiting stiffness for the bracing system. Therefore, stiffer connections can result in significant improvements in bracing behavior.

Figure 3.1 shows the conventional bent plate connection detail along with the proposed half pipe stiffener detail. In the proposed detail, a section of pipe that has been cut in-half is welded to the girder. A connection plate is then welded to the half-pipe stiffener. As seen in Figure 3.1 the bent plate and half pipe stiffener details can both be oriented to easily accommodate a variety of angles. In the case of the bent plate detail, the bent plate is normally shop welded to the cross frame, and field welded to the stiffener on the girder. An erection bolt is typically used to temporarily attach the bent plate to the stiffener until welding can be completed.

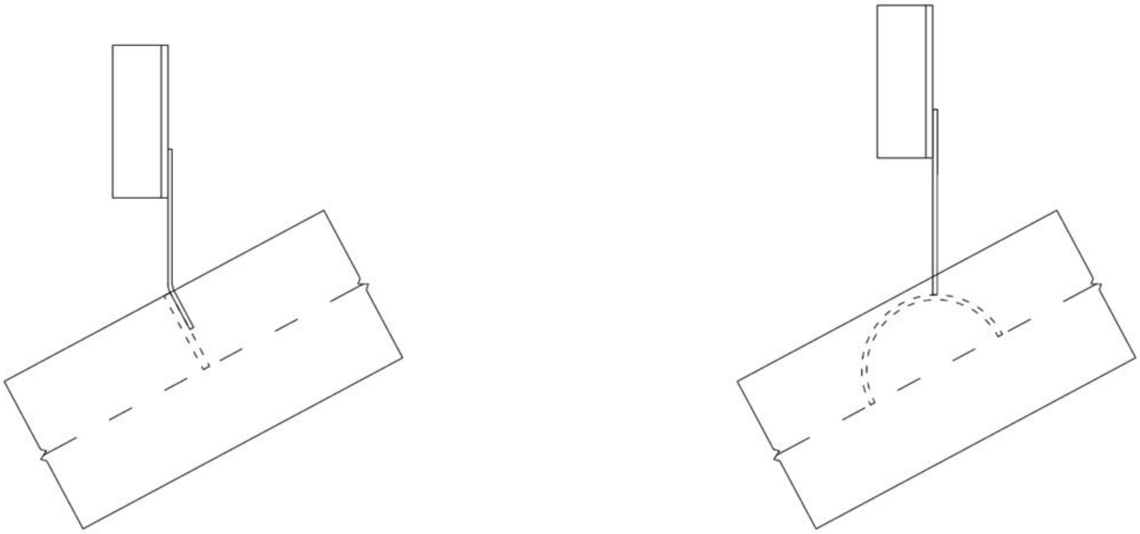


Figure 3.1 (a) Bent Plate Connection and (b) Half Pipe Stiffener Connection

On the other hand, the half pipe stiffener provides a more direct connection of the cross frame connection plates to the stiffener. It is anticipated that a steel tab can be connected to the pipe to allow construction workers to temporarily bolt the brace in place for welding.

In addition, the pipe stiffener offers a more universal connection. For instance, bent plates need to be fabricated at specific skew angles and come in a variety of shapes and sizes depending upon the cross frame size. It is anticipated that the pipe stiffener detail would come in a few select sizes suitable for the range of typical skewed plate girder construction. Due to the circular nature of the pipe, the straight plates framing into the stiffener will be perpendicular regardless of skew angle. Such a detail will also be beneficial in curved bridge construction where supports may also be skewed.

Relative to conventional stiffening practices around supports, the half pipe stiffener does not generally require more extensive fabrication efforts, and in some cases may actually have less welding than current stiffening methods. The current practice of construction with the bent plate is to align the skewed cross frames so the line of action of the forces they transfer to the girders intersects the center of the bearing stiffener as shown in Figure 3.2.

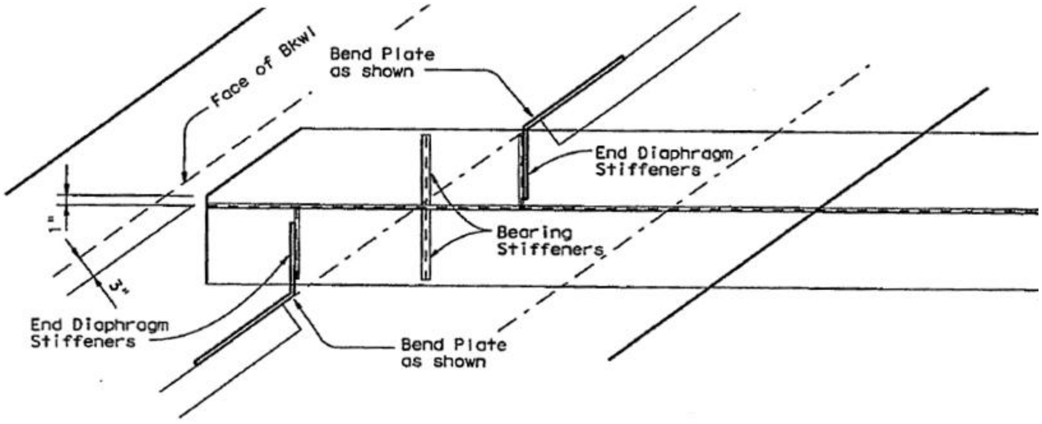


Figure 3.2 TxDOT Plan View of Bent Plate Detail

Current stiffening details typically make use of four separate stiffeners in the complicated end region of skewed steel bridges. Two stiffeners are provided for bearing, while the other two stiffeners are actually cross frame connection plates that are offset to enable the force line to intersect the bearing center.

Because of the large area of the pipe and the very large buckling strength as a column, the pipe stiffeners also have the ability to serve as the bearing stiffener.

Therefore, the proposed half pipe stiffener only requires two stiffeners to be welded. The circular geometry allows the line of action of the cross frame forces to pass through the center of the tube shape.

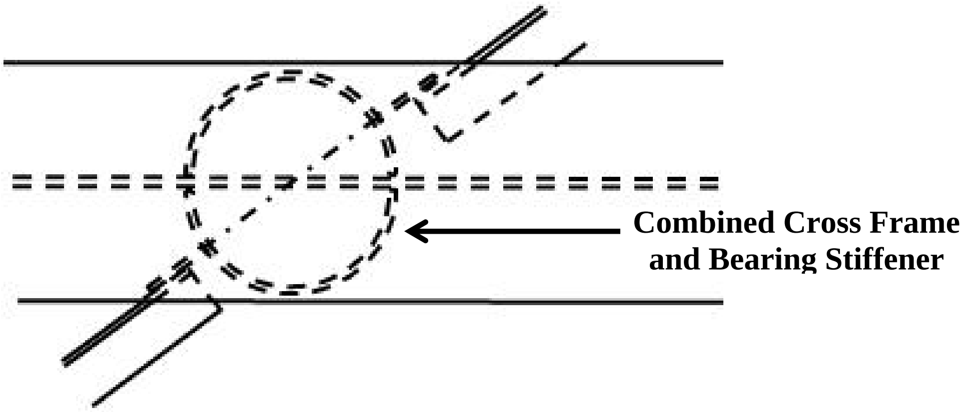


Figure 3.3 Plan View of Half Pipe Stiffener Detail

A major structural advantage of the pipe stiffener is the potential to increase the warping stiffness of the girders around the support regions. Since the pipe is welded to both the web and the two flanges, the resulting combination of the stiffener and the girder web consists of a closed shape with a very large torsional resistance. As a result the tubular stiffener provides a significant amount of restraint to warping deformations. The improved warping resistance will lead to improved buckling resistance around the support regions, thereby reducing the number of braces in the regions that are often highly congested. Reducing the number of cross frames leads to two main benefits: fewer cross frame regions that need to be inspected; and cross frame lines around the ends of the span that can be placed further from supports, thus helping to minimize differential deflections and enhance the service fatigue life.

As discussed in this section, the half pipe stiffener provides a viable alternative to the bent plate. The detail accommodates all skew angles, and may reduce fabrication requirements on the steel girder system. As a peripheral benefit, the closed pipe section provides restraint to warping deformation, which adds to the buckling capacity of the girder, allowing longer unbraced lengths and potential reduction of the number of cross frames required. With these factors in mind, current specifications and details are evaluated.

3.3 BACKGROUND

At present, AASHTO does not make any specific accommodations for using warping restraining devices in the design of steel bridges. However, AASHTO allows a “rational analysis” to be performed to proportion and place the intermediate cross frames [AASHTO 2007]. Provided the girder behavior is evaluated with a “rational analysis”, the provisions allow engineers to utilize the effectiveness of a warping restraint when determining the cross frame spacing.

While not widely used in structural engineering practice, warping restraints, such as the half pipe detail, have been previously studied. Ojalvo and Chambers authored an article titled “Effect of Warping Restraints on I-Beam Buckling,” published in 1977 [Ojalvo and Chambers 1977]. Their research focused on the restraining detail portrayed in Figure 3.4, mostly for use in building construction.

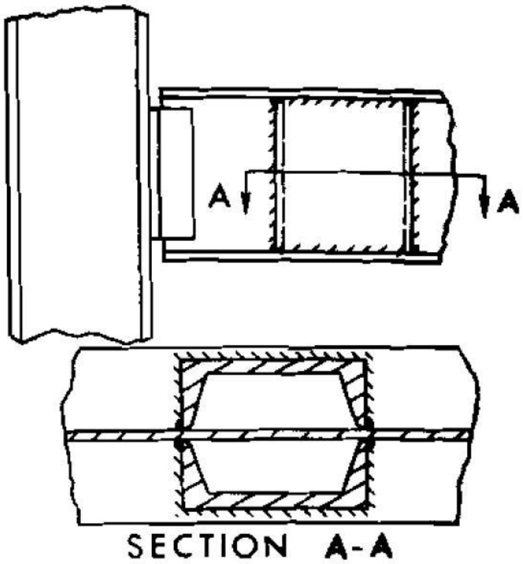


Figure 3.4 Tube-Type Warping Restraining Device [Ojalvo and Chambers 1977]

Reconsider the equation for critical buckling moment of an unbraced beam subjected to uniform moment [Timoshenko and Gere 1961]:

$$M_0 = \pi/L_b\sqrt{EI_yGJ + \pi^2E^2C_wI_y/L_b^2} \qquad (3.1)$$

where,

M_0 = *Critical Unbraced Buckling Moment*
L_b = *Length of Beam*
E = *Elastic Modulus*
I_y = *Moment of Inertia of the Section (weak axis)*
G = *Shear Modulus*
J = *Torsional Constant*
C_w = *Warping Constant*

The portion under the radical of Equation (3.1) can be separated into two terms; the first term under the radical (EI_yGJ) represents the St. Venant torsion capacity while the second term under the radical represents the warping stiffness of the beam. Utilizing a closed tube such as a pipe stiffener between the top and bottom flanges produces a torsionally stiff link between the flanges, thereby restraining warping deformations in the flanges. Such a detail can dramatically improve the buckling resistance of the member near the support regions. The critical unbraced buckling moment is then used in calculating the critical buckling moment of the bridge system as was detailed in Chapter 2.

Ojalvo and Chambers developed an analytical method utilizing a numerical integration procedure to determine the buckling capacity of a girder with a warping restraint device at each end. Their analysis of various rolled wide flanged shapes showed a 27-50 percent increase in buckling capacity for long beams (L/d = 30) and a 65-100 percent increase for short beams (L/d = 10). Finally, they cautioned that welding the warping restraining devices to the tension flange in areas of high cyclic stress could lead to problems [Ojalvo and Chambers 1977].

3.4 TXDOT DETAILS

With the theoretical background supporting the structural behavior of the half pipe detail, an investigation into some current practices was conducted. The following details were found in plans provided to the research team by TxDOT, as well as in discussions and visits to fabricator shops.

Figure 3.5 shows a skewed connection detail previously used on a bridge in Texas. The detail utilizes a quarter pipe inserted between the girder web and a regular stiffener.

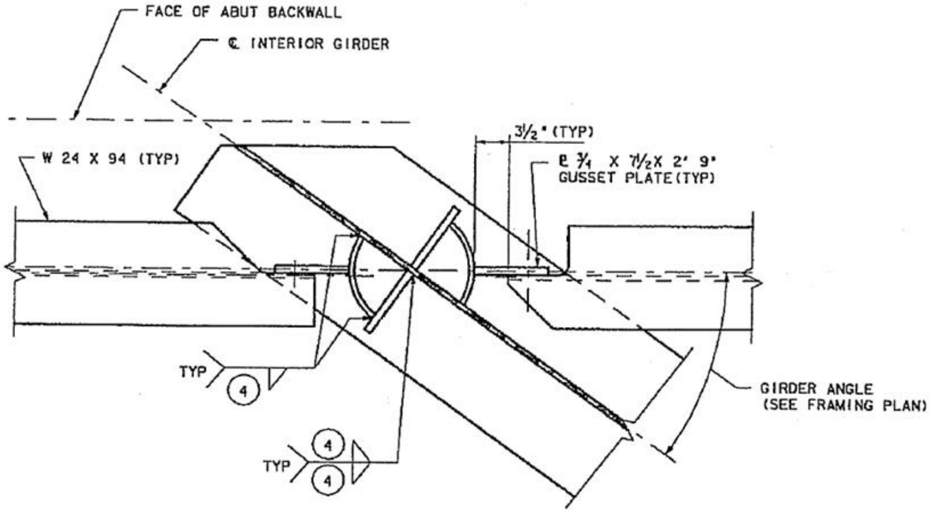


Figure 3.5 Plan View of Quarter Pipe Stiffener Detail

While the quarter pipe stiffener seems to be similar to the proposed solution, there are some important differences. For instance, the welding required to complete this detail is twice that required by the half pipe because the normal stiffener needs to be put in place, then the quarter pipe welded. Moreover, cutting the pipe into quarters requires an extra cut during fabrication, potentially offsetting any saving made in material. Lastly, since the torsional constant of a closed shape is related to the area enclosed, the quarter pipe does not provide as much warping restraint as the half pipe. Overall, the half pipe stiffener appears to offer several advantages over this quarter pipe detail.

Another similar detail used on a Texas bridge involved the use of a full pipe section. With this detail, the girder web was interrupted and was welded to the pipe. Figure 3.6 is a photo of this detail taken in a fabrication shop. While this detail requires about the same amount of fabrication work to construct as the half pipe solution, there could be negative behavioral impacts of interrupting the web. Specifically noted is placement of this detail across an interior support where the negative moment demand may be large. With the web non-continuous, the fatigue behavior will likely diminish as the connecting welds would become critical to transmit forces from the web on one side of the pipe, to the web on the other.

Figure 3.6 Pipe Stiffener Detail Inserted Through Web

The two details shown above were the only instances found of details that are similar to the proposed half pipe stiffener detail. However, it is believed that the half pipe stiffener offers advantages over these other two details, both in terms of cost and structural performance.

3.5 PIPE AVAILABILITY

An item of interest in assessing the viability of the half pipe stiffener detail is what sizes and grades of material are commonly available for steel pipe sections. It is anticipated that the majority of applications will require the pipe to have an outside diameter between 12 and 16 in with a wall thickness of at least 0.5 in. It is also expected that relatively small quantities of pipe will be needed for a given bridge system. Therefore, it is pertinent to contact various pipe supply companies and manufacturers to determine the availability of materials.

Three commonly used forms of steel pipe are the seamless, straight welded, and spiral welded varieties. Seamless pipe involves the progressive rolling of a steel cylinder until the desired wall thickness is achieved. The steel cylinder is formed by essentially coring a molten steel section. This type is typically used in the petroleum and utility (i.e. sewer, gas, and water lines) industries, and because of its formation costs, would prove uneconomical for structural applications. Straight welded pipe involves the bending of a steel plate into a tubular section, after which the seam is welded along the length. Spirally welded pipe involves long lengths of plate being progressively rolled into a helix that is then welded along the seam to create a tube. It is the latter two pipe types investigated herein.

Several manufacturers of steel pipe were contacted to investigate availability. The results from this survey are summarized in Table 3.1.

Table 3.1 Summary of Pipe Availability

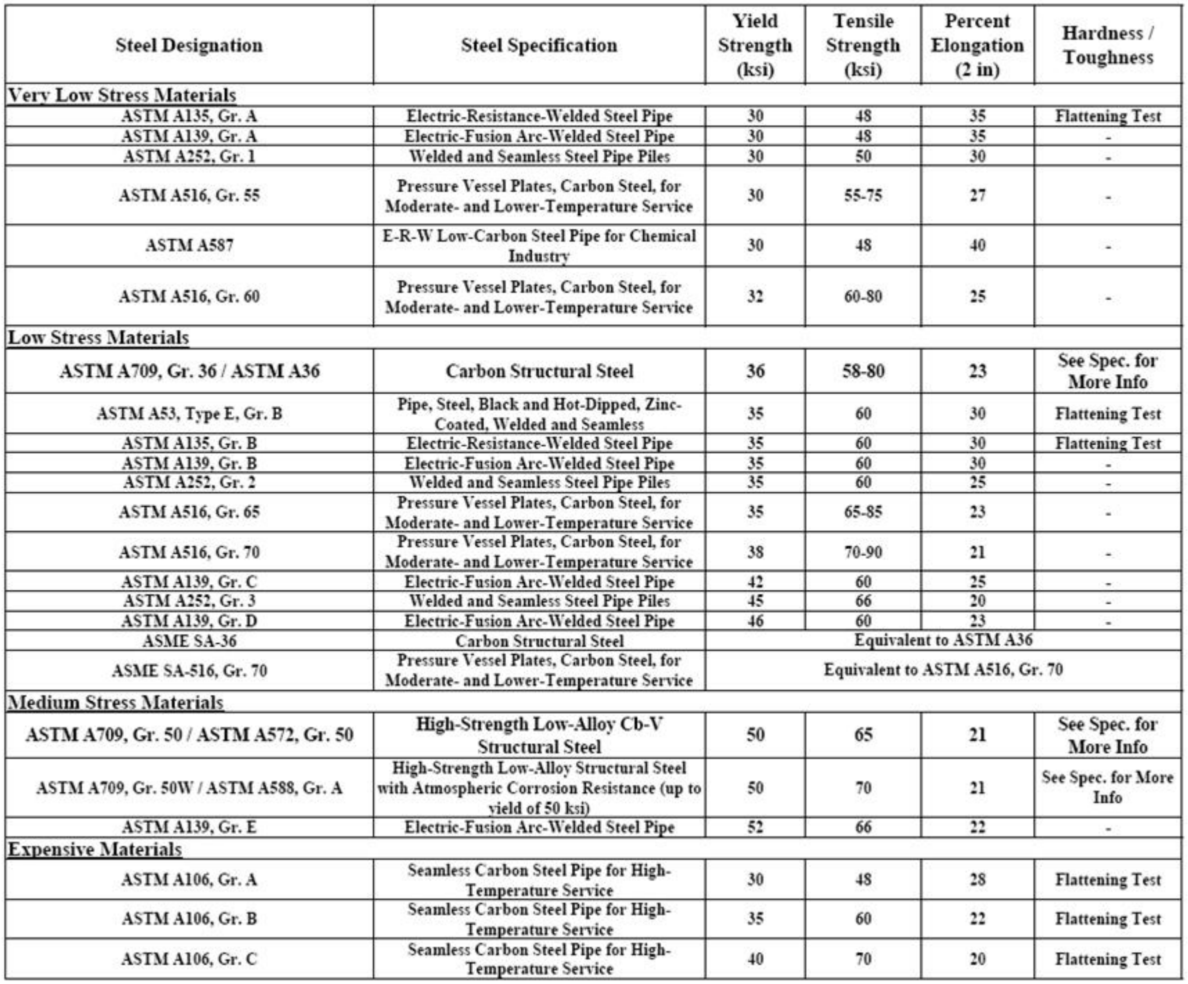
		Straight Pipe Manufacturers			Spiral Welded Pipe Manufacturers		
		Readily Available	Somewhat Available	Not Available	Readily Available	Somewhat Available	Not Available
Diameters	< 12 in	X				X	
	12 in - 16 in	X			X		
	> 16 in	X			X		
Thickness	≤ 0.25 in	X			X		
	0.375 in	X			X		
	≥ 0.5 in	X			X		
Material	A36	X			X		
	A252 Gr. 2,3	X			X		
	A572 Gr. 50	X			X		
	Weathering			X		X	
Lengths	~ 20 ft	X			X		
	~40 ft	X			X		
	~ 60 ft		X		X		

One of the important observations from the survey of pipe manufacturers was the limited availability of pipe in weathering grade steel. The survey concluded weathering steel was not available from any of the straight pipe manufacturers, but was available from makers of spiral welded pipe since these pipes are simply made from plate material. The advantage of the spiral welding process is the pipes are often made to order. Therefore, the manufacturer simply has to put a weathering grade steel into the machine to make the pipe. Although convenient, spiral welded pipe's creation may have effects on pipe strength and could cause problems with intersecting welds in details. The practicality of spirally welded pipe is still being considered by the research team on TxDOT Project 0-5701.

3.5.1 Material Information

As listed in Table 3.1, steel pipe comes in a variety of materials whose properties are designated by ASTM specifications. In the process of contacting steel pipe providers, it was found that many suppliers had a large selection of these materials. In particular, pipe designated as A36 and A572 Gr. 50 were of interest, as these are typical designations of structural steel members. Furthermore, A53 Gr. B is the AISC preferred material for structural pipe, and A500 is the typical grade for round HSS sections [AISC 2005]. The different grades of steel found for pipes were compared with those typically used in the bridge specifications to determine the grades which would deliver similar. Table 3.2 summarizes the material grades which would have comparable strengths, as well as welding properties.

Table 3.2 Summary of Material Grades [ASTM 2009]



Steel Designation	Steel Specification	Yield Strength (ksi)	Tensile Strength (ksi)	Percent Elongation (2 in)	Hardness / Toughness
Very Low Stress Materials					
ASTM A135, Gr. A	Electric-Resistance-Welded Steel Pipe	30	48	35	Flattening Test
ASTM A139, Gr. A	Electric-Fusion Arc-Welded Steel Pipe	30	48	35	-
ASTM A252, Gr. 1	Welded and Seamless Steel Pipe Piles	30	50	30	-
ASTM A516, Gr. 55	Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service	30	55-75	27	-
ASTM A587	E-R-W Low-Carbon Steel Pipe for Chemical Industry	30	48	40	-
ASTM A516, Gr. 60	Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service	32	60-80	25	-
Low Stress Materials					
ASTM A709, Gr. 36 / ASTM A36	**Carbon Structural Steel**	**36**	**58-80**	**23**	**See Spec. for More Info**
ASTM A53, Type E, Gr. B	Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless	35	60	30	Flattening Test
ASTM A135, Gr. B	Electric-Resistance-Welded Steel Pipe	35	60	30	Flattening Test
ASTM A139, Gr. B	Electric-Fusion Arc-Welded Steel Pipe	35	60	30	-
ASTM A252, Gr. 2	Welded and Seamless Steel Pipe Piles	35	60	25	-
ASTM A516, Gr. 65	Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service	35	65-85	23	-
ASTM A516, Gr. 70	Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service	38	70-90	21	-
ASTM A139, Gr. C	Electric-Fusion Arc-Welded Steel Pipe	42	60	25	-
ASTM A252, Gr. 3	Welded and Seamless Steel Pipe Piles	45	66	20	-
ASTM A139, Gr. D	Electric-Fusion Arc-Welded Steel Pipe	46	60	23	-
ASME SA-36	Carbon Structural Steel	Equivalent to ASTM A36			
ASME SA-516, Gr. 70	Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service	Equivalent to ASTM A516, Gr. 70			
Medium Stress Materials					
ASTM A709, Gr. 50 / ASTM A572, Gr. 50	**High-Strength Low-Alloy Cb-V Structural Steel**	**50**	**65**	**21**	**See Spec. for More Info**
ASTM A709, Gr. 50W / ASTM A588, Gr. A	High-Strength Low-Alloy Structural Steel with Atmospheric Corrosion Resistance (up to yield of 50 ksi)	50	70	21	See Spec. for More Info
ASTM A139, Gr. E	Electric-Fusion Arc-Welded Steel Pipe	52	66	22	-
Expensive Materials					
ASTM A106, Gr. A	Seamless Carbon Steel Pipe for High-Temperature Service	30	48	28	Flattening Test
ASTM A106, Gr. B	Seamless Carbon Steel Pipe for High-Temperature Service	35	60	22	Flattening Test
ASTM A106, Gr. C	Seamless Carbon Steel Pipe for High-Temperature Service	40	70	20	Flattening Test

3.6 FABRICATOR FEEDBACK

Just as important as material availability, feedback from the various fabricators was assessed to see if there was any potential resistance to the proposed detail. One of the issues discussed was the availability of the appropriate diameter and thickness of pipe in weathering steel, which was covered in the previous section.

An issue of concern regarding fabrication was whether significant difficulties would be encountered in fit-up of the half pipe stiffener within the girder. Fatigue test specimens (not discussed in this thesis) that included half pipe stiffeners welded into a steel girder were prepared at Hirschfeld Industries in San Angelo, Texas. In fabricating these test specimens, no significant fit-up problems were encountered. An example of the half pipe detail prior to welding, as constructed in the fabricator's shop, is displayed in Figure 3.7. The pipe was cut to length and split using a flame torch, and was ground as necessary to fit. The research team has also gained experience in the fabrication requirements of the pipe stiffeners versus the bent plate details since specimens have been fabricated "in-house" at Ferguson Structural Engineering Laboratory.

Figure 3.7 Half Pipe Stiffener Fabrication

Another important detail for the half pipe stiffener is the need to seal weld the half pipe to the girder. Seal welding refers to welding around the entire periphery of the pipe and is needed to prevent the accumulation of moisture and other debris inside the pipe.

The fabricator indicated the physical welding of the specimen would not be a hindrance, as the typical welding machines could still do the vertical web to stiffener portion, and welding by hand around the curved portion of the pipe would not be difficult.

3.7 CONCLUSIONS

The half pipe stiffener offers a potentially useful alternative to the conventional bent plate connection for skewed cross frames. The half pipe stiffener provides a stiffer connection between the cross frame and the girder relative to bent plate details, thereby improving the bracing effectiveness of the cross frames. It offers the added advantage of providing warping restraint to the girder. This warping restraint can increase the buckling capacity of the girders, and may therefore allow a reduction in the number of cross frames. An increase in the spacing between cross frame lines is desirable near the supports since these regions are often highly congested. Further, it appears that pipe sections for this application are commercially available, and that welding of the pipe stiffener to the girder should not create undue fabrication difficulties.

CHAPTER 4

Field Investigation

4.1 INTRODUCTION

The bent plate detail is frequently used in skewed steel bridges to connect the end cross frame to the girder web. Due to the complex behavior of these bridge systems, it is difficult to analytically determine the force demand on the skewed connection, particularly since the actual boundary conditions and connection conditions in heavily skewed bridges can be highly variable. Therefore, a field study of an end cross frame was conducted which provided an indication of the magnitude of forces transmitted to the bent plate of a highly skewed bridge. The information obtained gave insight to bridge performance and helped establish the amount of force one could expect the detail to sustain in service. The field investigation tracked the forces during the placement of the concrete deck, as well as under a controlled live load testing program. This chapter describes in detail the location and layout of the bridge, the instrumentation of the end cross frame, and the numerical results obtained.

4.2 BRIDGE INFORMATION

The bridge studied in this field investigation was part of a joint effort, working in conjunction with two other research studies funded by the Texas Department of Transportation (TxDOT) at The University of Texas at Austin. The primary investigation that was focusing on the bridge behavior was TxDOT Project 5-1172, which was an implementation project focusing on the use of lean-on bracing in bridges with skewed supports [Romage 2008, Fasl et al. 2009]. Capitalizing on the access to the bridge during construction, TxDOT Project 0-5706 which focused on the effects of overhang construction on steel bridge behavior was also active in the field monitoring. Because the bridge had heavily skewed supports (approximately 60 degrees) and used bent plates for the cross frames at the supports, it provided an excellent opportunity to gain realistic data for the research investigation on bent plate connections. In addition to the end cross frame, intermediate cross frames, lean-on braces, and multiple girders were instrumented to measure various structural effects. Further information on these other projects can be found in the listed references [Romage 2008, Fasl et al. 2009].

4.2.1 Location

The bridge investigated during the field monitoring was the westbound 19th Street overpass crossing US-82 in Lubbock, Texas (Figure 4.1). During the time of investigation, US-82 was under construction to create a corridor without traffic signals. In order to complete the thoroughfare, two bridges to carry the 19th Street traffic across the highway were being constructed. Since 19th Street was at grade elevation, US-82 was being constructed below grade by digging a passageway beneath the street. The westbound bridge was constructed first, while all traffic on 19th Street was diverted onto the existing eastbound side. Once the overpass was completed, the traffic would be directed onto it while construction of an eastbound bridge ensued.

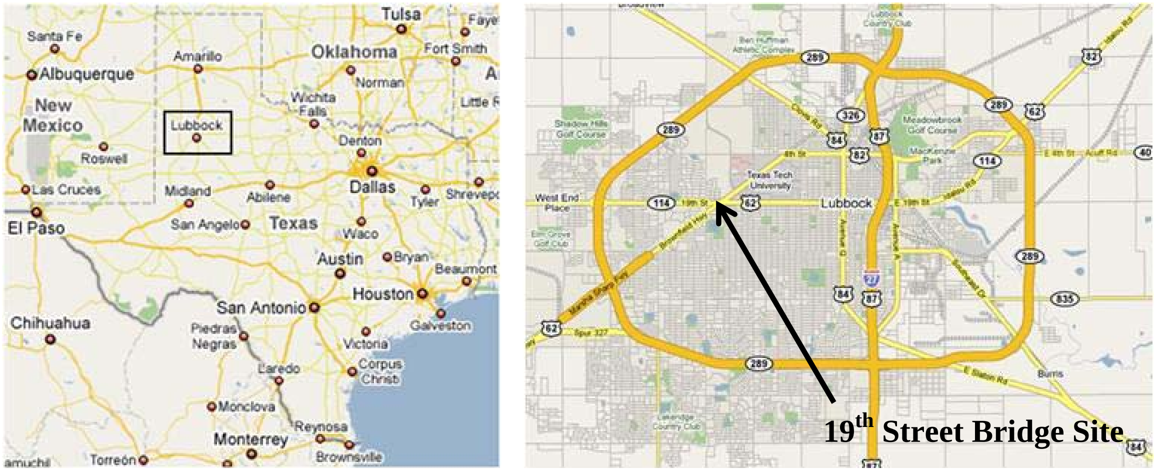


Figure 4.1 Location of Bridge in Lubbock, Texas [Google 2008]

4.2.2 Geometry

The bridge studied in the field investigation is a two span continuous structure situated at a 59.56 degree skew angle (59° 33′ 43.05″). Figure 4.2 shows an elevation view of the bridge, consisting of a 139.0 ft east span and a 150.5 ft west span. The bridge is comprised of 6 girders across the width, each measuring 56 in deep at the end supports and evenly spaced at 8.2 ft. The finished superstructure with overhangs has a width of 47 ft and supports three lanes of traffic.

The bridge utilizes bent plate details along the interior and end supports, while all other cross frames are placed normal to the girders per AASHTO guidelines which require this orientation for skew angles larger than 20 degrees [2007]. The cross frame instrumented for the study is located at the western support, in the second girder spacing from the south edge of the bridge as indicated in Figure 4.2.

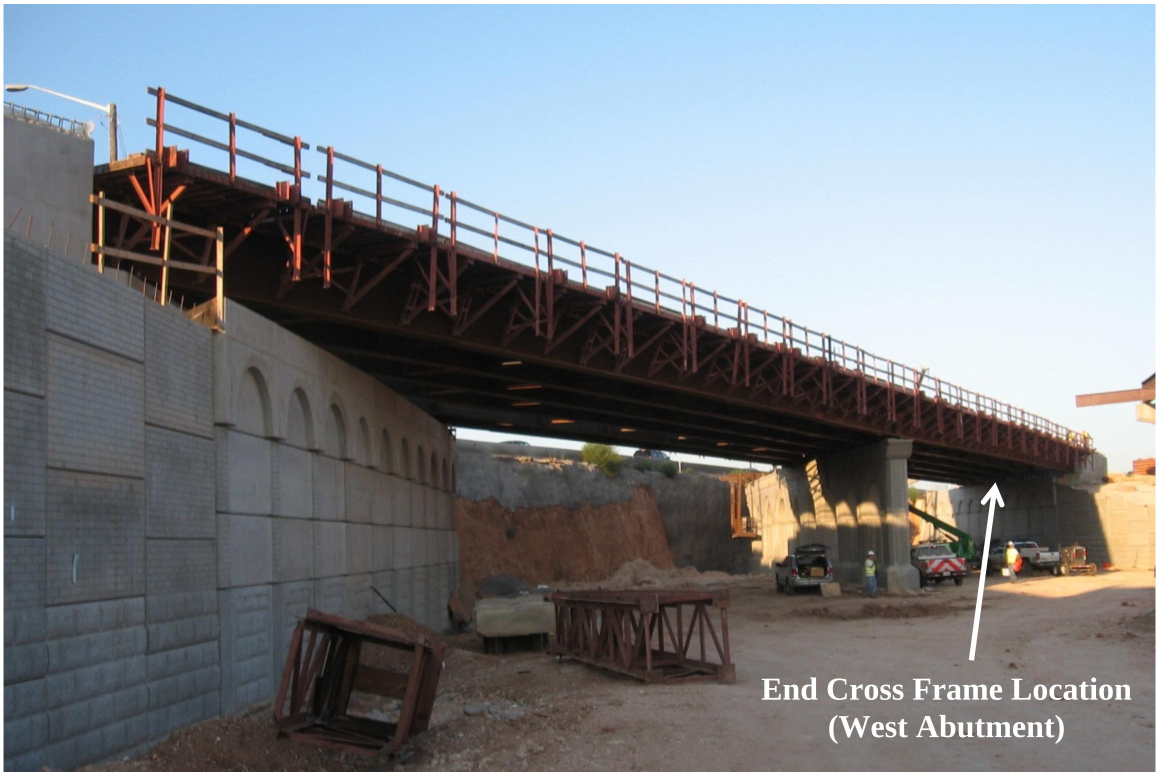


Figure 4.2 Elevation View of the 19th Street Westbound Bridge

4.3 INSTRUMENTATION

The following section of the report describes the instrumentation and techniques used to measure the forces and rotations of the end cross frame. Specific attention is given to the derivation of axial force from the strain gages of the angle members, as well as a brief discussion of the data acquisition equipment used.

4.3.1 End Cross Frame

The cross frame investigated is classified as an X-type brace, due to the two crossing diagonals (Figure 4.3). The cross frame measures just less than 54 in deep and approximately 190 in wide. The brace is attached to the girder with bent plates, roughly 18 in deep, 18 in wide, and 3/4 in thick that overlap the cross frame stiffener by 4 in. The cross frame members consist of L5x5x3/4 angles with a cross-sectional area of 6.94 in^2 and the geometry shown in Figure 4.4.

In order to determine the amount of force transmitted to the bent plate during the concrete deck placement and under live load service conditions, each cross frame member was instrumented with four strain gages. The locations and naming scheme for these gages is provided in Figure 4.4.

Figure 4.3 End Cross Frame

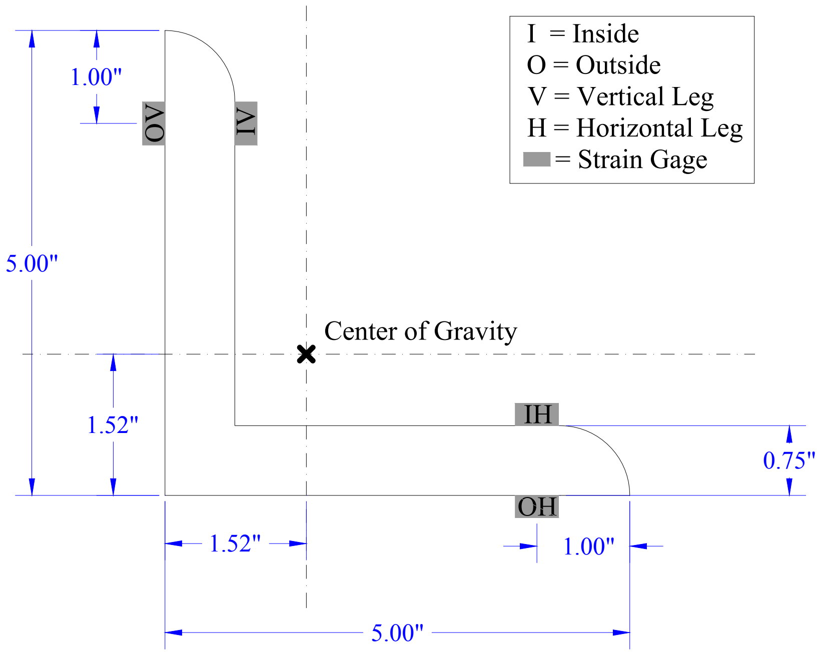


Figure 4.4 Angle Geometry and Location of Strain Gages

Following a procedure reported by Helwig and Fan [2000], the axial force in the angle can be determined from the strain values measured. Since the geometric centroid and shear center of the angle member do not coincide, its bending behavior is difficult to predict. Since these angles can be considered thin-walled members, minimal warping stresses will be induced in the angles when subjected to torsional moments. Therefore, longitudinal stresses only exist due to axial and bending moments. Helwig and Fan [2000] surmised the following mathematical regression procedure based on a least squares approach is adequate to calculate axial force values using the strain values from four carefully placed gages. The distribution of stress is linear, and can be represented by the equation:

$$f = a + bx + cy \tag{4.1}$$

where f is the longitudinal stress, a, b, c are constants, and x, y are the coordinate system of the cross-section of the angle. By placing the origin of the coordinate system at the geometric centroid, the axial force N in the member is determined by:

$$N = aA \tag{4.2}$$

with A being the cross-sectional area of the angle. The advantage of this procedure is it only requires three stress readings from non-collinear points to calculate the axial force.

4.3.2 Data Acquisition System

The data acquisition system used at the bridge site was a CR5000 Datalogger combined with AM416 Multiplexers manufactured by Campbell Scientific, Inc. The main advantages of the system included mobility, versatility, and durability, while still allowing for precision measurement. Since the loading cases studied were of a static nature, scanning properties were optimized by controlling settling times, integration times, and excitation reversal. Settling time refers to the time between when the datalogger sends an excitation to the device (strain gage) and when it receives and records the value. By using longer settling times, one can prevent an electronic lag from developing in the system. Integration time refers to the length of the interval the datalogger spends reading a particular sensor, with a longer time helping to filter noise from the measurement. Lastly, excitation reversal will reverse the signal and record a second reading for the measurement taken. It then averages the readings to help remove any voltage offset errors inherent to the measurement circuitry [Fasl 2008].

The strain gages used were manufactured by TML and consisted of type FLA-6-350-11-3LT, which are general purpose foil gages, 6 mm long with a 350 Ω resistance, and temperature-compensated for mild carbon steel. By splicing the lead wires to a thicker gage insulated wire, electronic interference in the field was minimized. To connect to the datalogger, Campbell Scientific 4WFB350 4-Wire Full Bridge Terminal Input Modules were used to complete the full bridge of the strain gage [Fasl 2008].

4.4 CONCRETE DECK PLACEMENT

Prior to casting the concrete deck on a bridge, the cross frames are the primary source of lateral bracing for the girders. Afterwards, the hardened concrete deck provides both lateral and torsional restraint to the girders, greatly reducing the stability-induced forces in the cross frames. Therefore, it is expected the concrete deck placement results in the largest forces induced in the end cross frames, and hence the largest transmitted to the bent plate connection.

4.4.1 Timeline

The casting of the concrete deck in the westbound 19th Street overpass in Lubbock, Texas took place on October 4, 2007. The finishing machine was oriented parallel to the skew, and therefore concrete placement also followed the skew line. The process began at the approach at 2:25 AM, and entered the west span at 4:27 AM. At approximately 8:15 AM, the placed concrete was 108 ft from the western support, and the contractor decided to preload the eastern span with concrete. This was done to prevent uplift from occurring as a direct result of the continuous bridge geometry. Placement along the western span resumed at 8:45 AM, and culminated at 10:05 AM. The eastern span was completed by 1:30 PM, however some problems were noted with the deck as the preloaded concrete had begun to set up and was no longer plastic during the cast. The total time to place the deck involved about 4.5 hours for the western span, and about 3.5 hours for the eastern span. Throughout the casting operation, a screed and two finishing bridges were utilized to create a smooth, even surface. As noted above, the screed and first finishing bridge were set along the skew angle and weighed approximately 16.7 kips and 8.0 kips respectively. The second finishing bridge weighed in at 3.6 kips and was situated perpendicular to the girders. Detailed notes were taken as to the relative position of the screed and the first finishing bridge throughout the cast and will be noted in relating figures. Figure 4.5 provides a summary of the concrete deck placement timeline.

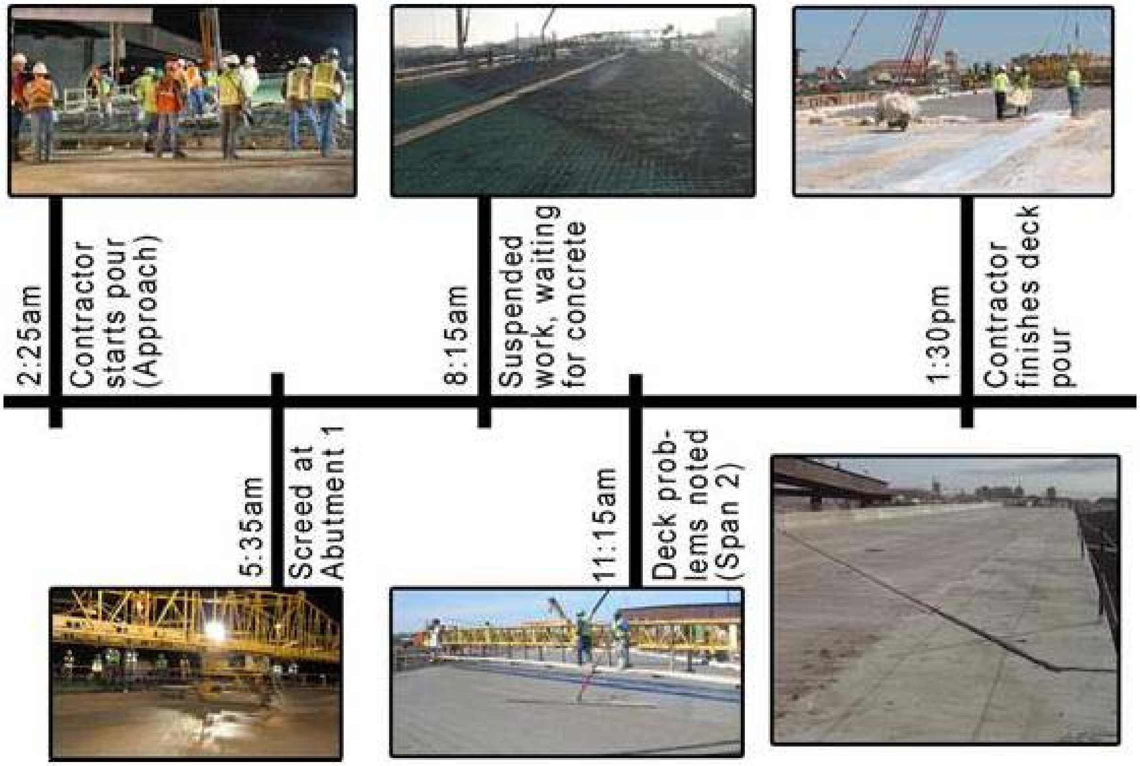


Figure 4.5 Timeline of Concrete Deck Placement [Fasl 2008]

4.4.2 Results: Cross Frame Forces

Throughout the placement of the concrete deck, strains were measured in each of the angles of the instrumented cross frames. Axial forces in the cross frame members were then computed from the strain readings using the technique described earlier.

Figure 4.6 shows the relative location of the strain gages on the end cross frame and designates the naming scheme utilized for each member. Figure 4.7 – Figure 4.10 show the results for axial force versus time in the different members of the end cross frame during the casting of the deck with positive values reflecting tensile forces.

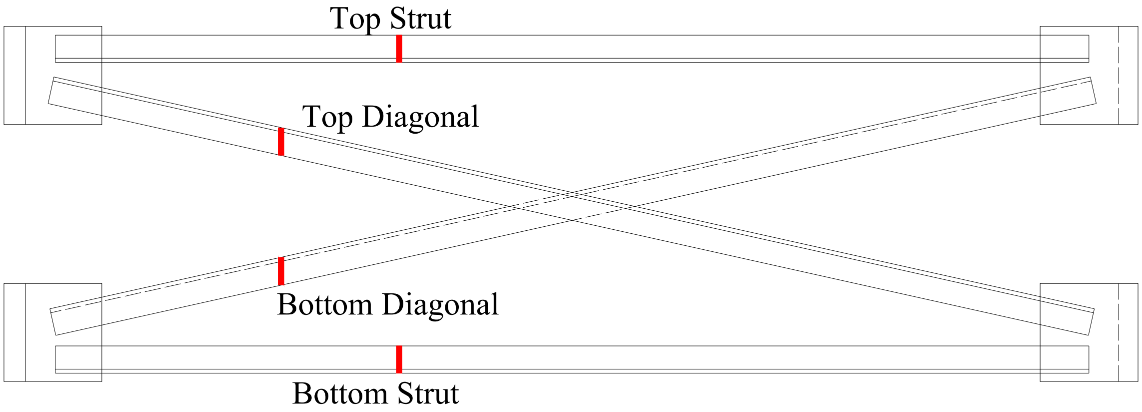


Figure 4.6 End Cross Frame Strain Gage Locations and Naming Convention

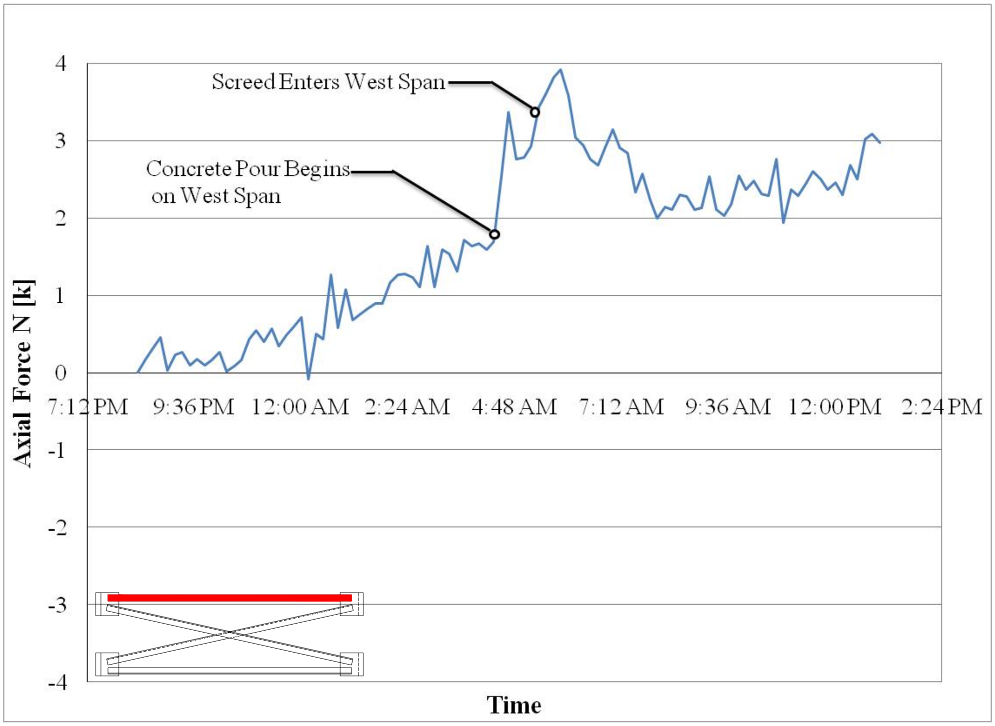


Figure 4.7 Axial Force vs. Time (Top Strut)

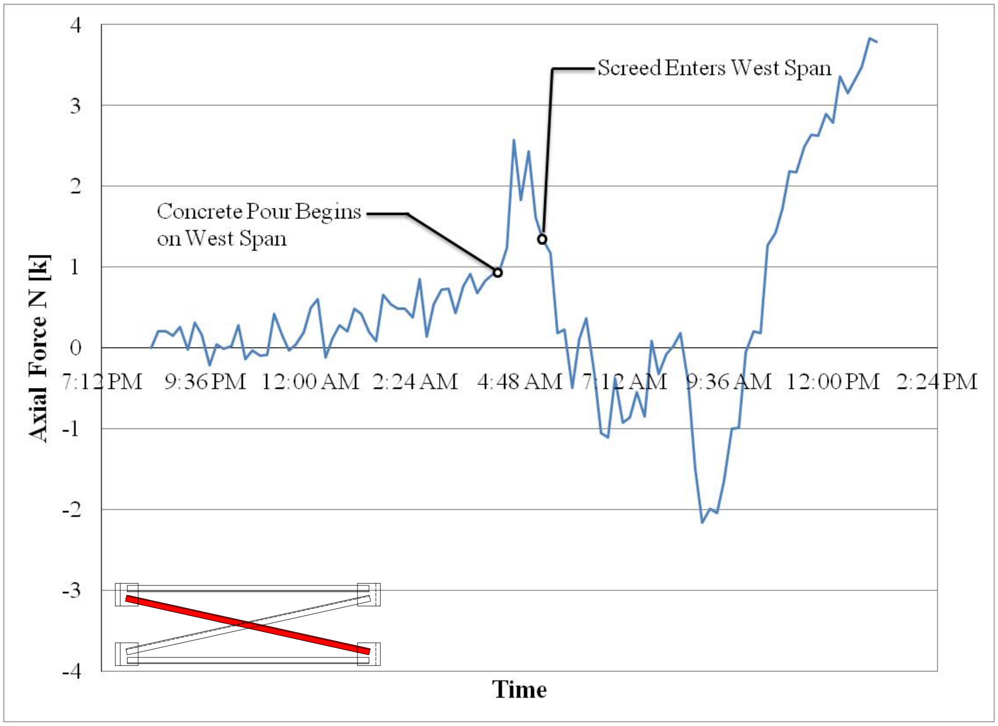


Figure 4.8 Axial Force vs. Time (Top Diagonal)

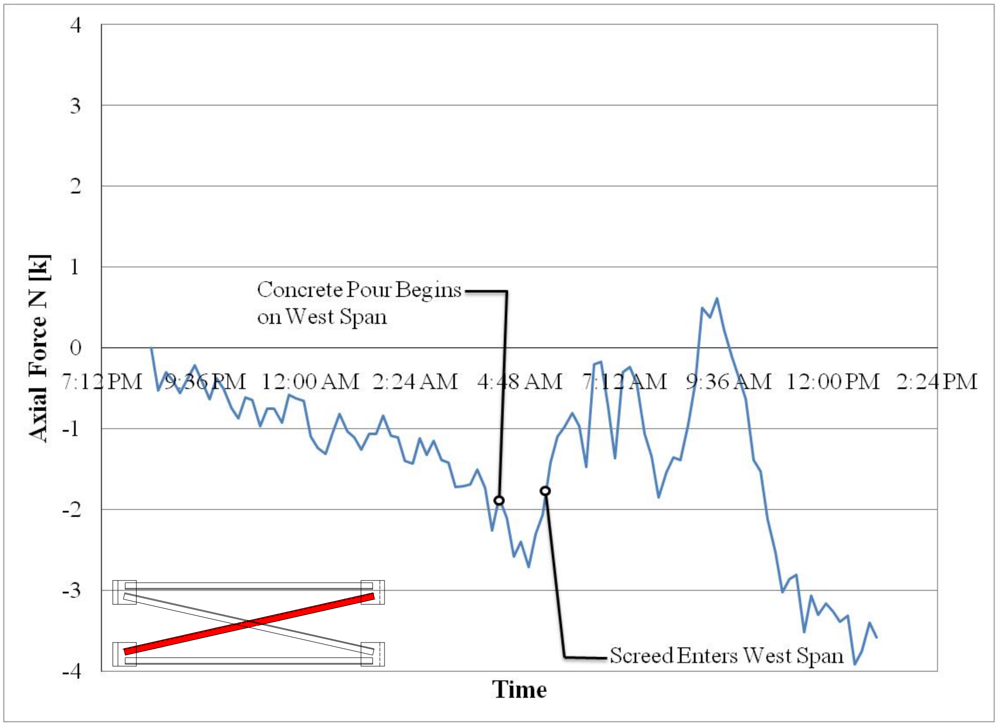


Figure 4.9 Axial Force vs. Time (Bottom Diagonal)

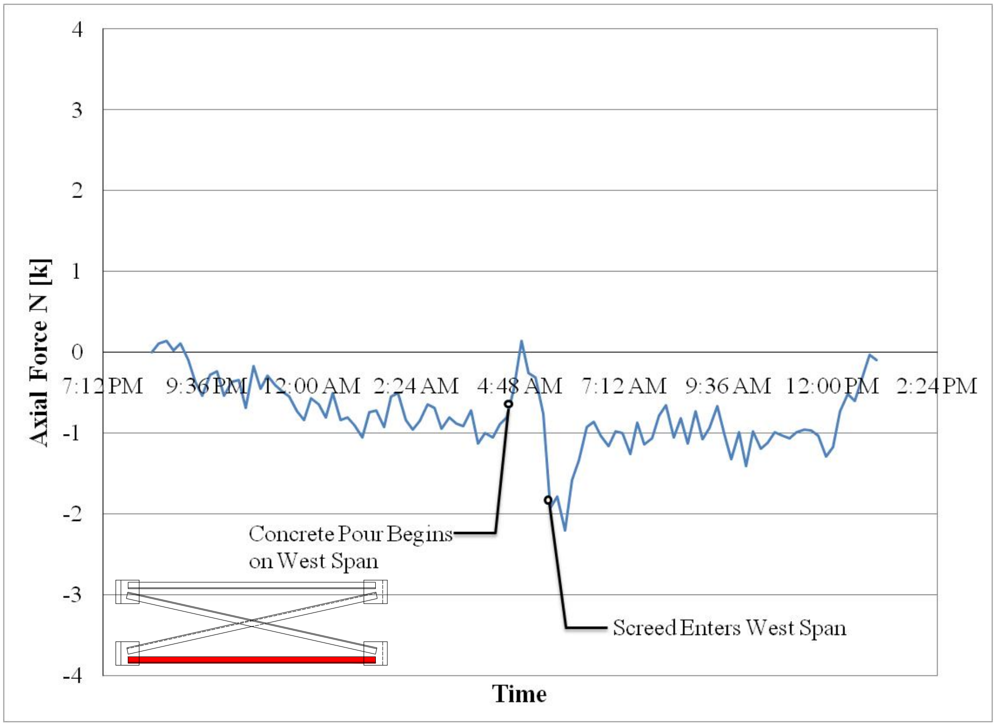


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Figure 4.10 Axial Force vs. Time (Bottom Strut)

These plots show the maximum force seen in any member of the cross frame during the placement of the concrete was just under 4 kips in both tension and compression. This translates into a relatively low stress of approximately 0.6 ksi.

In order to determine the net change in force from days prior to the cast and days succeeding the cast, strain values at similar temperatures during the early morning hours were considered. The early morning hours are selected to minimize errors caused by thermal gradients on the bridge that are highest in the daytime when the bridge may be exposed to sunlight. By comparing similar temperatures, any discrepancy in the gages due to temperature effects during the concrete deck placement is minimized. The strain readings at a given temperature were averaged, and then translated into axial forces. Figure 4.11 summarizes the net force changes in the end cross frame due to the concrete deck placement, which were relatively small.

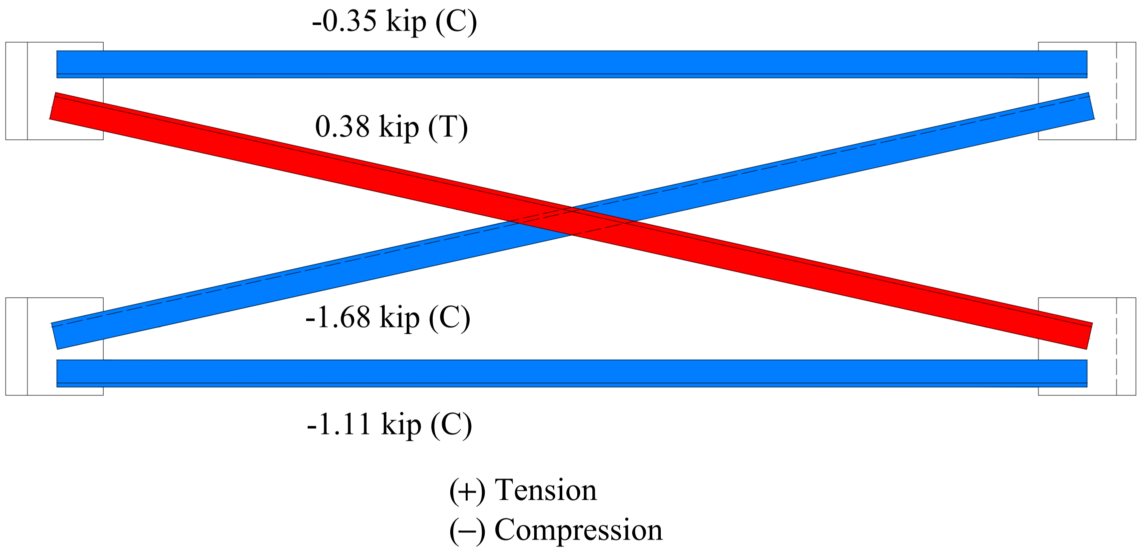


Figure 4.11 End Cross Frame Forces due to Concrete Deck Placement

4.4.3 Results: Girder End Rotations

Another key measurement taken to determine the effectiveness of the end cross frame was the rotation at the ends of the girders. To measure this deformation, a plumb line was suspended along the depth of the girder and the offset distance was measured before and after concrete placement to determine the amount of girder rotation. Measurements were taken relative to the bearing stiffener as shown in Figure 4.12. Rotations were calculated based upon the vertical distance between the lateral deformation readings. This measurement was performed along the southern fascia girder and the adjacent interior girder; however, bridge behavior implies all girders must rotate similar along a given cross frame line. Therefore, the rotations along the west abutment presented in Table 4.1 are representative of those experienced at the end cross frame that was investigated.

Figure 4.12 Measuring Twist at Girder Ends due to Concrete Deck Placement

Table 4.1 Girder End Rotations

Location	Initial Reading	Final Reading	Lateral Displacement	String Length	Rotation
West Abutment, Interior Girder	2.75”	3.09”	0.34”	37 $^{1}/_{8}$”	0.525°
West Abutment, Fascia Girder	2.77”	3.16”	0.39”	38 $^{3}/_{4}$”	0.577°
East Abutment, Interior Girder	3.27	3.39	0.12”	38 $^{1}/_{2}$”	0.179°
East Abutment, Fascia Girder	2.96	3.06	0.10”	39 $^{3}/_{8}$”	0.146°

4.4.4 Conclusions

The results from the field investigation of the end cross frame during the placement of the concrete deck indicate the brace is not subjected to significant amounts of force. Throughout the casting operation, forces in the struts and diagonals never exceeded 4 kips (0.58 ksi) in either tension or compression. The reason for the low forces is likely due in part to two primary sources: flexibility in the bent plate connection and the use of relatively rigid Fabreeka pads. With low stiffness of the bent plate connection and therefore low stiffness of the bracing system, large girder end rotations may have been anticipated. However, the measured girder end rotations (Table 4.1) are not unusually large. The explanation for this result likely lies in the type of bearing pads used on the 19th Street Bridge. Rather than elastomeric bearing pads, this bridge utilizes extremely stiff Fabreeka pads. As Figure 4.13 shows, under the self-weight of the steel girder system, the bearing pad remains rigid, and there is a visible gap beneath the pad where the concrete was slightly uneven.

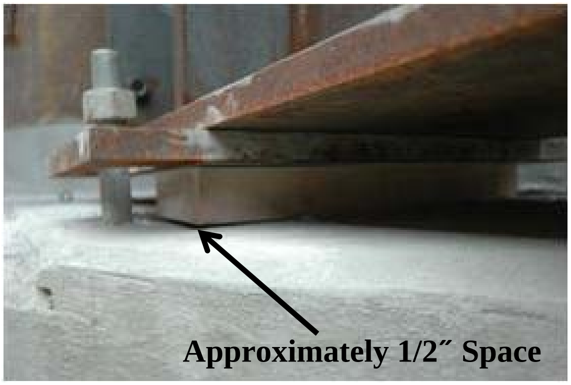


Figure 4.13 Fabreeka Bearing Pads

The rigid support provided by these bearing pads gives rise to a tipping restraint. Rather than rotating about a point near the bottom flange to web interface, the girder must instead rotate about the outermost point on the bottom flange (Figure 4.14). Since the main component of vertical force in the system is in line with the initial position of the girder web, an eccentricity between this axis and the point of rotation develops. By increasing the eccentricity using the rigid bearing pad, the gravity forces in the girder are helping to counteract the developing twist. Therefore, the restoring effect of this restraint helps prevent large rotations from occurring, as was the case at the 19th Street Bridge.

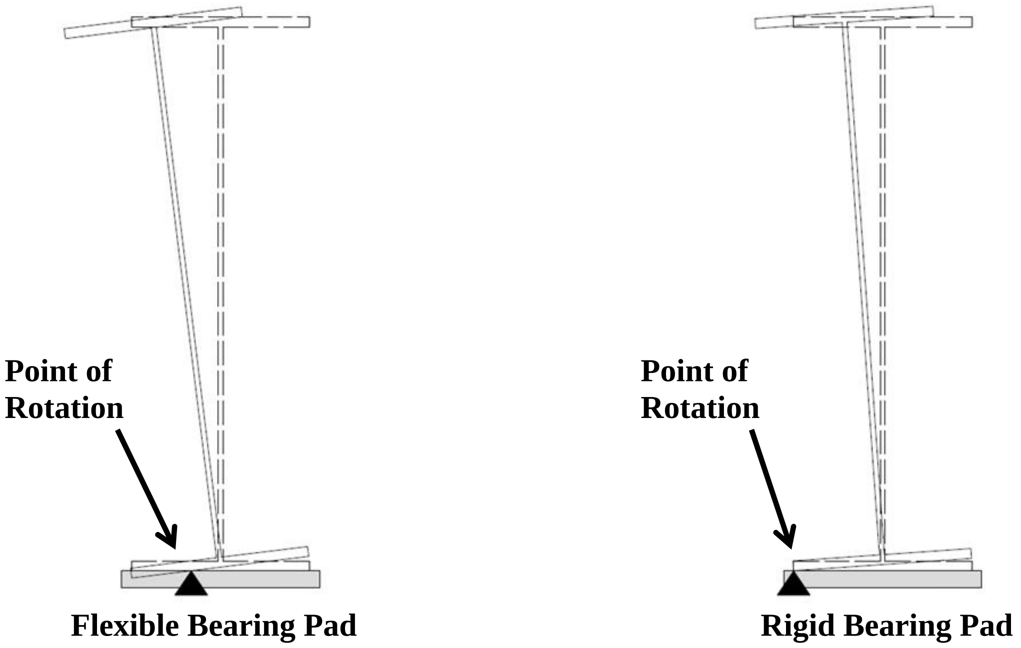


Figure 4.14 Illustration of Tipping Restraint

Finally, the rotations measured at the girder ends exhibited the behavior common to skewed bridge systems. With skewed supports, there are two main forces driving the buckling behavior of the beams (Figure 4.15). First, there is the initial imperfection in the system causing buckling in one primary direction. Second, there is the effect of the skewed orientation, which will either offset or aid buckling relative to the initial imperfection. These two effects will add along one support of the bridge, and subtract on the other. While Figure 4.15 shows the behavior for a simplistic twin girder situation, it is a concept that can be extended to any skewed bridge system. While the exact buckling mode may not be easy to analyze in the continuous bridge studied, a difference in rotations was encountered at each abutment according to Table 4.1. In a non-skewed bridge, these rotations would be expected to be the same at either abutment, thereby suggesting the skew angle impacted this measurement to some extent.

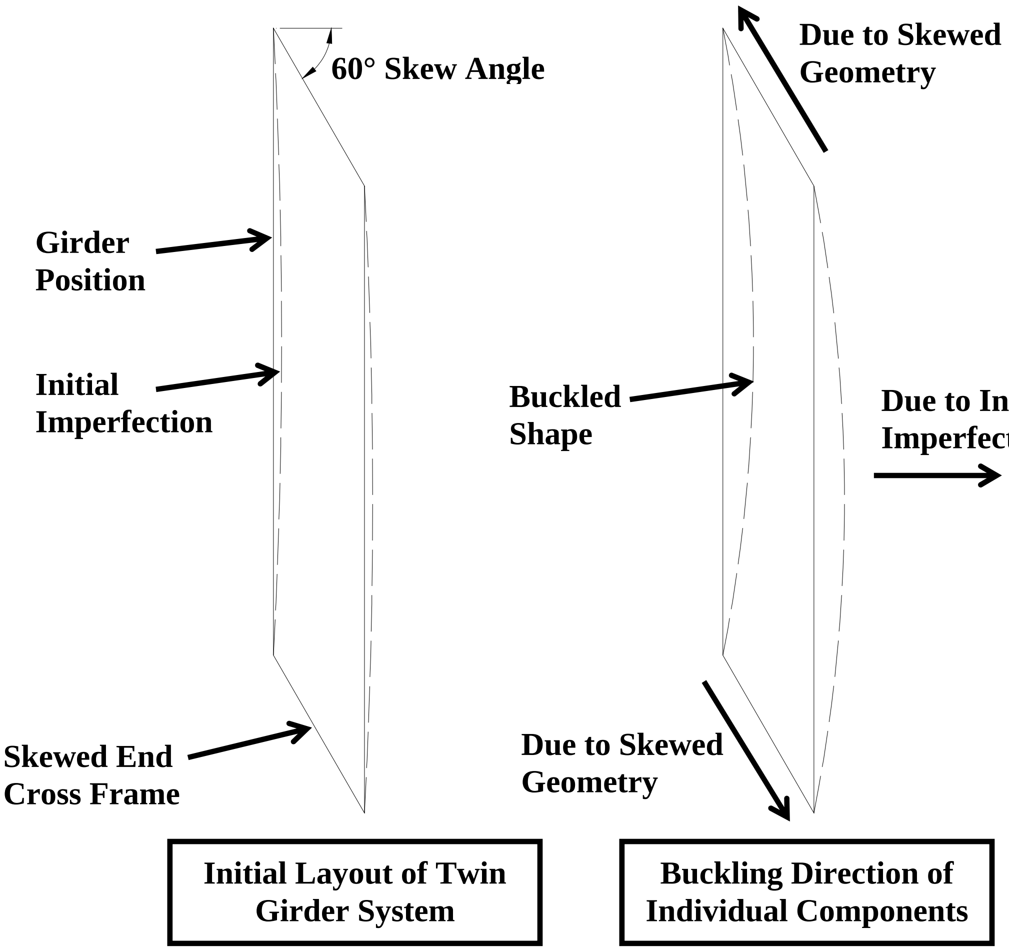
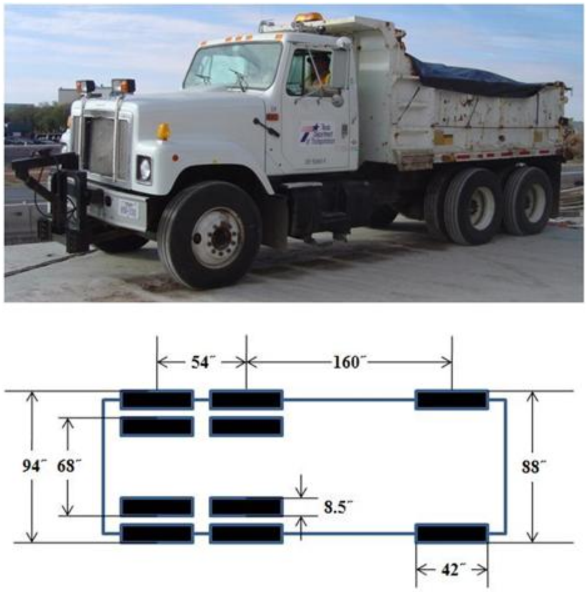


Figure 4.15 Skewed Support Effect on System Buckling Direction

4.5 LIVE LOAD TESTING PROGRAM

In addition to measurements made during the concrete deck placement, the axial forces in the end cross frame were also monitored under a live load test after the concrete deck was in place. The live load consisted of two Texas Department of Transportation sand trucks, weighing approximately 48.5 kips each (Figure 4.16). The trucks were oriented and positioned at various locations along the span length to produce the maximum force effects in the various components studied.



Truck ID	Front Axel Weight (lbs)	Back Axel Weight (lbs)	Total Weight (lbs)
5240G	12,240	36,180	48,420
5060F	11,700	37,200	48,900

Figure 4.16 TxDOT Sand Truck Dimensions and Weight

4.5.1 Timeline

The live load testing program was conducted on November 6, 2007 and consisted of a series of six live load tests. Each test represented a different configuration of the two trucks and is summarized in Figure 4.17: staggered ahead (parallel to skew angle - 1), staggered behind (perpendicular to skew angle - 2), side by side (south edge - 3), side by side (north edge - 4), end to end (south edge - 5), and end to end (center - 6).

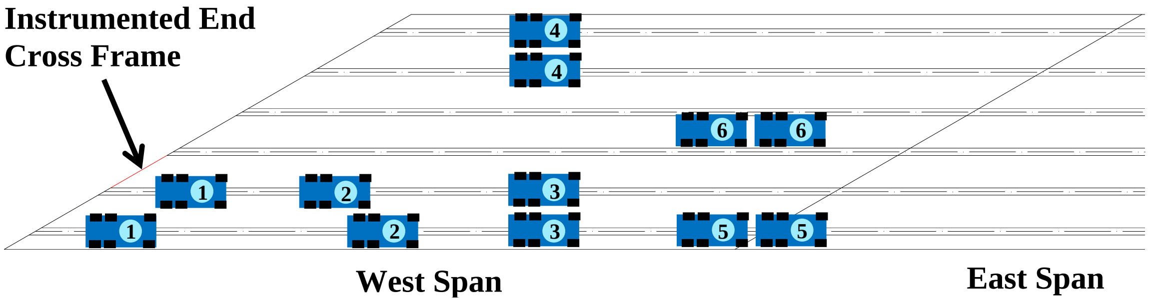


Figure 4.17 Summary of Configurations used in Live Load Testing Program

The positions of the trucks were coordinated at 20 ft increments along the bridge length beginning from the southwest corner of the bridge. Additional measurements were taken at 10 ft increments near the negative moment region at the interior support to capture the transition as the trucks passed from one span to the next. Figure 4.18 shows the case where the trucks were positioned parallel to the 59.6 degree skew angle (Case 1 in Figure 4.17). Prior to the test, the appropriate lengths along the span were measured and marked. By signaling to the drivers, it was possible to accurately place the trucks on the required marks. The entire test was conducted pseudo-statically in which the trucks were positioned at each station for approximately 1 minute to ensure that static readings could be obtained for each truck position. Since the datalogger was scanning every 10 seconds, multiple readings were obtained and later averaged. The time of positioning was recorded and had been synchronized with the datalogger's time stamp to assist in subsequent analysis of the data. Additionally, the baseline readings for all the instrumentation were taken immediately prior to the beginning of each test. Therefore, minimal temperature effects were experienced by the gages, since the effects would only span the duration of a given test, which was approximately 45-60 min. Temperature induced strains were determined by comparing the strain readings before and after the test. Temperature effects were then accounted for by assuming a linear variation with time over the test duration.

Figure 4.18 Positioning Live Load Trucks Parallel to Skew Angle

4.5.2 Results: End Cross Frame Forces

Similar to the concrete deck placement, the strains in the end cross frame were tracked during the live load test. These values were then transformed into axial forces. The forces developed were less than those of the concrete deck construction, with the maximum being just under 1 kip in tension or compression (0.14 ksi). The maximum forces developed in each member during all the loading scenarios are summarized in Table 4.2. A representative graph for axial force versus bridge distance is shown in Figure 4.19 for the top diagonal of the cross frame. All the information regarding specific truck weights, geometry, as well as axial force versus bridge distance for all the loading scenarios may be found in Appendix A.

Table 4.2 Maximum Axial Force in Cross Frame Members during Live Load Testing

Member	**Tension**		**Compression**	
	Axial Force	**Load Case**	**Axial Force**	**Load Case**
Top Strut	0.28 kip	Perpendicular to Skew Angle	0.34 kip	Side by Side (South Edge)
Top Diagonal	0.47 kip	Perpendicular to Skew Angle	0.96 kip	End to End (Centerline)
Bottom Diagonal	0.86 kip	Perpendicular to Skew Angle	0.49 kip	End to End (South Edge)
Bottom Strut	0.82 kip	Perpendicular to Skew Angle	0.69 kip	End to End (Central)

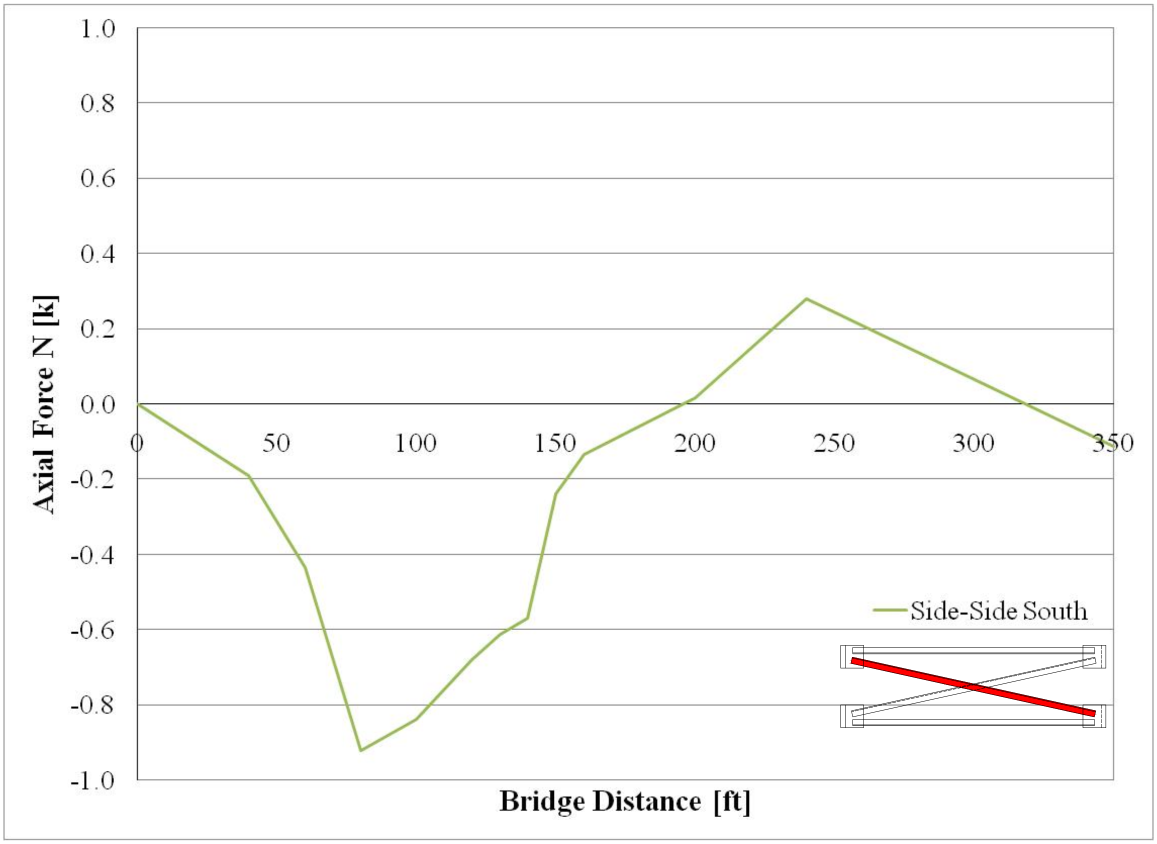


Figure 4.19 Axial Force vs. Bridge Distance (Top Diagonal)

4.5.3 Conclusions

Similar to the construction of the concrete deck, little force was required to be resisted by the end cross frame during the live load testing program. Despite the six different loading patterns, the maximum axial force in any member was only 0.96 kip, showing the end cross frame is not subjected to large live load forces. These low cross frame forces likely reflect the large bracing effect provided by the hardened concrete deck. Additionally, as mentioned previously, the tipping restraint of the rigid bearing pads also contribute to girder stability and help to reduce demands on the cross frame.

4.6 FIELD TEST CONCLUSIONS

The motivation for the field investigation was to quantify the range of forces one might expect the bent plate detail to sustain during construction and in service for a skewed steel bridge. These field measurements are intended to provide insights into the behavior of the cross frames and to provide data for validation of finite element models of this bridge being conducted in other phases of this research project.

Field measurements made during construction of the concrete deck revealed low forces in the end cross frame suggesting the cross frame was not efficiently utilized. The flexibility of the bent plate detail may have contributed to the low cross frame member forces. Recall the total system stiffness formulation, where the total will always be less than the stiffness of any individual component [Yura 2001]:

$$\frac{1}{\beta_{system}} = \frac{1}{\beta_{web}} + \frac{1}{\beta_{brace}} + \frac{1}{\beta_{girder}} + \frac{1}{\beta_{connection}} \tag{4.3}$$

When considering the girder rotations during the casting of the deck, it appears the rigid Fabreeka bearing pads contributed to the stability of the system. Had elastomeric bearing pads been used, less tipping restraint would likely have been available, and the low stiffness of the bent plate detail may have resulted in larger girder end rotations, and potentially problematic behavior.

Lastly, the large bracing capacity of the completed concrete deck combined with the rigid bearing pads further limited the forces developed in the end cross frame under live loading conditions.

While examining the bent plate detail in the field proved very useful to enhance understanding of structural behavior and performance, it was determined further examination of the detail would be necessary. In the field, the loading conditions were very hard to control; therefore, a small-scale laboratory experiment was conducted to strictly focus on the bent plate connection. A complete description of the testing setup, the results, and the conclusions are presented in the following chapter.

CHAPTER 5

Laboratory Experiments

5.1 INTRODUCTION

In order to better understand the behavior of the bent plate connection, laboratory tests were performed to look at the potential structural implications of the bent plate. Additionally, these tests served to validate a finite element analytical (FEA) model developed simultaneously in another phase of the research study. It was important for the model to accurately capture the behavior of the bent plate, as it was later utilized to conduct parametric analyses of bridge systems. As tests were completed, the experimental results were compared to the computational results and differences in the model were resolved. The laboratory tests helped identify certain details of the connection that significantly contributed to the overall stiffness and therefore, needed to be included in the FEA model. The following sections will outline the layout of the test setup, the fabrication of the various specimens studied, and experimental results and conclusions. Finite element models of the connection are outside the scope of this thesis; however the development and validation of the FEA model will be presented in a dissertation by Quadrato to be published in 2010 and will be available in the Texas Department of Transportation (TxDOT) Research Report 0-5701 at the completion of the investigation.

5.2 TEST SETUP

The experimental tests of the bent plate connection were conducted in the Ferguson Structural Engineering Laboratory (FSEL) at The University of Texas at Austin. The controlled setting allowed researchers to focus on the structural behavior of the bent plate under axial loading and to accurately measure the connection's response. The majority of the test setup and specimen fabrication was performed at the laboratory, with assistance from UT Facilities Services for certified welding and from Hirschfeld Industries for their input on and help with bending the plates for the connection.

The following sub-sections provide a detailed discussion on the fabrication of the various components that contributed to the small scale laboratory testing program. The process of bending plates to the required skew angle is highlighted, as well as the fabrication of the different specimens, including the bent plates at varying skew angles and bend radii, a bolted bent plate connection, and the proposed half pipe stiffener solution.

5.2.1 Testing Frame

The testing frame was constructed using four columns in a 4 ft by 4 ft square grid anchored to the laboratory's strong floor using four 1 in diameter threaded rods (see Figure 5.1). The geometry of the columns allowed for approximately 36 in of space between opposing column flanges, which is approximately the depth of the W36x135 rolled section used to create the specimen. Adjacent columns were connected with coped beams, which then support the center transfer beam from which the hydraulic ram is suspended. The orientation of the transfer beam allowed it to be repositioned during different tests so the loading ram could be aligned with the axial direction of the bent plate. The advantages and implications of the ram position are further discussed in Section 5.4. The completed frame with the 45 degree specimen in place to be tested is shown in Figure 5.2.

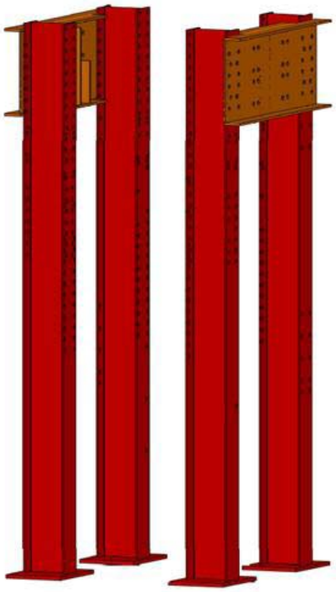


Figure 5.1 Three Dimensional Drawing of Laboratory Test Frame

Figure 5.2 Completed Test Frame with 45 Degree Specimen

5.2.2 Fabrication of the Bent Plate

In an effort to investigate present practice regarding the implementation and manufacture of the bent plate connection, a site visit to Hirschfeld Industries was conducted at their steel bridge fabrication plant in San Angelo, Texas. The visit enabled researchers to understand the typical procedure for bending the plates to match the desired skew angle. Once complete, a similar procedure was developed in the laboratory to allow the production of connections with various bend radii.

5.2.2.1 Steel Bridge Fabricator's Method for Bent Plates

The machine used in the fabrication of the bent plates is known as a press break, as shown in Figure 5.3a. The plate bending process began with the marking of the plates at the location where the bend was to be formed. The marking was done with chalk and measured using a tape ruler. The mark was then aligned in the press break machine so the pointed edge of the press matched up with the marked line Figure 5.3b.

Figure 5.3 (a) Press Break and (b) Aligning Plate for Bending

Using a pedal, the point, which was about two inches wide tapered to a rounded point (Figure 5.4a), was lowered onto the plate. As the pointed edge was lowered, the plate began to bend upward on either side of the point. A magnetic angle finder attached to the free edge as shown in Figure 5.4b was monitored to achieve the desired angle.

Figure 5.4 (a) Point of Press Break and (b) Monitoring Angle while Bending

Since there was some elastic recovery from unloading the press break, the final angle was checked to ensure the angle was within acceptable tolerances using the angle function of a combination square as shown in Figure 5.5. If the bend was not within approximately 1 to 2 degrees of the desired angle, the plate was realigned in the press break and bent further.

Figure 5.5 Checking Accuracy of Angle with a Combination Square

In the discussions with the fabricator, it was indicated that a typical order for bent plates often consist of over 200 plates. The large quantity of plates allows the workers to become accustomed to the amount of elastic recovery for a given plate geometry and therefore understand the required amount of bending to meet the desired angle. Although the press break is wide enough for multiple plates, the fabricator only bends plates one at a time. It was also discussed that a wide variety of bent plate skew angles have come through the shop, and the angle is directly dependent upon the specific job and there is no common range. The entire process takes about three to four minutes per plate, depending on if the accuracy is achieved within the first bending. Also, if the design requires a specific radius of curvature, the fabricator sends the plates out to be bent by another company. However, most jobs are easily handled by the press break machine described above. An example of a bent plate provided by the fabricator is shown in Figure 5.6.

Figure 5.6 Completed 60 Degree Bent Plate

Upon returning to the laboratory, the angles of all the fabricated bent plates were checked with a similar measurement device, with the results presented in Table 5.1. Multiple plates were requested at the 30° and 60° skew angles to determine if the fabricator could consistently repeat the requested angle. As can be seen, all the plates except one were within 1 degree of the desired angle. The other plate was within 1.5 degrees.

Table 5.1 Accuracy of Skew Angle of Bent Plate

Requested Angle	Measured Angle
15°	14.0°
30°	31.0°
30°	28.5°
45°	46.0°
60°	60.0°
60°	59.5°

Another parameter investigated in the laboratory tests was the bend radius of the specimens. They were measured at the different skew angles for comparison to current code provisions and recommendations as well as inclusion in the finite element model. The measurement of this quantity was difficult, as the press break seemed to provide different results at each angle. Discs of a known radius were inserted into the bend and visually inspected for agreement. For the specimens bent at the steel bridge fabricator, the measured bend radii are listed in Table 5.2.

Table 5.2 Bend Radius at Skew Angle

Skew Angle	Bend Radius
15°	0.50″
30°	0.84″
45°	0.59″
60°	0.63″

5.2.2.2 Laboratory Method

As mentioned previously, the fabricator (Hirschfeld Industries) opts to send the plate to a different manufacturer if a required radius of curvature is requested. Instead of sending the plates away, it was decided a plate bending apparatus could be fabricated at the laboratory, allowing the creation of different radii of curvature at a given skew angle. Figure 5.7 shows the setup used for bending the plate with a 0.94 in radius.

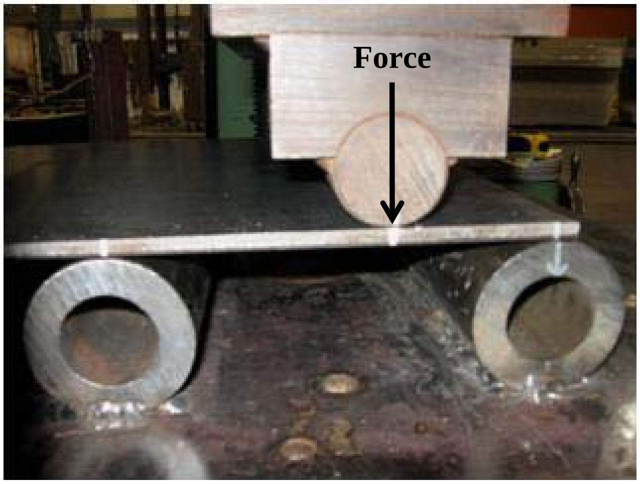


Figure 5.7 Plate Bending Apparatus

Basically, a vertical force is applied transversely to the rod with the desired radius of curvature. This action causes the plate to react upon the supports. Once the force becomes great enough, the plate begins to yield, conforming to the desired radius. By calculating the position of the load relative to the supports, the geometry dictates the required angle one side of the plate needs to achieve for a given skew, and can therefore be tracked throughout the process. By using a relatively thick base plate and welding along the length of the supports, the horizontal thrust developed by the plate bending did not deform the device. Additionally, the thickness of the loading mechanism provided an even force to be distributed from the head of the compression machine to the length of the bent plate. Figure 5.8 shows the bent plate connection after yielding has occurred on the specimen with a 2.41 in bend radius.

Figure 5.8 Bending Plate to 2.41″ Radius

The difference in the bend radius increases the eccentricity of the connection. The larger radius increases the distance between the center of the connection and the line of action of the applied force. A larger eccentricity equates to a larger moment arm, causing the connection to experience more torque, and hence larger deflections. Figure 5.9 shows multiple bend radii for a 45 degree skewed bent plate.

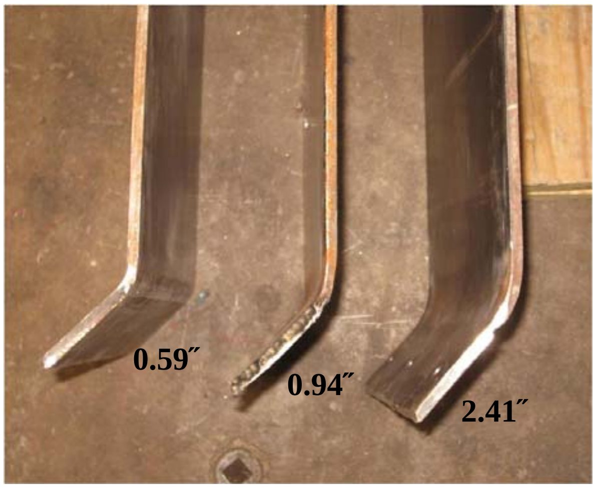


Figure 5.9 Varying Bend Radius at 45° Skew Angle

5.2.3 Fabrication of the Skewed Bent Plate Specimens

To create a completed test specimen, current TxDOT details were consulted to make the test setup comparable to a skewed end cross frame located in the field. The dimensions of the bent plate were set at 18 in by 18 in to match the approximate size of the detail studied in the field investigation (Chapter 4). However, rather than using the full 3/4 in thickness measured in the field, a 5/16 in thick plate was selected to enhance the magnitude of deflections ensuring more accurate measurements and to simplify the laboratory setup by reducing the required applied force.

The loading mechanism to the bent plate connection was an angle member, as this simulates a typical cross frame component framing into the plate. The angle was an L4x4x3/8 member and overlapped the plate by 5 in, consistent with the details provided by TxDOT. The hole located at the end of the angle had a 7/8 in diameter, 13/16 in edge distance, and was centered along the angle's width. Using a shackle and bolt, the clevis pin connected to the hydraulic ram could be linked to the bent plate connection, thus providing an axial force on the connection. Figure 5.10 schematically shows the bent plate and angle assembly.

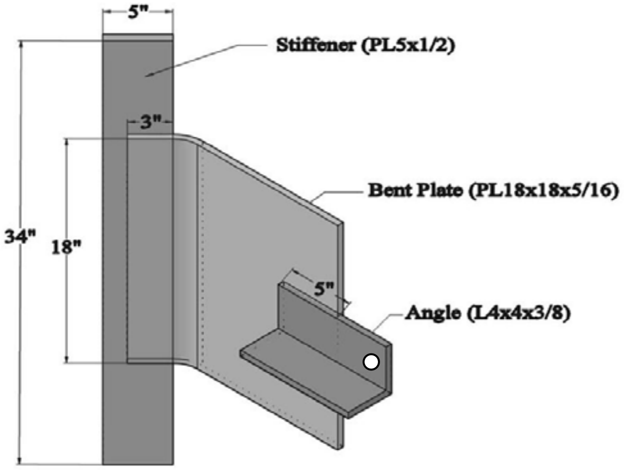


Figure 5.10 Bent Plate and Angle Dimensions

To finish the specimen, the bent plate was attached to a 5 in wide, 1/2 in thick stiffener located in a W36x135 girder with a web slenderness of 54.1. The depth of the girder served three purposes as it conveniently fit the test frame, was economically available for a small scale test, and allowed us to measure any web flexibility. Since the web slenderness of plate girders is generally much larger than typical rolled sections, the most slender rolled section was chosen to allow investigation of the connection’s interaction with the web. The completed specimens are shown in Figure 5.11 at the four skew angles studied.

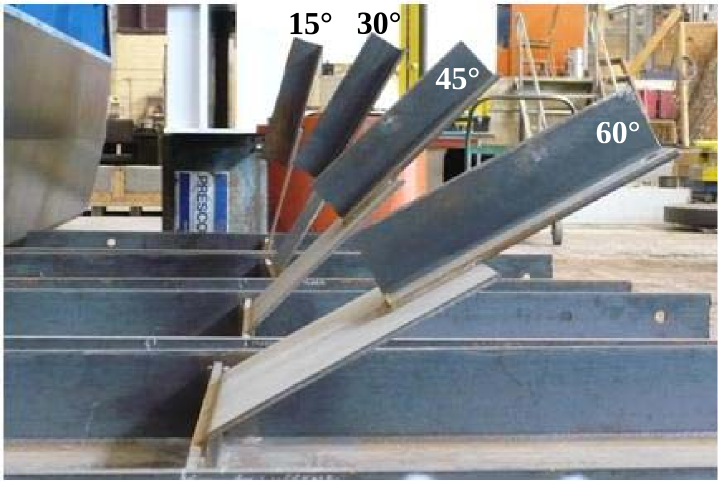


Figure 5.11 Completed Test Specimens at Various Skew Angles

Due to the importance of the weld to the stiffness of the connection, all the welding needed to connect the angle members, bent plates, and stiffeners, was performed by a certified welder. The welds attaching the angle to the plate and the plate to the stiffener were 3/16 in fillet welds, welded along all adjacent sides. The stiffener to girder welds were 5/16 in fillets, welded to both the web and the flanges. All welds terminated approximately 1/4 in from free edges, and were completed with an E70XX electrode. The welding details can be seen in Figure 5.12.

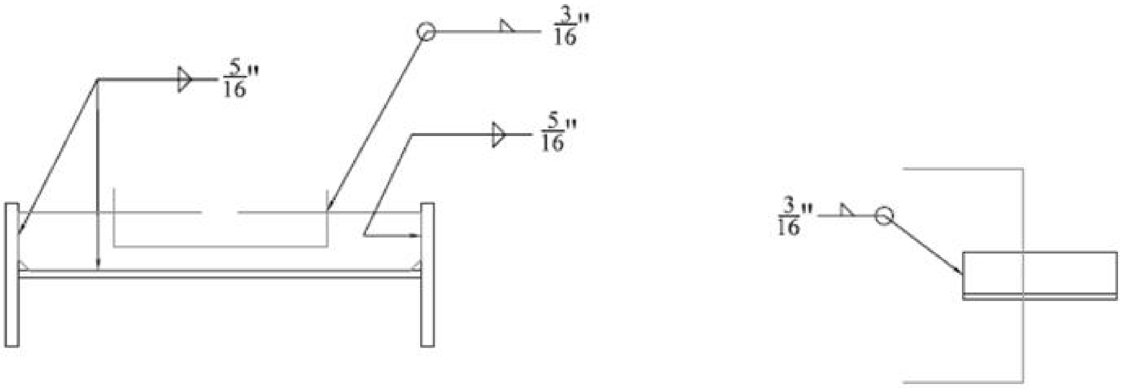


Figure 5.12 Specimen Weld Details for (a) Stiffener and Bent Plate and (b) Angle

The welding procedure used in the small scale test specimens was in accordance with the construction of the 19th Street Bridge in Lubbock, TX that was discussed in the previous chapter. According to the TxDOT provided plans, the angle must overlap the bent plate by a minimum 4 in. Additionally, all welds between the angle, plate, stiffener, and girder measured 5/16 in, ending 1/4 in from all free edges. The setup utilized the 5/16 in thick weld between the stiffener and girder, but because of the reduced thickness of 5/16 in for the laboratory bent plate versus the field value of 3/4 in, a 5/16 in weld was not recommended. Therefore the minimum possible 3/16 in weld was requested.

5.2.4 Fabrication of the Varying Bend Radius Bent Plate Specimens

To investigate the effect of varying the bend radius of the bent plate, one skew angle was selected for comparison. The 45 degree specimen was chosen for this purpose. To create the specimens for this test, the girder and stiffener from the 45 degree skewed bent plate test were reused by manually grinding out the weld between the bent plate and stiffener as shown in Figure 5.13.

Figure 5.13 (a) Grinding Bent Plate off Stiffener and (b) Specimen after Grinding

Once the previous bent plate was off the specimen, the bent plate fabricated to a specific bend radius could be attached. Close-up views of the final specimens when placed in the test setup are seen in Figure 5.14. Note the 2.41 in radius specimen seems to follow a more gradual, smoother curve than the 0.94 in specimen due to the increased arc length across the bend.

Figure 5.14 (a) 0.94˝Bend Radius and (b) 2.41˝ Bend Radius Specimens in Test Setup

5.2.5 Fabrication of the Bolted Bent Plate Specimens

In addition to the tests with bent plates welded to the girder stiffener, there was an interest in examining the detail as a bolted connection. While TxDOT prefers to field weld the bent plate detail during construction, many other states use the bent plate in conjunction with bolts to brace the bridge girders. For instance, the Churchman Road Bridge in Delaware discussed in Chapter 2 used bolts to connect the bent plate to the stiffener. Therefore, a bolted bent plate specimen was fabricated for study.

The skew angle chosen for the bolted connection test was 45 degrees, as the most data had been collected for this angle. A similar procedure of grinding out the previous bent plate as outlined in the previous subsection was employed. The connection comprised three A325 bolts, each with a 1/2 in diameter. The bolts were positioned on a centerline 1.5 in offset from the long edge of the bent plate. One bolt was centered transversely, with the other bolts 7 in apart to either side. The completed specimen is depicted in Figure 5.15. The bolts were designed to be slip-critical, and were tightened according to the “turn-of-the-nut” method.

Figure 5.15 Bolted Bent Plate Connection

The bent plate for these tests was at the 2.41 in bend radius, and tests were conducted with the bent plate on either side of the stiffener. This comparison was done to see if there was a major behavioral difference of the connection dependent upon initial positioning of the plate relative to the stiffener. Figure 5.16 shows the bent plate when it is located on the same side of the stiffener as the tensile force of the ram and when it is on the reverse side. The term prying side is used to describe the former case, when the plate wants to pry off the stiffener, and the term restricted side is used to describe the latter case, when the bent plate movement towards the inside of the bend radius is restricted by the stiffener.

Figure 5.16 Bolted Bent Plate Connection on (a) Prying Side and (b) Restricted Side

5.2.6 Fabrication of the Half Pipe Stiffener Specimens

Lastly, the proposed half pipe stiffener detail was investigated. To create the specimens, ASTM grade A53 pipe with an outside diameter of 10.75 in and a wall thickness of approximately 0.34 in was cut to length to fit the girder. Once the proper length, the pipe was split longitudinally using a track torch. When cutting the pipe with the torch, the pipe opened up at the completion of the cut releasing its internal stresses (Figure 5.17).

Figure 5.17 Longitudinally Splitting Pipe for Half Pipe Stiffener

Once the pipe was successfully cut into two half pipes, the rough edges were ground smooth and the pipe was polished with a wire brush. Additional grinding was necessary to fit the half pipe into the girder cross-section, especially in the K regions, where the pipe corner needed to be rounded for good fit-up. Once complete, the specimens were welded in place using 5/16 in fillets on the pipe to girder interface. The detail was tested at a 0 and 45 degree skew angle. Figure 5.18 shows the specimens when they were placed in the test frame.

Figure 5.18 Half Pipe Stiffener Detail at Skew Angles of (a) 0° and (b) 45°

The manufacturing process was not particularly difficult as compared to normal stiffener construction, and the fit-up of the different pieces was no more difficult than fabrication of the bent plate specimens. The welder also commented that welding the curved portion of the pipe was not troublesome. In discussions with Hirschfeld Industries, a Texas steel bridge fabricator who constructed this detail for fatigue specimens, the shop foreman agreed the detail was not very cumbersome and with more experience, would be no different than creating regular stiffener connections. As previously discussed in Chapter 3, a savings with the half pipe detail is the elimination of separate end bearing stiffeners from end cross frame stiffeners, as well as the potential for a reduced number of intermediate cross frames due to the increased buckling capacity gained from the warping resistance of the pipe.

5.3 INSTRUMENTATION

Once the specimens were completed, each was tested in the laboratory. For comparison of the different parameters and details investigated, measurements at specific locations were taken during each test. These values define the behavior of the bent plate connection and were crucial to validation of the finite element model. A completely instrumented specimen is shown in Figure 5.19.

Figure 5.19 Instrumented 45 Degree Specimen in Testing Frame

5.3.1 Horizontal Deflections

One of the interesting behaviors of the bent plate from a structural standpoint is the tendency of the plate to deflect out of plane when subjected to an axial force through a skewed cross frame member. For example, when a tensile force is applied to the plate in Figure 5.19, not only does the plate move vertically in the direction of the load, but it also deflects horizontally towards the inside of the bend (to the right in the figure). In order to measure the magnitude of this movement, various devices were employed. All horizontal measurements were taken along the transverse centerline of the connection.

First, linear variable differential transformers (LVDTs) were located at the outer edge of the stiffener and along the bent plate beyond the termination of the bend radius (Figure 5.20). These devices measure displacements and had an accuracy of 0.00075 in. Using small angle theory, the readings from the LVDT perpendicular to the stiffener edge were transformed to provide a horizontal and vertical displacement.

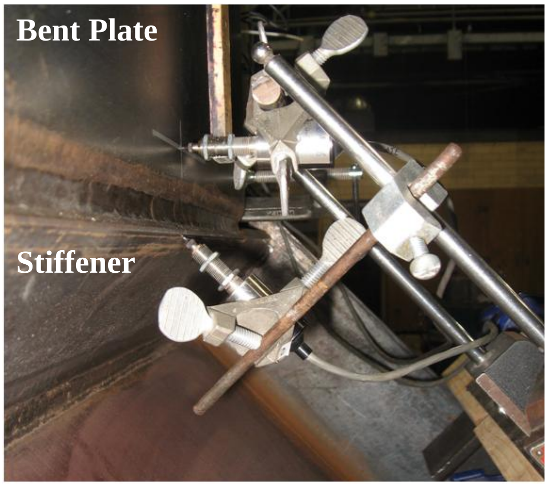


Figure 5.20 LVDT Measurement Devices at Stiffener and Bent Plate

Each LVDT was calibrated before use in the testing program by measuring the voltage difference when displaced a known quantity. This was achieved by using a Mitutoyo Gage Block Set, accurate to 0.0001 in.

Next, linear string potentiometers were connected at the top edge of the bent plate, along the angle member, and perpendicular to the web at the stiffener location (Figure 5.21). The devices on the bent plate and web had a 2 in stroke length, yielding a resolution of 0.0030 in, while the device on the angle member had a 5 in length and resolution of 0.0075 in. Due to its lesser accuracy, results from the 5 in device were difficult to analyze and are excluded in this thesis. Both 2 in string potentiometers were calibrated on a machinist table, displacing the string at a 0.0005 in resolution and monitoring the voltage output. It was concluded these devices were within the accuracy provided by the manufacturer.

Figure 5.21 String Potentiometers Located on (a) Bent Plate, Angle and (b) Web

5.3.2 Vertical Deflections

Similarly, deflection measurements were recorded in the vertical direction (see Figure 5.19) to understand this component of movement throughout the bent plate detail. As described above, displacements taken by the LVDT at the stiffener, and the 2 in string potentiometer perpendicular to the web were converted into horizontal and vertical components. In addition, a dial gage, accurate to 0.0001 in was positioned at the top of the bent plate (Figure 5.22). It was determined local effects of the loading pattern would not affect the overall vertical movement of the top edge of the bent plate; therefore, the device was situated on a corner of the bent plate, but is assumed to represent the same vertical displacement at the center of the connection.

Figure 5.22 Dial Gage to Measure Vertical Deflection of the Bent Plate

5.3.3 Rotations

Rotational measurements were taken at the bottom of the plate (coincident with the LVDT position) and at the top of the plate (Figure 5.23). These were recorded using two CXTLA01 single axis tilt sensors manufactured by Crossbow. Each device has an angular resolution of 0.03° and a ±20° range, and was calibrated prior to installation in the test setup. The calibration curve was developed by measuring the voltage output of the device under a level condition, then recording changes when rotating the device to known angles using machinist blocks.

Figure 5.23 Tilt Sensors Positioned to Measure Rotation of Bent Plate

5.3.4 Load

The load applied to the connection was tracked using an Interface load cell (model 1220-AF) rated for a maximum load of 25 kips. By calibrating the load cell in a compression machine, it was measured to have a maximum output of 4.2327 mV/V/kip, consistent with the data from the manufacturer. Figure 5.24 shows the load cell as it was attached to the hydraulic ram.

Figure 5.24 Load Cell Connected to Hydraulic Ram

5.4 PROBLEMS ENCOUNTERED WITH LABORATORY TESTS

The laboratory testing program was designed to capture the behavior of the bent plate detail and measure its response to an applied force. While performing the tests, certain aspects of the test frame setup and specimen fabrication were identified as impacting the resulting measurements. Accordingly, adjustments were made where possible. As the primary reason for these tests was validation of the finite element model, it was often feasible to include these effects into the model.

5.4.1 Restoring Force of Hydraulic Ram

The first notable experimental issue in the setup was a restoring force provided by the hydraulic ram. Under load, the bent plate tended to deflect horizontally towards the inside of the bend radius as depicted in Figure 5.25. When this occurred, the ram was no longer directly in line with the plate, as it had been forced to pivot about its base. With a lateral deflection, the ram pulled on the detail at an angle. As the plate continued to shift horizontally, the angle of the ram increased thereby increasing the magnitude of the horizontal component of force the ram provided in the direction opposite the plate movement.

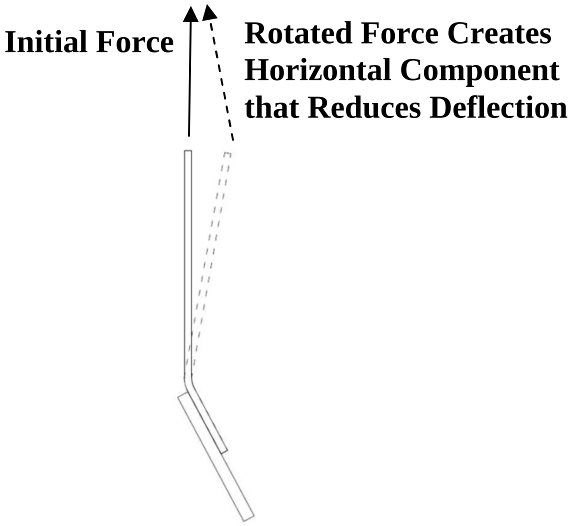


Figure 5.25 Restoring Force Provided by Hydraulic Ram on Bent Plate

While this phenomenon may not take place in real cross frame systems, it played a significant role in the deflections measured in the test setup. Since the primary goal of these tests was for validation of a finite element model, this effect was successfully included in the analysis by modeling the ram using a truss element with temperature expansion/contraction capabilities and applying the load by specifying a thermal change in the element. In terms of the data presented later in this chapter, the effect was present in all tests at different skew angles and bend radii, therefore not greatly affecting comparisons between the various connection details.

5.4.2 Ram Offset

A similar problem to the restoring force of the ram is termed a ram offset. Basically, this offset represents the distance between the pinned center of the base of the hydraulic ram and the straight line extension of the angle member through which the connection details were loaded. As seen in Figure 5.26, an initial offset in the ram position generates a horizontal force on the connection either increasing or decreasing the lateral deflection. While the offset could be measured for each test for comparison to computer analyses, variable offsets affect comparative data. Therefore, offsets for the data presented in this chapter were set to zero by moving the hydraulic ram position, except where noted.

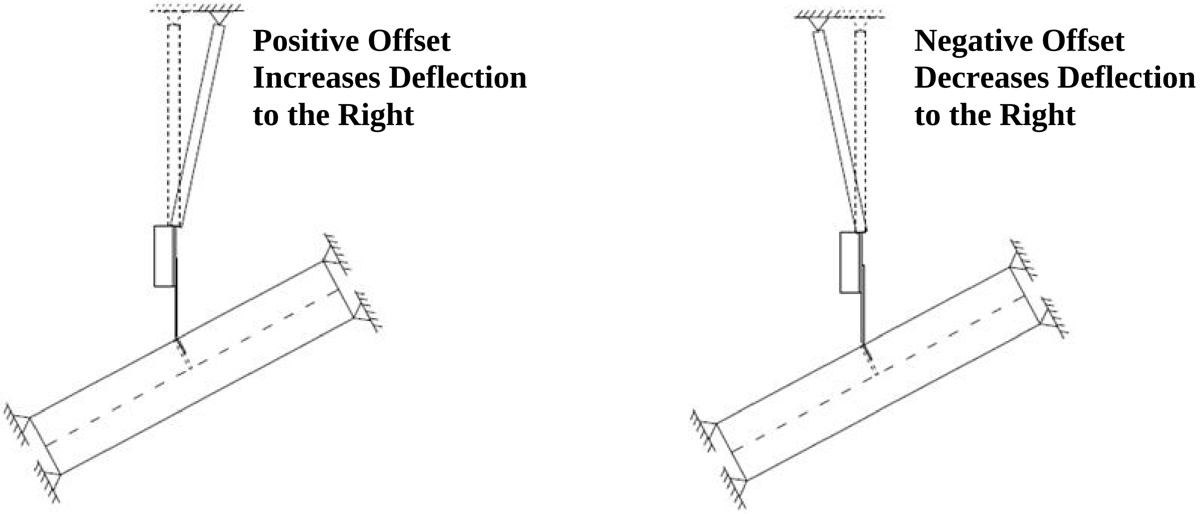


Figure 5.26 Effect of Hydraulic Ram Offset

5.4.3 Load Clevis Rotation and Sliding

The connection between the actuator and the test specimen was made with a clevis as shown in Figure 5.27. Another issue some specimens had when tested was the initial positioning of the load clevis relative to the angle. In every test, the clevis was held in place as the initial load was placed on the detail. Similarly, the ram was adjusted to be in line with the plate. Sometimes, these two items were not coincident, causing the bolt to rotate in the hole in the angle (see Figure 5.27). Since the bolt was the connecting element to the bent plate detail, the rotation would cause the load to be applied at an angle, thus affecting the recorded measurements. To overcome this problem, tests in which the hook placement was visually poor were noted and not included in the reported data sets.

Figure 5.27 Rotation of Hook Relative to Angle Member

The bolt of the hook also slid to one side during a couple of the tests as the horizontal movement of the plate detail was significant enough to overcome the friction developed at the bolt location. This was especially prevalent at the 60 degree bent plate tests. In order to establish a baseline for comparison, any test data after sliding had occurred in tests was ignored.

5.4.4 Weld Details

The last notable problem encountered in the testing program concerned the weld details. All of the welds between the plates and the stiffeners were requested to be 3/16 in fillets. Upon measuring the completed specimens, some of the weld sizes were slightly larger than specified, thus adding a source of variability into the stiffness of the connection. While the welds have been measured for inclusion in the finite element model, there is no particular way to numerically include the difference in the data presented in this chapter. Also, the 60 degree specimen had some slight bowing in the plate, most likely a product of the heat of welding on a rather small thickness plate. All the other specimens did not have the same magnitude of imperfection.

5.5 LABORATORY TEST RESULTS: BENT PLATE DETAIL

Now that the description of the test setup, the fabrication of all the specimens tested under this laboratory program, the location of instrumentation, and a discussion of some potential sources of error in the test results have been covered, the data collected during the experiments is presented in this section.

The data shown in each plot represents the average of all the tests conducted on a particular specimen, with the error bars showing the maximum and minimum recorded values for the particular measurement across all tests performed. Typically, each specimen was loaded elastically to 7 kips, with the tests repeated six to eight times. To check for repeatability within a test run, load was applied to 7 kips, reduced to 3 kips, and reapplied to 7 kips to make sure the maximum value remained consistent. These runs were performed on each of the specimens at least once, with all specimens exhibiting consistent results. The only variable between tests of a specimen was the initial positioning of the clevis to angle member connection, which was set into approximate alignment by the researcher using a magnetic angle finder.

5.5.1 Effect of Skew Angle

The first comparison to be made is among the bent plate details set at different skew angles. It is theorized the deflections measured for the different bent plates will increase with increasing skew angle. To make sense of this, consider the positioning of the force relative to the stiffener as shown in Figure 5.28. With increasing skew angle, the component of the force perpendicular to the stiffener increases, thus suggesting an increase in lateral deflection.

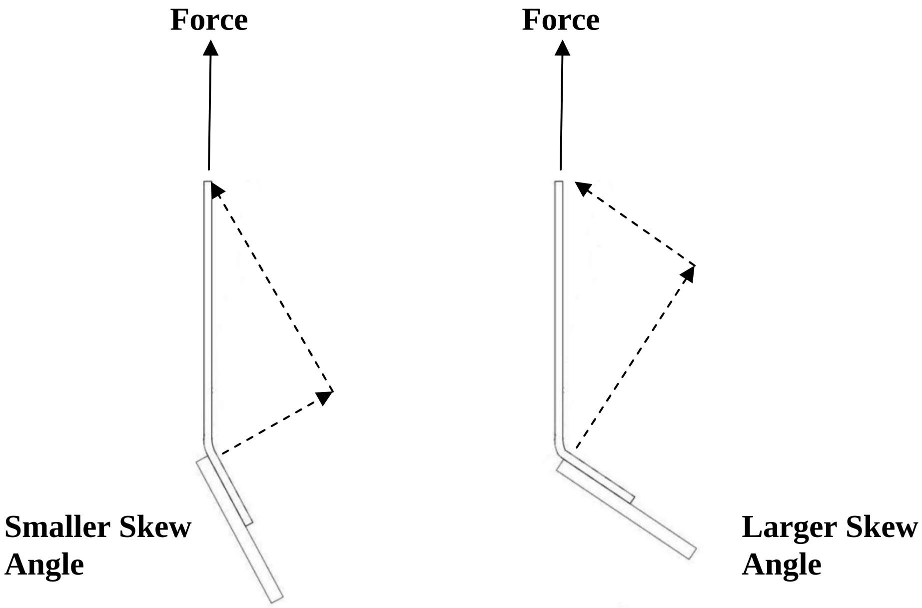


Figure 5.28 Force Transferred to Stiffener at Different Skew Angles

To numerically validate this hypothesis, deflection measurements were taken at the top of the bent plate in both the horizontal and vertical directions and are presented in Figure 5.29 and Figure 5.30. The horizontal direction is the deflection component directly perpendicular to the top of the bent plate, while the vertical direction coincides with the applied force. Each line represents a different skew angle as indicated.

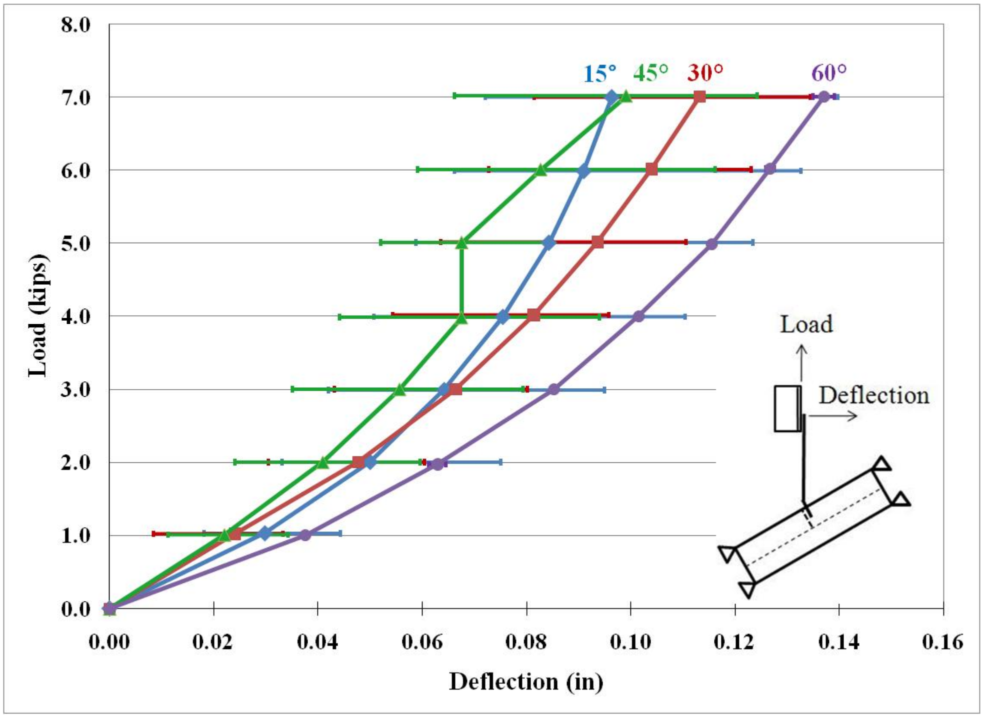


Figure 5.29 Horizontal Deflection at the Top of the Bent Plate vs. Load

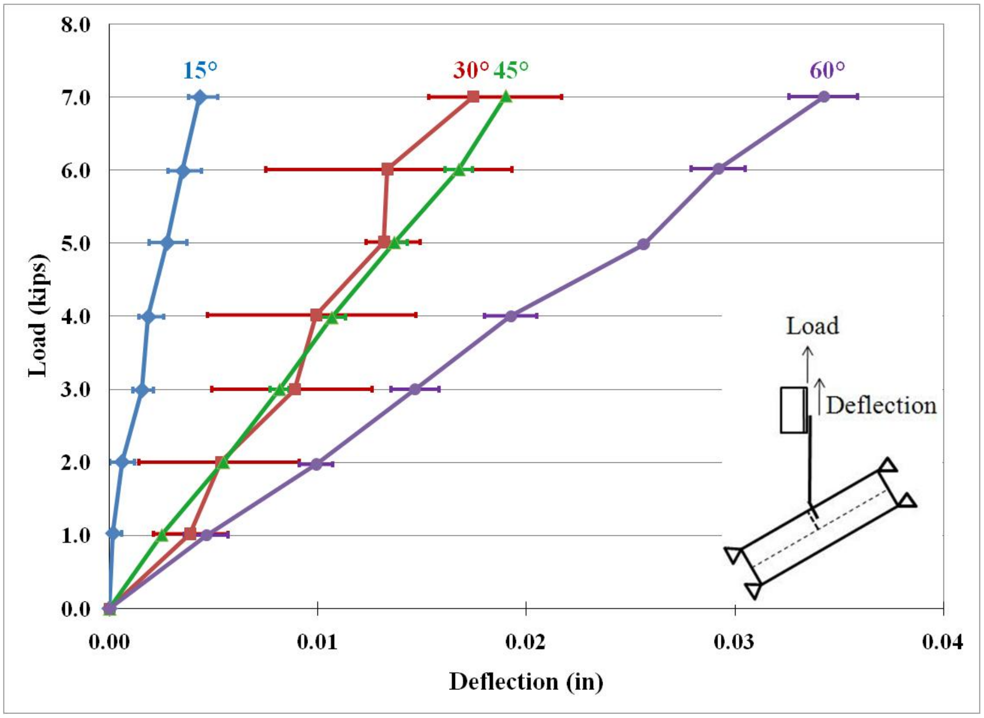


Figure 5.30 Vertical Deflection at the Top of the Bent Plate vs. Load

The horizontal deflection presented in Figure 5.29 supports the assumption that increasing skew angles lead to an increase in deflections with the exception of the 45 degree case. As alluded to in the previous section concerning problems with the laboratory tests, the 45 degree specimen had a negative offset of the ram (see Figure 5.26) leading to less deflection than experienced with a zero offset. Unfortunately, the discovery of the offset problem in the test setup occurred after grinding out the bent plate of the 45 degree specimen to accommodate the varying bend radii tests, so it could not be retested at the zero offset condition.

However, data in the vertical direction at the top of the bent plate is significantly less affected by offset errors. The bent plate has relatively low stiffness out of plane, allowing small forces to have a significant impact on the horizontal deflection measurements. The vertical direction is much stiffer, so the small decrease in the force caused by the ram misalignment has less impact on the deflection measurements. Figure 5.30 shows vertical deflection does increase with the larger skew angles. As the forces in the cross frame are primarily in this direction, its contribution to the stiffness is greater.

Additionally, the concept of the perpendicular component of force on the stiffener contributing to the movement in the vertical direction is supported by the data. Figure 5.31 shows measurements recorded in the vertical direction at the stiffener directly below where load is applied. When compared with the data in Figure 5.30, it can be seen that deflection of the stiffener accounts for the majority of the movement in the vertical direction rather than deformation of the bent plate. Therefore, an increased skew angle would be detrimental to this connection because it requires the cross frame stiffener to sustain higher out of plane forces.

Another recorded measurement that further supports the influence of the stiffener is the horizontal deflection at the bottom of the plate. While the top of plate was sensitive to out of straightness of the loading arrangement, the bottom of the plate depended more on the movement of the stiffener. This measurement, shown in Figure 5.32, was taken at the point of tangency along the curve of the bend radius. Again, a similar pattern emerges where increasing skew angles leads to increasing deflections.

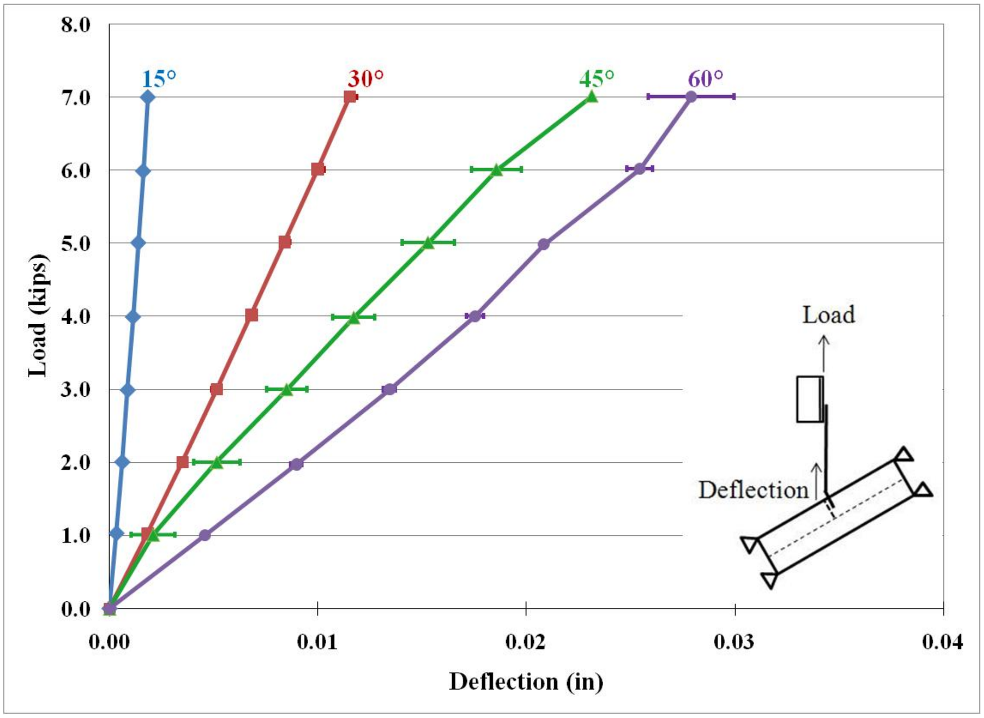


Figure 5.31 Vertical Deflection at the Stiffener vs. Load

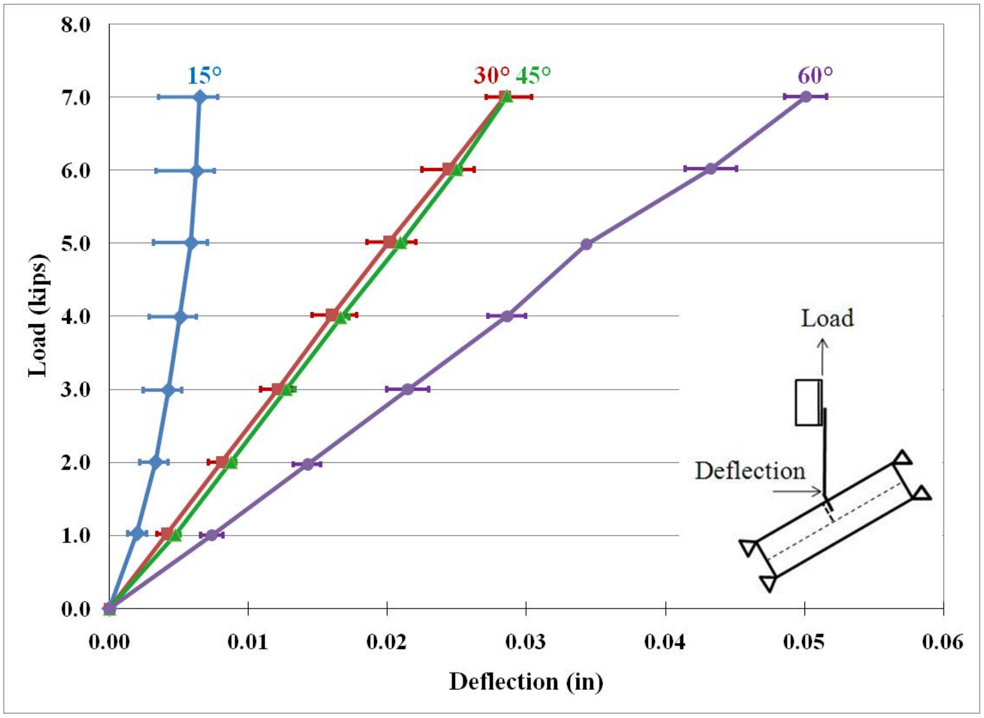


Figure 5.32 Horizontal Deflection at the Bottom of the Bent Plate vs. Load

The last deflection investigated was taken perpendicular to the web on the opposite side of where the stiffener was attached. This quantity was studied to see if there was any movement of the web due to the applied force. In plate girder construction, web slenderness is often high, which can lead to significant distortion of the web. However, measurements taken in the laboratory at the mid-depth of the W36x135 beam showed very little displacement. Of the bent plates at various skews, the maximum value recorded was 0.006 in at 7 kips on the 60 degree specimen. The other three skew angles had maximum values less than 0.003 in, which was less than the resolution of the string potentiometer used.

Lastly, plots for the two tilt sensors used to measure rotations at the top and bottom of the bent plate are shown in Figure 5.33 and Figure 5.34. The rotation at the top of the bent plate had significant variability between each test. The tilt sensor, with an accuracy of 0.03 degrees, was extremely sensitive to vibrations in the plate during loading, especially at this location. However, the averages of the data show all skew angles had about the same rotation at this location, with the exception of the 45 degree test which had the ram offset error. This means the rotation at the top of the plate was most likely an artifact of the test setup rather than reflecting the physical behavior of the connection. Since the hydraulic ram was fixed at a single location, the bent plate was forced to stop rotating due to the restoring force provided by the ram.

The rotation at the bottom of the bent plate though was more representative of the rotation experienced by the cross frame stiffener. This rigid body rotation increases with the skew angle as indicated in Figure 5.34, following the behavior previously discussed.

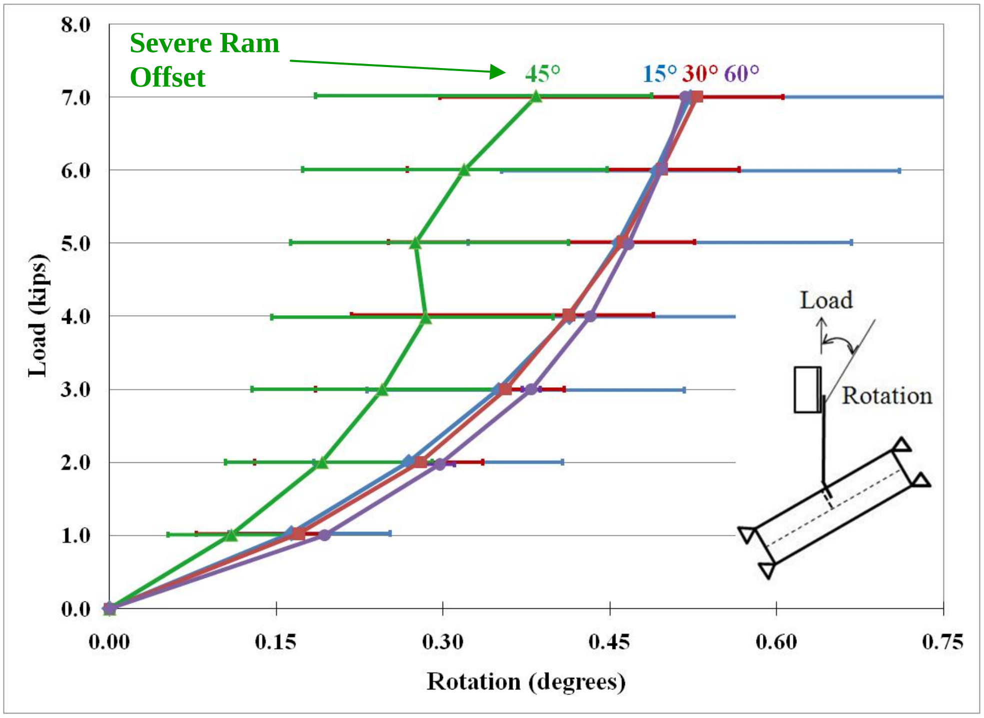


Figure 5.33 Rotation at the Top of the Bent Plate vs. Load

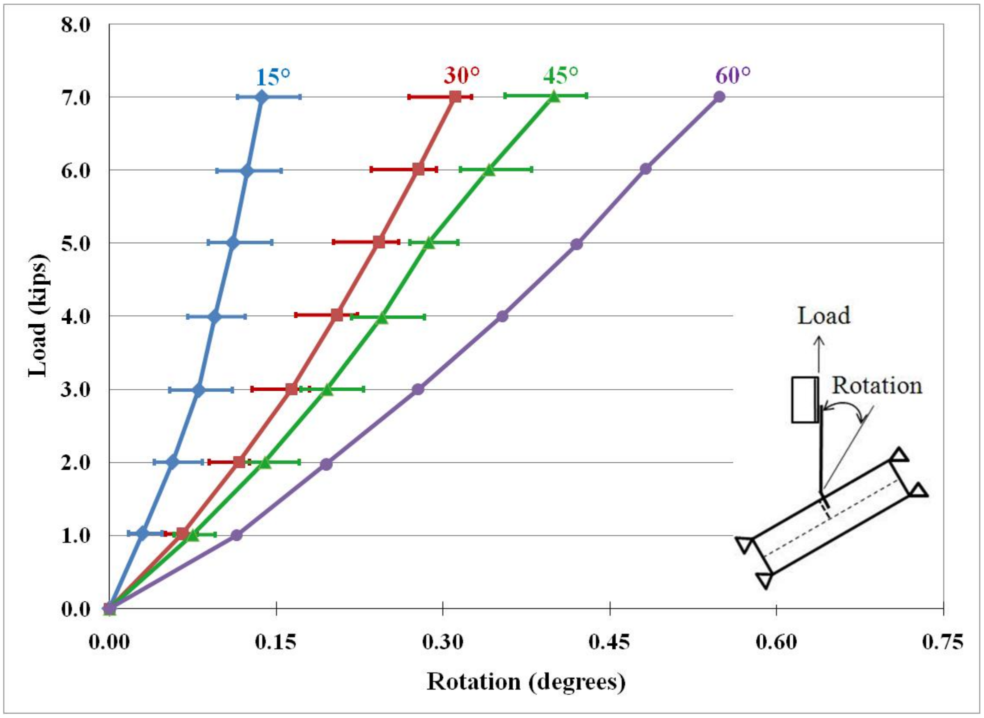


Figure 5.34 Rotation at the Bottom of the Bent Plate vs. Load

The data presented on the effect of the skew angle with regard to the bent plate detail shows that an increase in skew angle leads to increasing deflections. While the measurements are small in magnitude, the data shown was within the resolution of the instrumentation. The horizontal deflections revealed this trend, but load position difficulties made it difficult to confirm. Vertical deflection measurements, along with the rotation at the bottom of the bent plate, were not affected by load alignment and more clearly show this aspect of the bent plate's structural behavior.

5.5.2 Effect of Bend Radius

In this section, the effect of the bend radius is examined. As illustrated in Figure 5.35, an increase in bend radius in the bent plate increases the eccentricity between the load and the point of attachment of the bent plate to the stiffener. In turn, vertical deflections at the stiffener should increase. To investigate the impact of changing the bend radius, three different radii specimens were tested at a 45 degree skew angle.

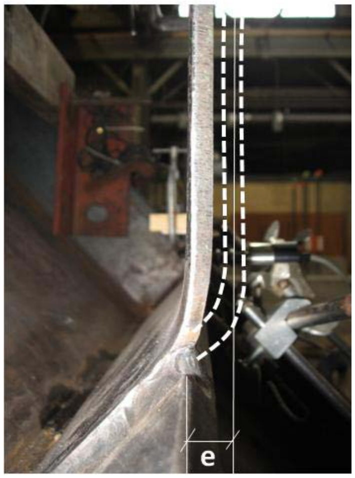


Figure 5.35 Increased Eccentricity to Connection due to Increased Bend Radius

Following the format of the bent plate skew comparison tests, deflections were measured at the same locations for the bend radii specimens. A graph of the horizontal deflection measured at the top of the bent plate versus load at a 45 degree skew angle is graphed in Figure 5.36 for three different bend radii as indicated. Recall, the error bars plotted bound the maximum and minimum values obtained during all tests that were completed. This data does not support the expectation that increasing bend radii increases deflection. However, it is believed the data was affected by difficulties with ram offset. The 2.41 in radius specimen had a negative offset of 0.25 in (negative offset leads to less deflection and was also present in the 0.59 in radius specimen- see Figure 5.26) while the 0.94 in radius specimen had a positive offset of 0.125 in. Preliminary finite element models showed the measured behavior was not indicative of the actual behavior, as the model set to zero offset had the 2.41 in being slightly more flexible than the 0.94 in sample. As was explained in the bent plate skew test subsection, the horizontal deflection of the top of the bent plate is very sensitive to out of plane forces. The vertical deflection though, is not as sensitive and should therefore be subject to less experimental error.

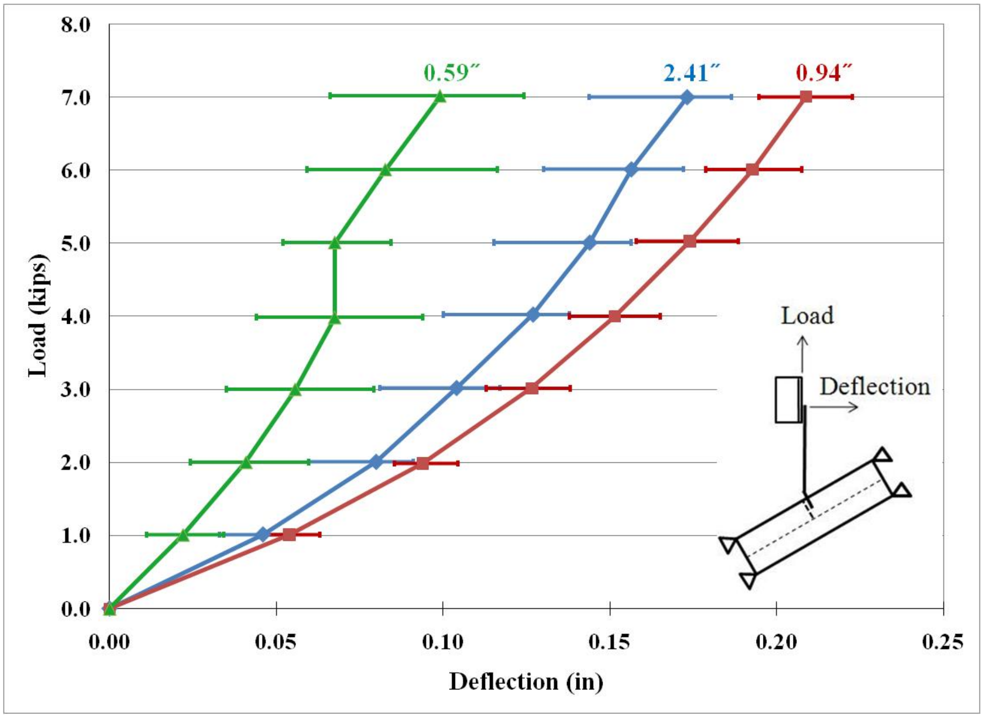


Figure 5.36 Horizontal Deflection at the Top of the Bent Plate vs. Load

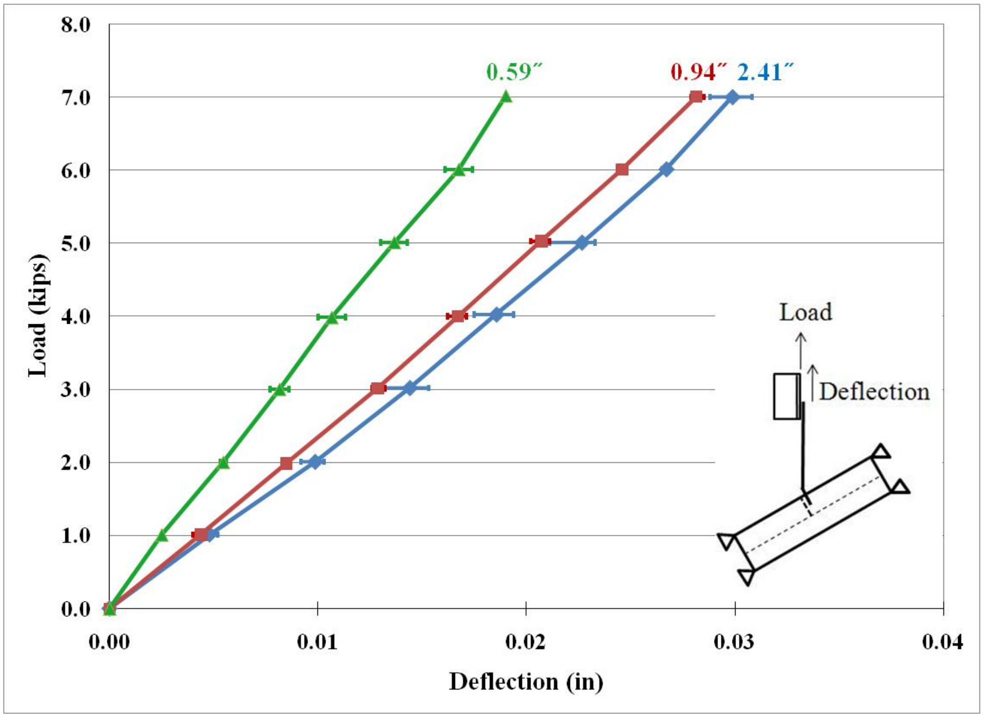


Figure 5.37 Vertical Deflection at the Top of the Bent Plate vs. Load

The vertical deflection of the bent plates at varying bend radii is plotted in Figure 5.37 and indicates increasing deflection associated with larger bend radii. As explained about the skew tests, the vertical deflection arises from vertical movement at the stiffener (Figure 5.38). With the increased bend radius, the eccentricity on the stiffener increases, leading to greater vertical displacements. The error bars bracketing the maximum and minimum recorded values in Figure 5.36 through Figure 5.38 are very small, so the test data gave consistent results.

Deflection measurements were also taken in the horizontal direction at the bottom of the bent plate, as well as rotations at the top and bottom of the plate, with all data supporting the trend of increased deformations at larger bend radii. These results can be found in Appendix B for reference.

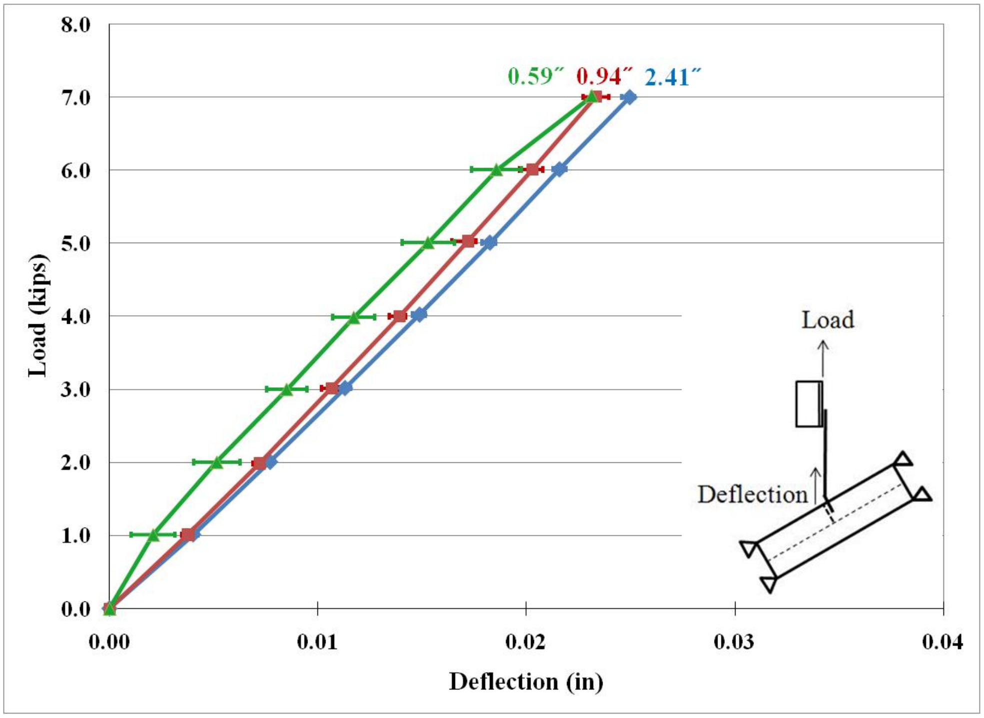


Figure 5.38 Vertical Deflection at the Stiffener vs. Load

To conclude the results for bend radius, it was seen an increase in radius leads to larger deflections. Similar to the bent plate skew tests, the deflection in the horizontal direction at the top of the plate was variable and significantly influenced by experimental error. The vertical deflection was less sensitive to experimental error and was very repeatable. The vertical deflection at the top of the bent plate was linked to the movement measured at the stiffener, which increased with bend radius and was due to the eccentricity of the load to the connection.

5.5.3 Effect of Welded Versus Bolted Connections

The next investigation in the series was to compare the performance of the bent plate detail when it is welded to the stiffener versus using tightened bolts. The purpose of testing the bolted connection was twofold. Primarily, while TxDOT opts to perform field welds on the cross frame connections to the girders, some other states use bolted details to facilitate construction, so the behavior of such a connection is important. Secondly, in light of simplifying construction, large scale laboratory tests on girder and cross frame systems planned for another phase of this research project seeks to use bolted connections to facilitate changing braces. Hence data was needed to validate finite element models of the bolted connection detail. To see the effect of using bolts, a welded specimen was identified for comparison. The 45 degree skew was selected with a bend radius of 2.41 in. The bent plate was bolted on both sides of the stiffener as featured in Figure 5.16. The term prying side refers to the plate being positioned on the same side of the load, while restricted side is on the opposing side (i.e. the position of the plate to stiffener shown in the inset of Figure 5.39 is on the prying side).

Before running the tests, it was expected the bolted connection would be more flexible than the welded connection, especially on the prying side. Even though the bolts were pretensioned, the absence of the weld was expected to reduce connection stiffness by allowing more movement between the bent plate and the stiffener, leading to larger deflections.

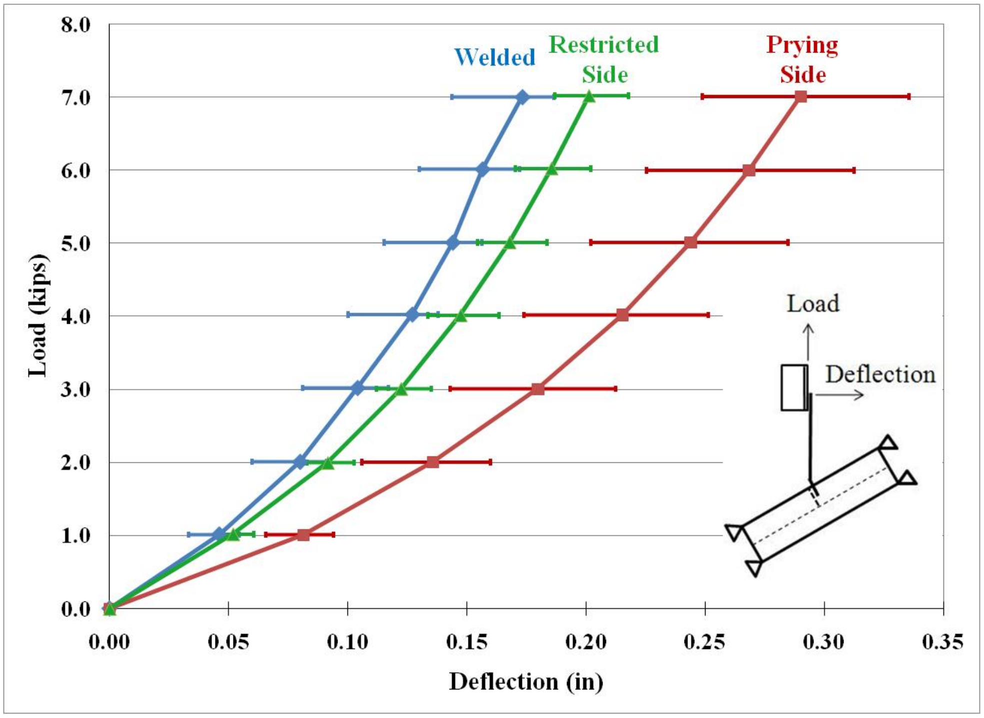


Figure 5.39 Horizontal Deflection at the Top of the Plate vs. Load

Figure 5.39 shows the effect of using bolted connections. The prying side plate had a large increase in horizontal deflections at the top of the bent plate, almost twice as large as the welded connection. The restricted side showed less deflection than the prying side, exhibiting a behavior closer to that of the welded detail. This behavior occurs because on the prying side, the portion of the bent plate nearest the stiffener edge (above the bolts) immediately begins to pull away from the stiffener once load is applied. On the contrary, on the restricted side, this portion of the plate is restrained by the stiffener, while the lower portion of the plate is clamped into place by the pretensioned bolts.

The bolted connections were both more flexible than the welded connection in the vertical direction, as indicated by Figure 5.40. A possible explanation lies in the way the connection is constructed. Recall the vertical deflection is largely a result of the deflection at the stiffener. With the bolted connection, the centroid of the connection is further offset from the load than the welded connection. Theoretically, the centroid of the welded detail is at the same location, but the weld along the backside of the bend likely stiffens the plate.

The horizontal movement at the bottom of the plate was also evaluated (Figure 5.41). The prying side exhibited more displacement than the restricted side, which in turn was more flexible than the welded connection. This deflection helps one to see the effectiveness of each connection type: one with a weld restricting movement, one with contact force of the stiffener limiting deflection, and one without a direct restraining force near this location.

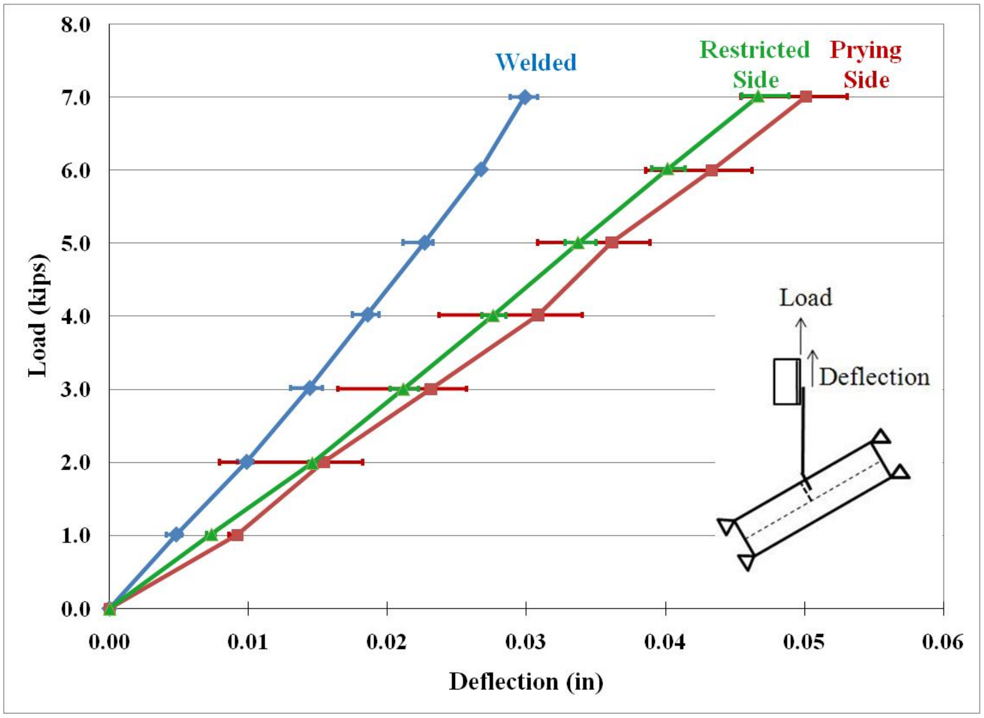


Figure 5.40 Vertical Deflection at the Top of the Plate vs. Load

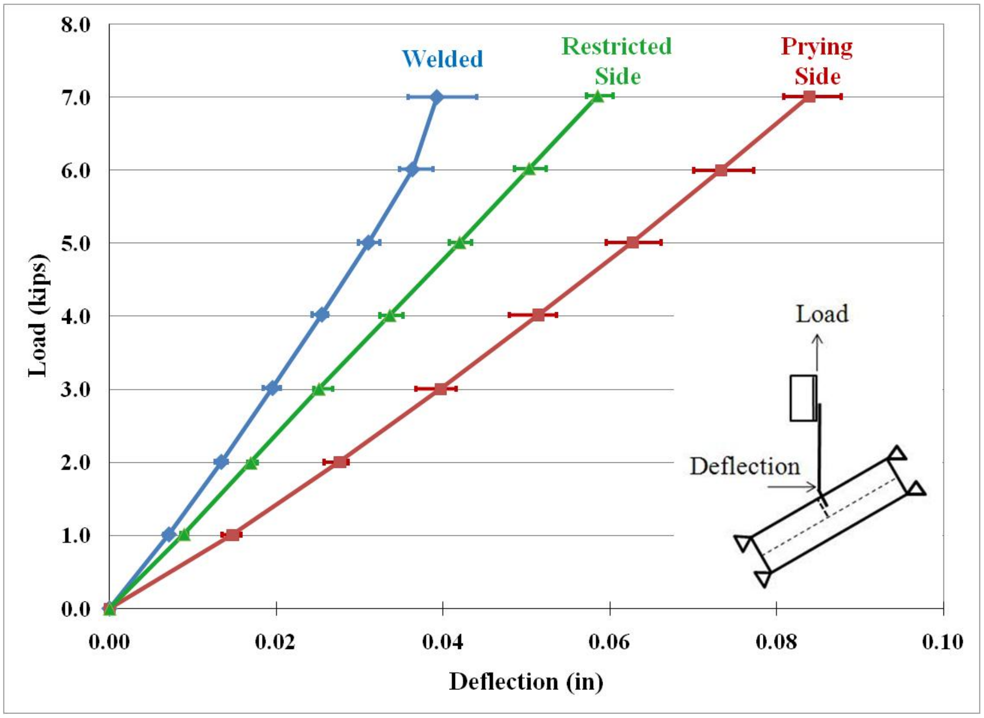


Figure 5.41 Horizontal Deflection at the Bottom of the Plate vs. Load

The remaining measurements are found in Appendix B and further confirm these conclusions.

In summary, the bolted type connections responded differently than the welded connections. While the restricted connection exhibited a similar response to the welded connection at the top of the bent plate, the vertical bending behavior at the stiffener was significantly different. Overall, the bolted connection details show higher deflections than the welded detail.

5.6 LABORATORY TEST RESULTS: HALF PIPE STIFFENER DETAIL

Before comparing the bent plate connection to the half pipe stiffener connection, a comparison between skew angles of the half pipe specimen is presented. Since the plates used to make this connection were not bent, no horizontal movement of the plate occurred. Additionally, with the force directly framing into the pipe, it is thought the vertical stiffener movement will decrease provided the wall thickness of the pipe is enough to prevent large local deflections.

The two skew angles evaluated were the 0 degree and 45 degree conditions. The 45 degree specimen provides a comparison to the bent plate detail as numerous tests have been conducted at this angle. The 0 degree case should have the most pipe wall flexibility as the force is farthest from the web.

Lastly, it is noted these specimens had some initial imperfections. For instance, the 45 degree specimen had a skew approximately 46.5 degrees, while the 0 degree specimen was about a 1 degree skew. These irregularities were accounted for by adjusting the ram offset to zero.

5.6.1 Effect of Skew Angle

Figure 5.42 shows the results for horizontal movement of the top of the plate versus load for the half pipe stiffener. Surprisingly, the order of magnitude of the horizontal deflection was similar to those measured in the bent plate skew tests. The finite element model of the half pipe stiffener specimen showed similar trends. Based on an evaluation of results of the finite element model, it appears that the large horizontal deflections resulted from eccentricity caused by application of load through the angle member. With the difference in stiffness between the angle member and the plate, in combination with the biaxial bending of the angle structural shape, an out of plane force develops causing horizontal displacement.

If one considers the measured horizontal deflections shown for the half pipe stiffener at a 0 degree skew in Figure 5.42, these horizontal deflections are very close to those reported for the skew tests on the bent plate connection. This leads to the observation that the horizontal deflections of the bent plate specimen may be influenced by this out of plane force, with the increasing skew angles moderately amplifying the results.

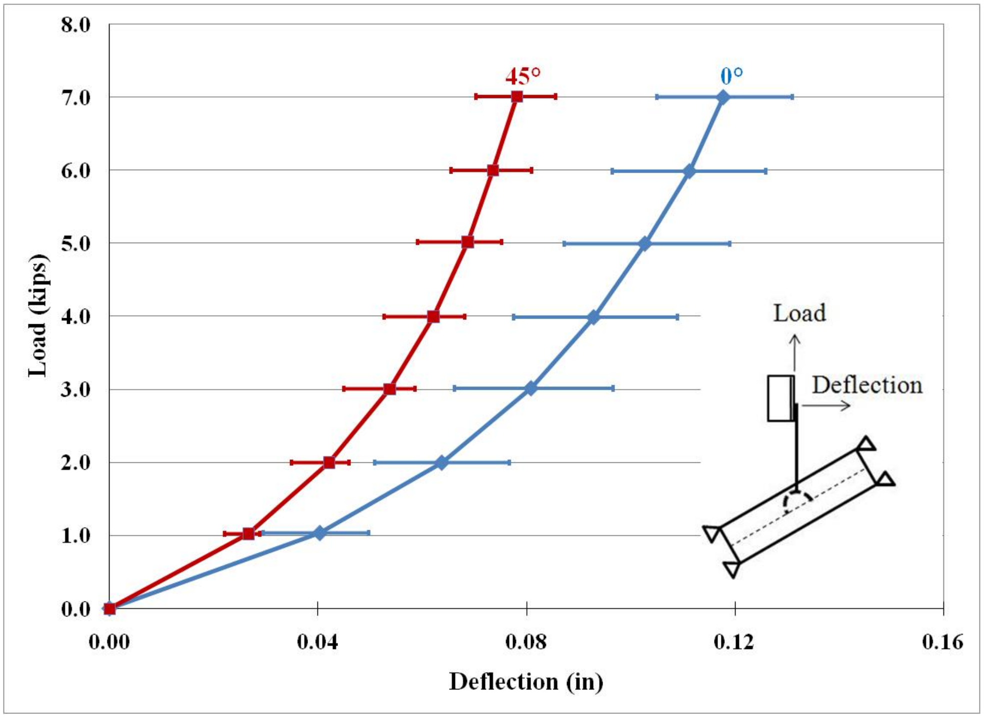


Figure 5.42 Horizontal Deflection at the Top of the Plate vs. Load

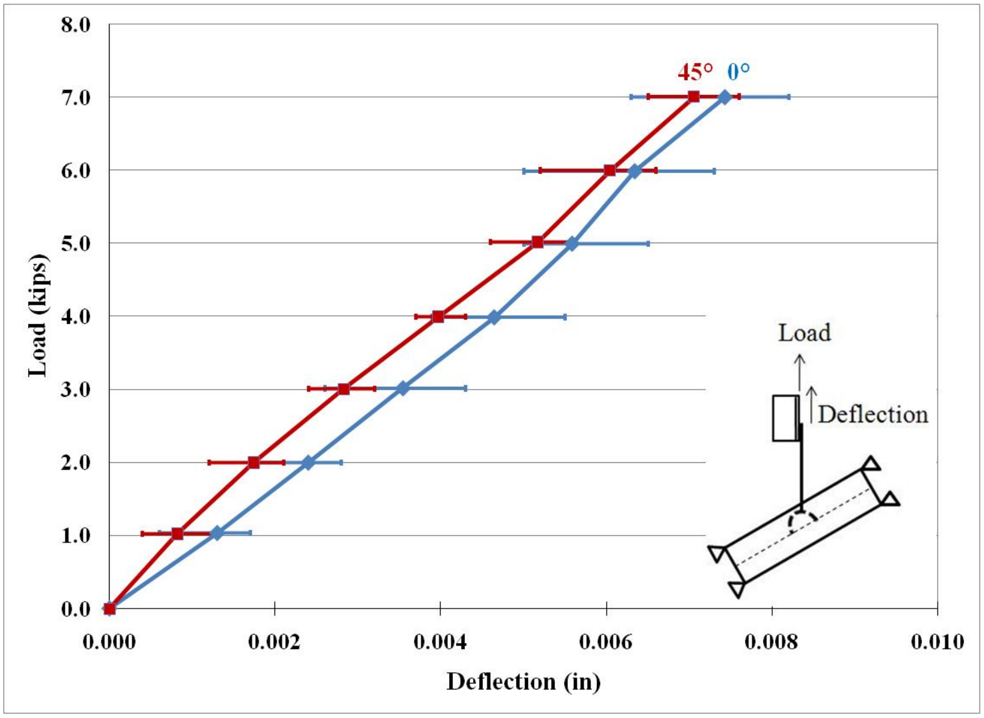


Figure 5.43 Vertical Deflection at the Top of the Plate vs. Load

In the vertical direction of the half pipe tests, the 0 degree skew and the 45 degree skew specimens essentially showed the same results. The total movement was just less than 0.008 in as shown in Figure 5.43. These small deflections indicate the half pipe detail is very stiff axially, with the deflection again dependent upon deformation in the stiffener. Rather than the flexible cross frame stiffener used with the bent plate, the pipe does not introduce an eccentricity.

5.7 LABORATORY TEST RESULTS: BENT PLATE DETAIL VERSUS HALF PIPE DETAIL

Finally, it is of interest to compare the bent plate detail to the half pipe stiffener detail. A major objective of this research project is to propose a suitable cross frame detail with better performance compared to the bent plate. It is thought the half pipe detail accomplishes this task by providing a stiffer connection. To investigate the comparative behavior of the connections, graphs of measurements for the 45 degree skew case are considered.

First, the horizontal deflection at the top of the plate is compared in Figure 5.44. The half pipe detail behaved similar to the low bend radius bent plate specimen. This observation suggests the tightly bent plates' horizontal deflection at the top of the plate was dependent upon the varying stiffness of the angle member and the plate creating a load eccentricity, rather than an effect of the skew. However, the half pipe clearly exhibits less horizontal deflection than the larger bend radii specimens.

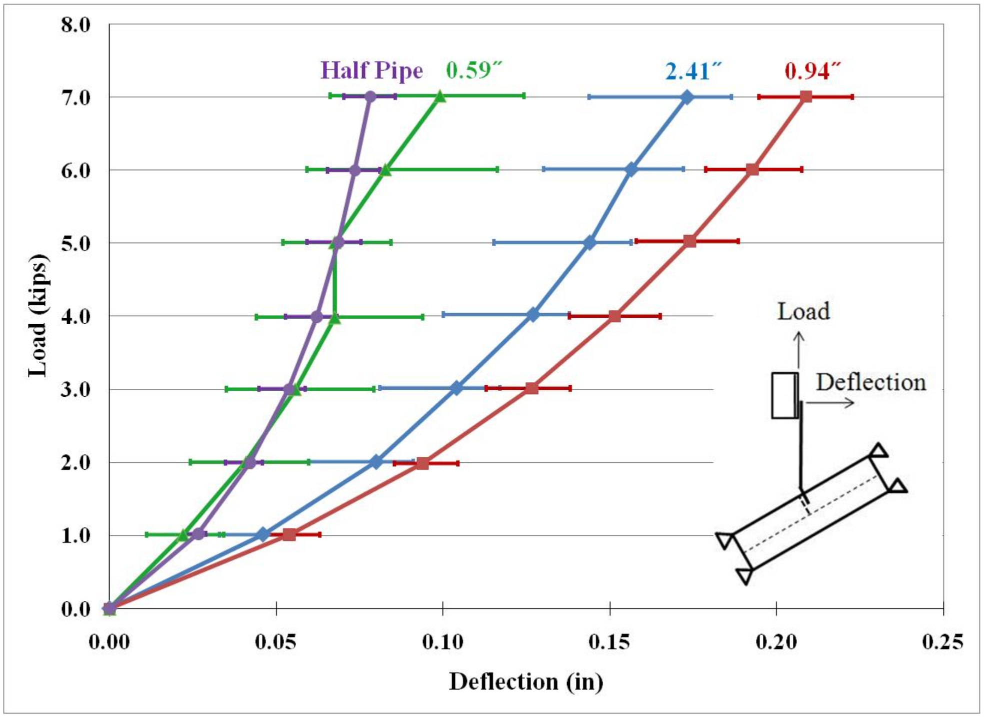


Figure 5.44 Horizontal Deflection at the Top of the Plate vs. Load

Next, the vertical deflection at the top of the plate is analyzed, with results plotted in Figure 5.45. The half pipe stiffener shows significantly less deflection than the bent plate specimens. Vertical deflections with the half pipe stiffener were approximately 37 percent of the deflection in the 0.59 in bend radius specimen, and 24-25 percent of the 0.94 in and 2.41 in specimens. This data suggests the half pipe stiffener detail provides significantly higher stiffness than the bent plate detail.

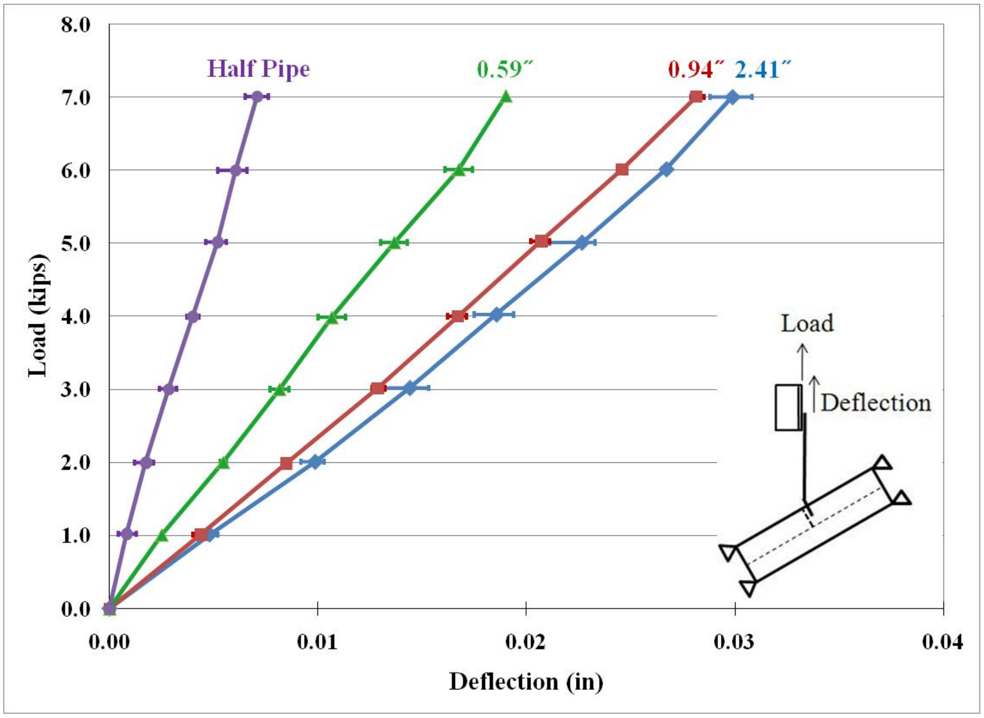


Figure 5.45 Vertical Deflection at the Top of the Plate vs. Load

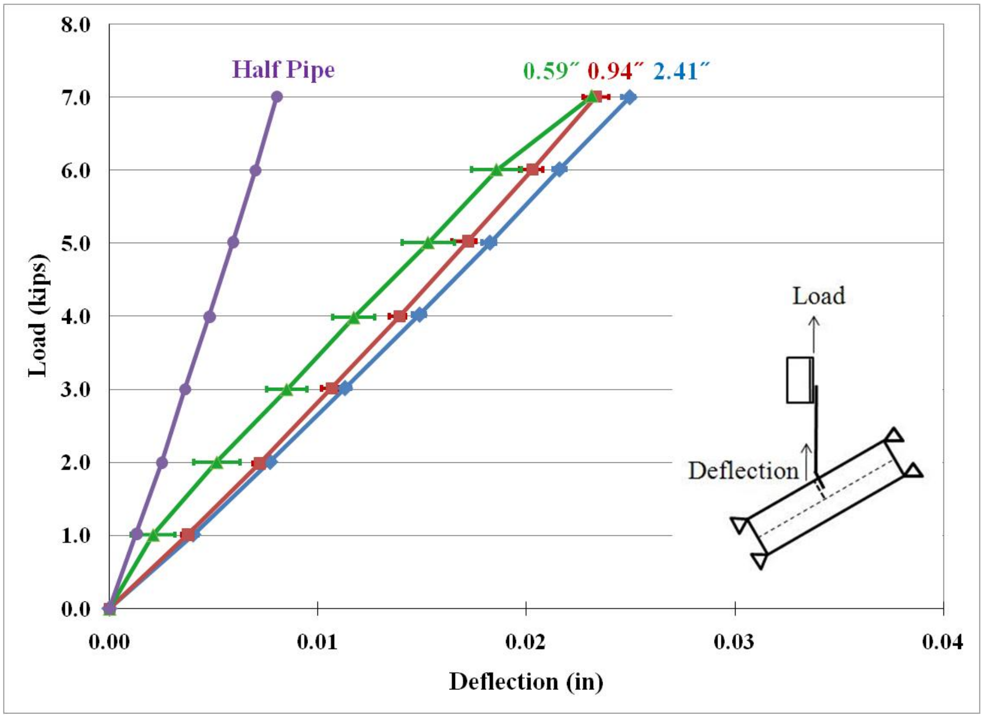


Figure 5.46 Vertical Deflection at the Stiffener vs. Load

Figure 5.46 further confirms the behavior in the vertical direction, again indicating the deflection at the stiffener comprises the majority of movement for the bent plate detail. This plot further supports the advantageous stiffness of the half pipe connection detail.

Results for horizontal deflection at the bottom of the plate are shown in Figure 5.47. The graphs show the bent plate details experience measurable movement at this location, while the half pipe detail experiences essentially none. This happens because the stiffener in the bent plate deforms under the load causing horizontal movement and the plate. The lack of eccentricity in the half pipe detail minimizes horizontal movement.

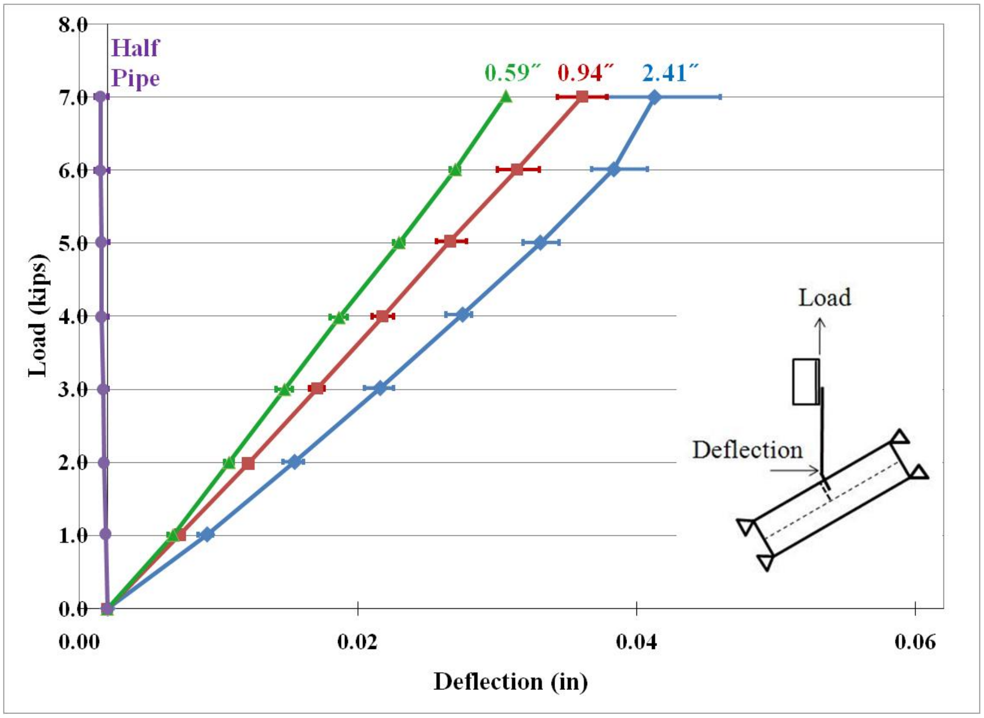


Figure 5.47 Horizontal Deflection at the Bottom of the Plate vs. Load

Measured rotations of the plate also indicate the half pipe stiffener leads to practically no bending of the plate (Figure 5.48 and Figure 5.49). Rotations at the top and bottom of the plate were close to zero for this connection, well below the 0.03 degree accuracy of the tilt sensors. Meanwhile, the bent plates had a measurable rotation, as indicated in the figures.

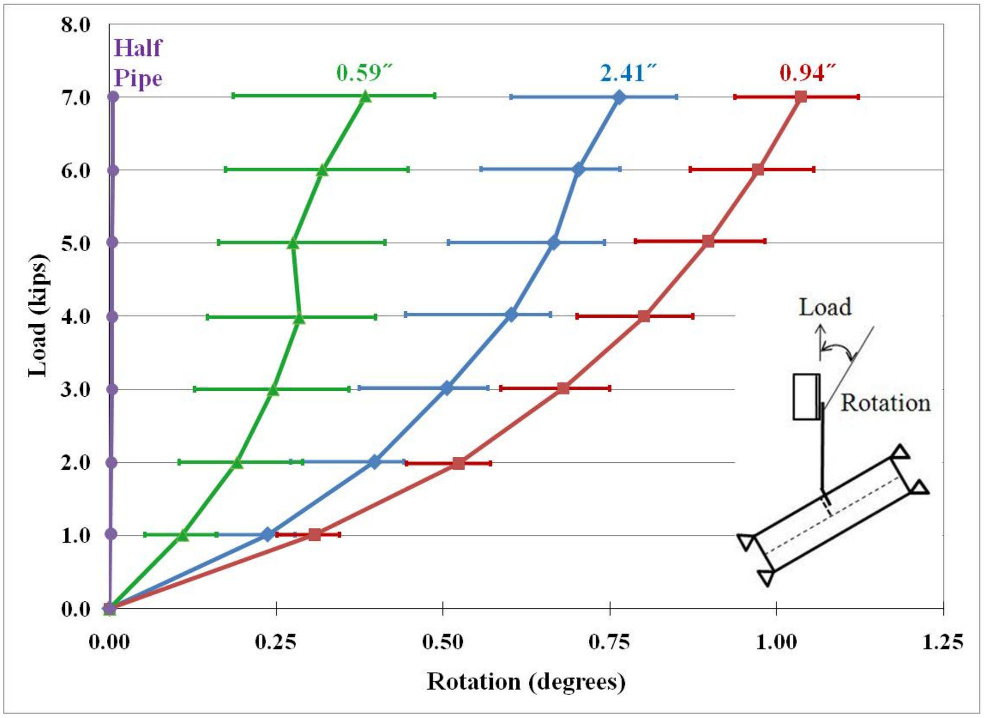


Figure 5.48 Rotation at the Top of the Plate vs. Load

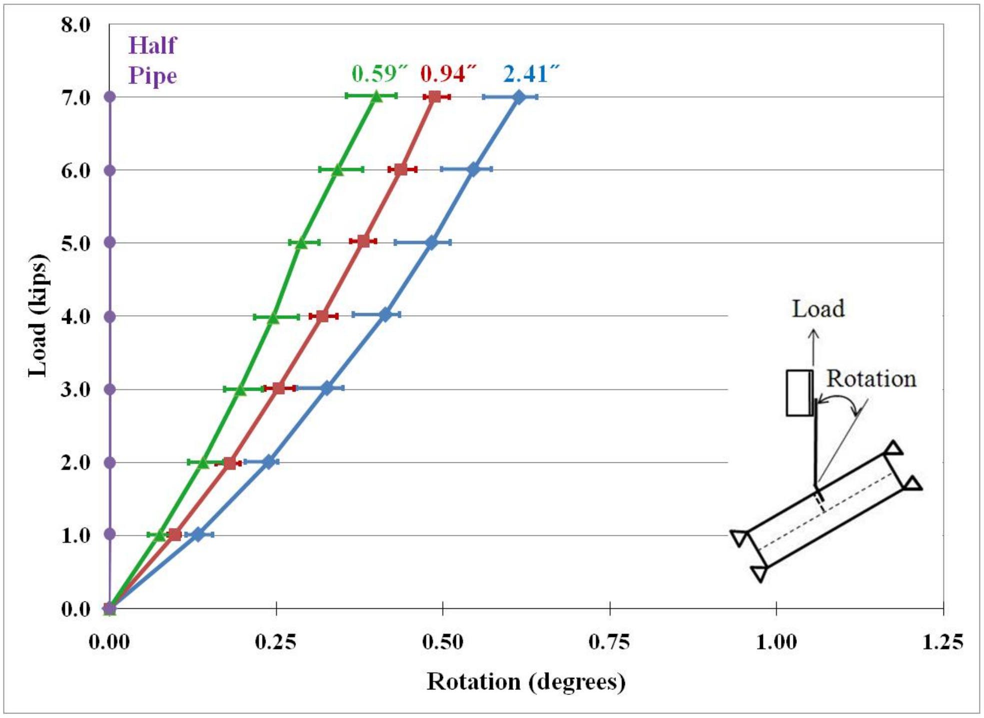


Figure 5.49 Rotation at the Bottom of the Plate vs. Load

In conclusion, the half pipe stiffener showed significantly less deflection and rotation compared with the bent plate detail, as indicated by the plots in Figure 5.44 through Figure 5.49. These measurements indicate the half pipe connection detail is stiffer than the bent plate detail.

5.8 LABORATORY TEST CONCLUSIONS

The small scale laboratory tests discussed in this chapter were conducted to obtain a better understanding of the behavior of cross frame connection details and to provide data to validate finite element models of the connections. Currently, the bent plate detail is used to facilitate the construction of skewed steel bridges. However, the flexibility this connection may have, especially in light of the problems experienced at the Churchman Road Bridge in Delaware [Winterling 2007], could result in ineffective cross frames. As cross frames are the primary source of stability for the steel girders during construction, reducing their stiffness could compromise structural safety.

To gain insight to this problem, ten separate specimens were created for comparison, as well as validation for finite element analyses. The specimens sought to determine the effects of varying the skew angle and bend radius of the bent plate, as well as the difference between welding and bolting this connection. Tests were also run on a proposed half pipe stiffener solution, to see if changing the skew angle had any impact on connection stiffness.

Finally, the bent plate and half pipe stiffener details were compared. The bent plate detail showed a trend of increasing deflections in the horizontal and vertical directions as the skew angle was increased. The measured horizontal displacements were very small and significantly influenced by experimental error in some tests. The measured vertical deflections were much less influenced by experimental error and therefore provided more useful data on connection stiffness. For the bent plate detail, an important observation from the measurements is the majority of the vertical deflection is caused by deformation of the stiffener rather than deformation of the bent plate. This suggests that increasing the thickness of the bent plate may not significantly increase connection stiffness.

The tests demonstrate that increasing the bend radius of the bent plate increases deflections and therefore decreases connection stiffness. A larger radius leads to an increased eccentricity between the load imposed by the cross frame member and the connection of the bent plate to the girder stiffener. Tests confirmed this behavior, showing bent plates with the radii of 0.94 in and 2.41 in to have approximately twice the deflection of the 0.59 in bend radius.

As was expected, the bolted connections were less stiff than the welded bent plates, mainly because the weld better clamps the plate to the stiffener than the bolts. The bolted connection on the prying side was about twice as flexible as the welded detail in all measured deformations. By bolting the plate on the restricted side, flexibility is reduced compared to the case where the plate is bolted to the prying side. Nonetheless, even with the plate is bolted to the restricted side, the stiffness of the bolted connection was still less than that of the welded connection detail.

Tests run at different skew angles for the half pipe stiffener show that changing the skew angle has little effect on the stiffness of the detail. The specimens at 0 and 45 degrees had the same vertical displacement and similar horizontal behavior.

Finally, these tests have demonstrated the half pipe connection detail showed significantly less horizontal and vertical deflection and much less rotation as compared with the bent plate detail. These results support the hypothesis that the half pipe detail can provide a significantly stiffer cross frame to girder connection compared to the bent plate detail, and may therefore offer improved behavior and safety in skewed bridges.

CHAPTER 6

Summary and Conclusions

6.1 INTRODUCTION

The research presented in this thesis was conducted as a part of TxDOT research Project 0-5701, Cross Frame and Diaphragm Layout and Connection Details. The overall project incorporates field tests, laboratory tests, and finite element analyses with a goal of developing improved connection details between cross frames and girders in skewed bridges. This thesis presents the results of field tests and small scale connection tests. The scope of Project 0-5701 also includes large-scale laboratory tests on girder and cross frame systems, fatigue tests, as well as extensive parametric finite element studies. Results from these portions of the study will be reported in a future dissertation and thesis by Quadrato (2010) and Wahr (2010).

This thesis has described the current practices with regard to the stability of skewed steel bridges and improvements that can be made at cross frame connections. Background information on code provisions, as well as basic bracing principles are reviewed. Previous research on the bent plate detail has been limited, with construction problems at the heavily skewed Churchman Road Bridge in Delaware at the forefront. To better understand the structural performance of the bent plate, a field test on the 19th Street westbound bridge over US-82 in Lubbock, Texas was conducted. Next, the bent plate connection was carefully evaluated in the laboratory to see the effect of varying parameters like the skew angle, bend radius, or bolted/welded construction. Lastly, a new connection was proposed that would use half pipes to replace the cross frame stiffeners, and laboratory data concerning this detail was reported. The following sections provide a summary of the purpose of the research, review important results from the field and laboratory tests, make recommendations for cross frame connections, and describe future work.

6.2 SUMMARY OF PROBLEM

During bridge construction, cross frames provide stability to the steel girders, helping to restrain lateral torsional buckling and to resist lateral loads. Once the concrete bridge deck is made composite with the girder system, the role of the cross frames is diminished since the hardened concrete helps to provide stability to the girder system. Cross frames often contribute a significant percentage to the overall bridge cost due to fabrication complexities and construction fit-up issues. Additionally, service fatigue issues arising from large live load forces can cause cracks to develop at cross frame connections, further increasing life-cycle costs of the structure. These service fatigue problems are enhanced in skewed steel bridges, as differential deflections between girders can induce the live load forces.

Skewed bridges are necessary when the underlying roadway or terrain necessitates the bridge superstructure to rest on supports that are not perpendicular to the girder cross-sections.

In skewed bridges, the end cross frames are normally placed parallel to the skew. Interior cross frames may be placed either parallel to the skew or perpendicular to the girders, depending on the skew angle. When cross frames are placed parallel to the skew, the cross frames must connect to the girder cross-section at an angle. To make this connection, bent plates matching the skew angle are utilized by many states. While this connection detail may be convenient from a fabrication point of view, the flexibility of this connection can significantly reduce the effectiveness of the cross frames in bracing the girders. The stiffness of the cross frame bracing system is always less than the least stiff component in the system. Consequently, a flexible connection between the cross frame and the girder can cause a large reduction in overall brace stiffness. To improve stiffness of the cross frame to girder connection, a detail using half pipe stiffeners is proposed. Small scale laboratory tests on the half pipe detail and the bent plate detail showed that the half pipe detail provides a stiffer connection. Furthermore, the warping restraint provided by connecting the pipe to the top and bottom flanges may increase the girder buckling capacity, thereby providing an additional benefit (i.e. longer unbraced lengths).

6.3 SUMMARY OF RESULTS

In order to study the bent plate detail's impact on structural behavior, a testing program was developed, which included field monitoring of an end cross frame in a highly skewed bridge and small scale laboratory tests focusing on the connection stiffness. In addition, the proposed half pipe stiffener detail was examined in the laboratory to compare its performance to the bent plate.

6.3.1 Field Tests

The field tests took place on the 19th Street westbound overpass at US-82 in Lubbock, TX. The bridge, situated at a 60 degree skew angle, is a two-span continuous structure utilizing bent plate details at the abutments and interior support. Strain gages were located on an end cross frame. Data was recorded during the placement of the concrete deck and under a controlled live load test after the deck had hardened. The strain measurements were then used to compute forces in the cross frame members.

Forces measured in the cross frame members were very low, both during the deck placement and during the subsequent live load test. For both cases, the average axial stress in the members were less than 1 ksi.

These low forces in the cross frames indicated the frames may not have been effective in bracing the girders due to the flexibility of the bent plate connections. Nonetheless, no problems were encountered with girder stability or movement during the concrete deck placement, as evidenced by the very small measured girder end rotations. The girders in this bridge were supported on Fabreeka bearing pads, as compared to the more commonly used elastomeric bearing pads. Fabreeka pads are much stiffer than elastomeric pads, and may have contributed to girder stability through tipping restraint. These observations suggest the girder bearing stiffness may influence cross frame demands. The effect of bearing stiffness on girder stability and cross frame requirements will be investigated in later phases of Project 0-5701.

6.3.2 Laboratory Tests

A series of small scale laboratory tests were conducted on the bent plate connection detail. The objectives of these tests were to better understand the factors influencing the stiffness of the bent plate detail and to develop data for validation of finite element models of the connection. Test parameters included the skew angle, bend radius, and the use of bolts versus welds to connect the bent plate to the girder stiffener. Tests were also conducted on the proposed half pipe stiffener detail to compare its performance with the bent plate.

Data collected on the effect of skew angle for the bent plate detail show the stiffness of the connection decreases with increasing skew angle. The main reason for this behavior is the component of force perpendicular to the stiffener causing bending of the stiffener. This component increases with the skew angle, leading to larger deflections and lower stiffness.

With increasing bend radius, the deflections also increased. Larger bend radii create larger eccentricities from the connection, increasing the moment arm on the stiffener. The stiffness, therefore, also decreases with increasing bend radius.

Next, bolted connections were found to be more flexible than the comparable welded connection. Bolted connections were placed on both sides of the stiffener with the restricted side (side opposite load direction) being more stiff than the prying side. The prying side was roughly twice as flexible as the welded connection.

For the bent plate detail tested in the laboratory, a bent plate was welded or bolted to a full depth stiffener that, in turn, was welded to the girder. This is similar to the detail commonly used in bridges. An important observation from the experiments on the bent plate detail is that much of the flexibility of this detail comes from deformations of the stiffener rather than deformations of the bent plate. The bent plate causes an eccentricity between the applied load and the stiffener, causing bending of the stiffener. This eccentricity is increased as skew angle increases and as bend radius increases. A consequence of this observation is that increasing the thickness of the bent plate may not significantly increase connection stiffness. Rather, an increase in stiffener thickness may be more beneficial.

For tests on the half pipe connection detail, skew angle seemed to have no effect on the stiffness, with the 0 and 45 degree specimens performing approximately the same. This occurs because the plate now frames directly into the half pipe creating a more rigid connection.

Lastly, when comparing the two details, the half pipe's structural performance is superior to the bent plate. Vertical deflections, which form the main indication of stiffness in the cross frame direction, were 63-75 percent less for the half pipe than the bent plate. Additionally, no rotation of the plate was measured with the half pipe detail. Overall, the results of the small scale laboratory tests on skewed cross frame to girder connections confirm that the proposed half pipe connection details provides significantly larger stiffness than the conventional bent plate detail.

6.4 CONCLUSIONS AND FURTHER WORK

When a cross frame must be connected to a girder at a skew, the most common detail used in current practice is the bent plate connection detail. The flexibility of the bent plate detail can reduce the effectiveness of the cross frame for bracing the girder, and can therefore lead to inefficient and potentially unsafe designs. An alternative cross frame to girder connection utilizing a half pipe stiffener has been proposed to provide a stiffer connection, and therefore more effective bracing of the girder. The half pipe stiffener may offer an added benefit of providing increased torsional warping restraint to the girder, thereby increasing the buckling capacity of the girder.

The potential benefits of using the half pipe stiffener detail for connecting cross frames to girders in skewed bridges is being evaluated in TXDOT Research Project 0-5701, along with the development of design guidelines. The work reported in this thesis represents only a portion of the full scope of research for Project 0-5701. The field and laboratory tests conducted as part of this thesis has provided data for validation of finite element models being developed in other phases of Project 0-5701. However, the laboratory data generated in this thesis has confirmed the hypothesis that the half pipe connection detail is significantly stiffer than the bent plate detail, and provides a basis for quantifying connection stiffness. Thus, the key conclusion of this thesis is that the half pipe connection detail can, in fact, provide improved connection stiffness, and merits continued investigation.

Further work is continuing on Project 0-5701. This work includes development of detailed finite element models of the bent plate and half pipe connection details, finite element models of skewed bridge systems, including cross frames and cross frame connections, large scale laboratory tests on two and three girder bridge systems for further validation of the finite element models, and fatigue tests on the proposed half pipe detail. Results of these further studies will be presented in subsequent reports planned for late 2010.

APPENDIX A

Live Load Testing Results

A.1 LIVE LOAD TEST POSITIONING

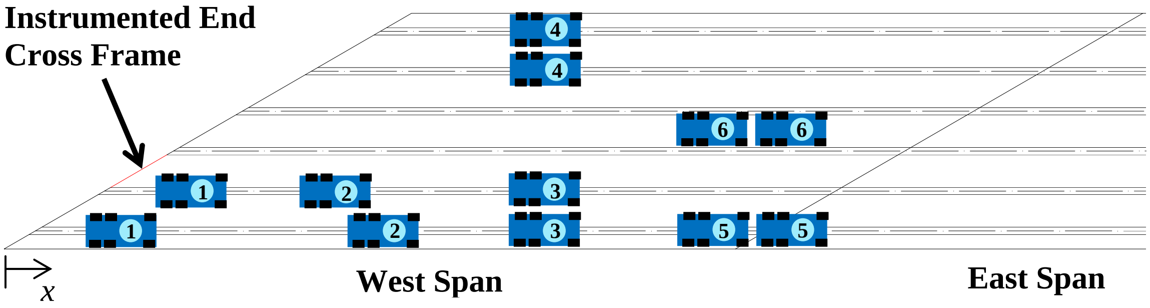


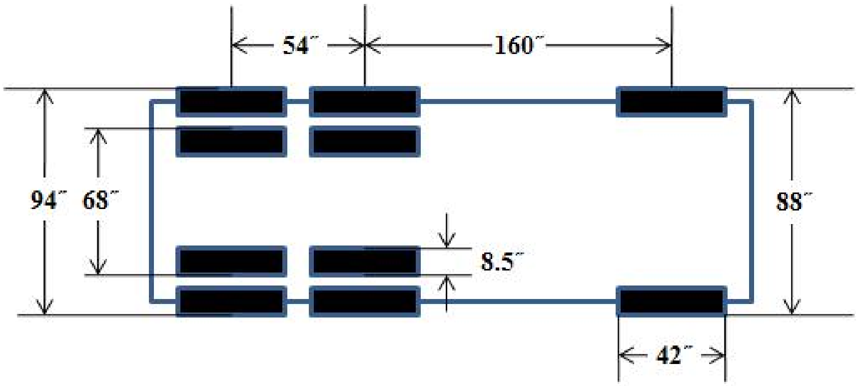
Figure A.1 Summary of Configurations used in Live Load Testing Program

1. Staggered Ahead (Parallel to Skew Angle)
2. Staggered Behind (Perpendicular to Skew Angle)
3. Side by Side (South)
4. Side by Side (North)
5. End to End (South)
6. End to End (Center)

The positions of the trucks were coordinated at 20 ft increments along the bridge length beginning from the southwest corner of the bridge. Additional measurements were taken at 10 ft increments near the negative moment region at the interior support.

A.2 LIVE LOAD TRUCK INFORMATION

Figure A.2 TxDOT Sand Truck



Truck ID	Front Axel Weight (lbs)	Back Axel Weight (lbs)	Total Weight (lbs)
5240G	12,240	36,180	48,420
5060F	11,700	37,200	48,900

Figure A.3 TxDOT Sand Truck Dimensions and Axle Weights

A.3 LIVE LOAD TEST DATA: STAGGERED AHEAD

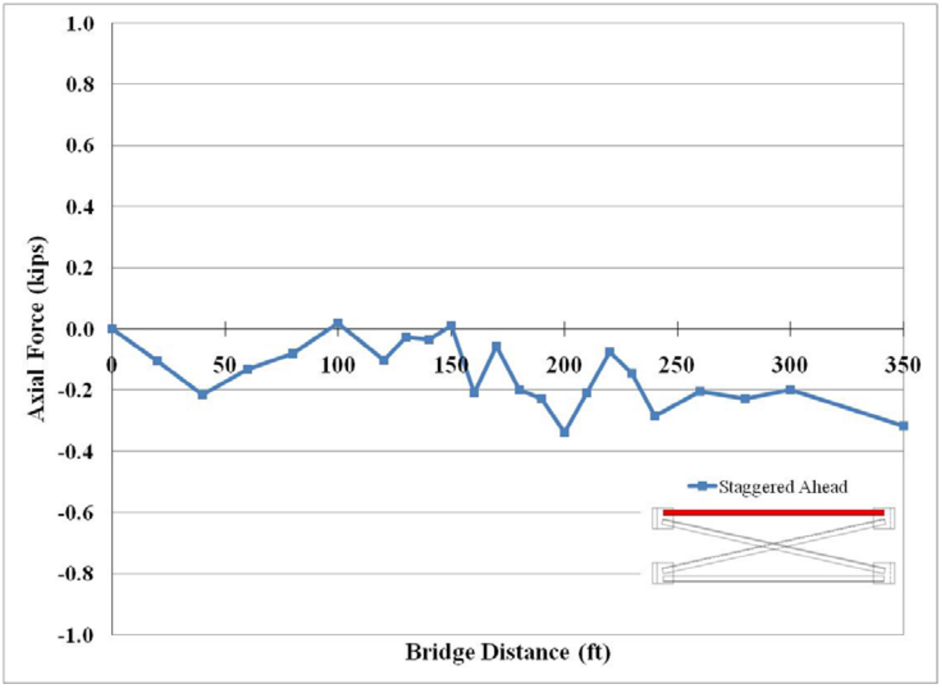


Figure A.4 Axial Force versus Bridge Distance for Top Strut

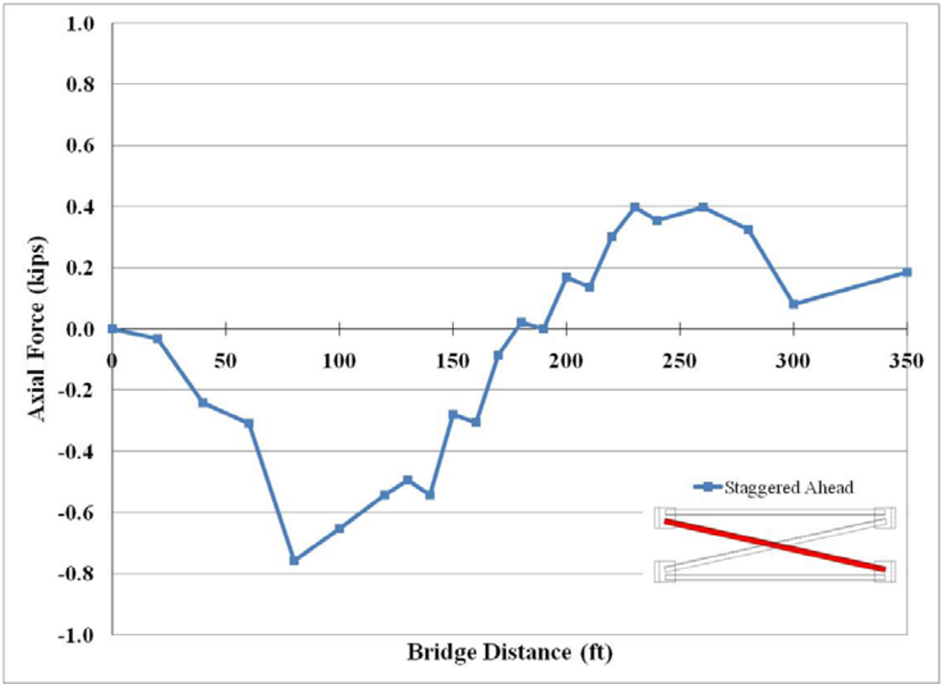


Figure A.5 Axial Force versus Bridge Distance for Top Diagonal

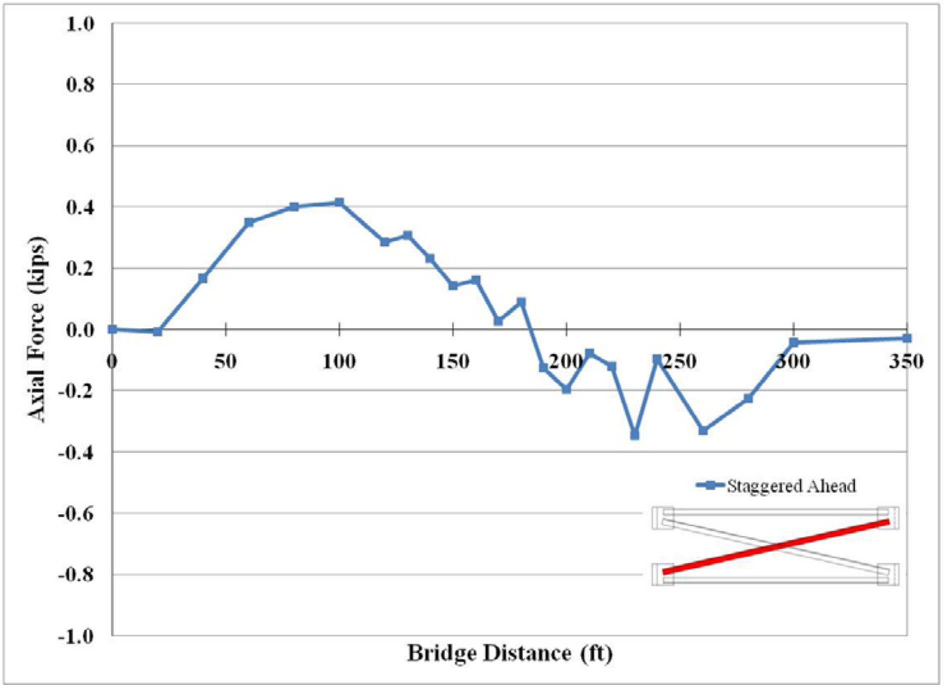


Figure A.6 Axial Force versus Bridge Distance for Bottom Diagonal

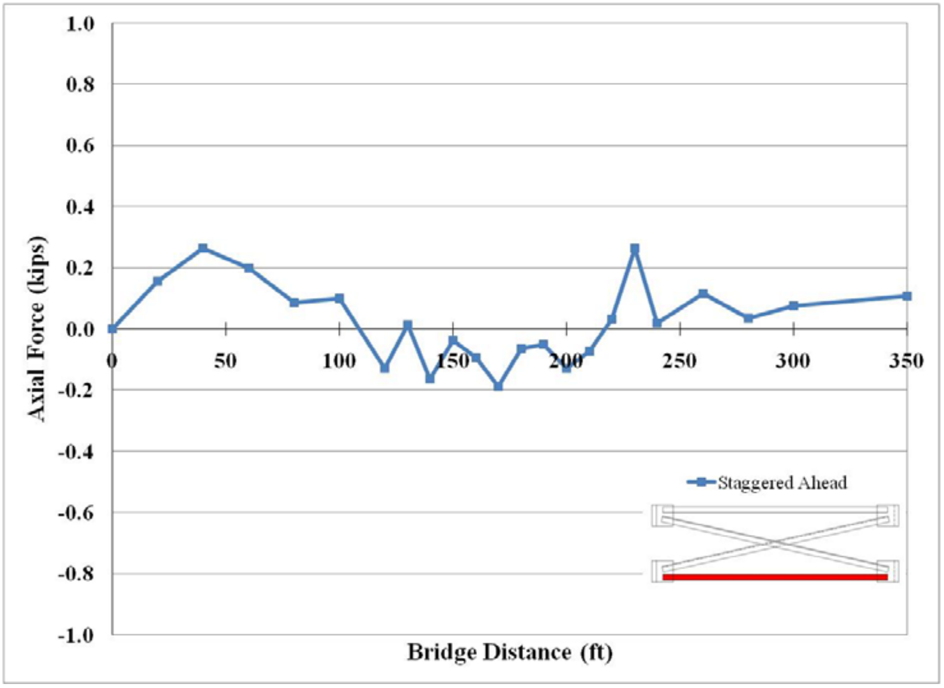


Figure A.7 Axial Force versus Bridge Distance for Bottom Strut

A.4 LIVE LOAD TEST DATA: STAGGERED BEHIND

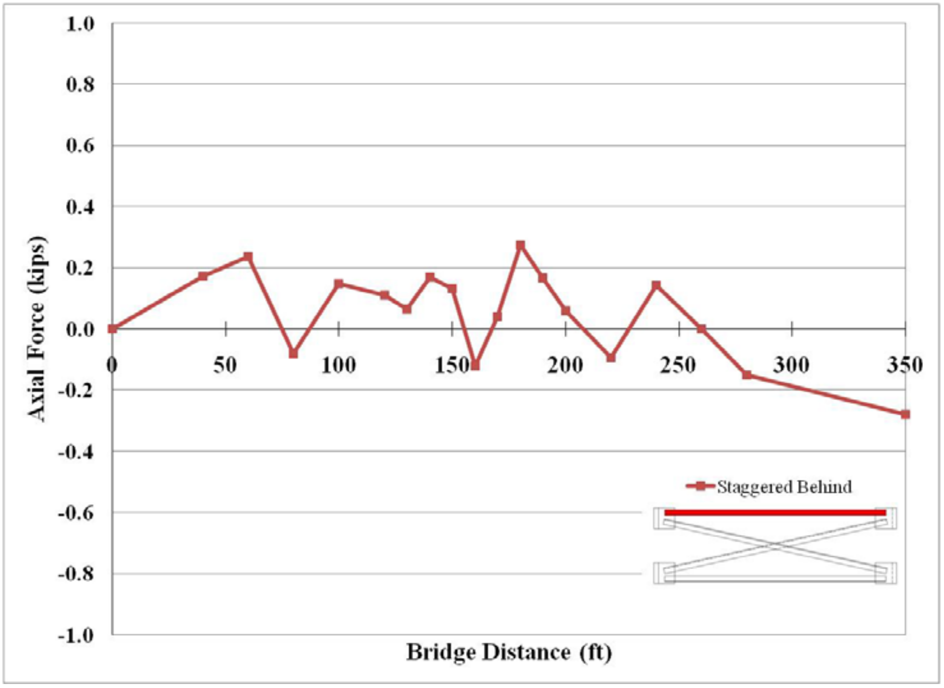


Figure A.8 Axial Force versus Bridge Distance for Top Strut

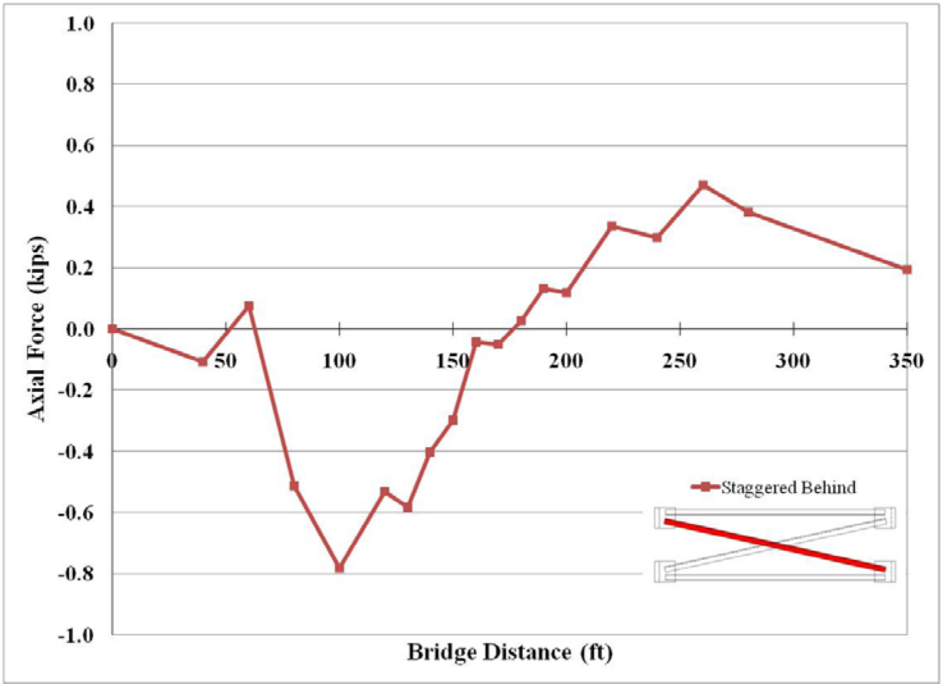


Figure A.9 Axial Force versus Bridge Distance for Top Diagonal

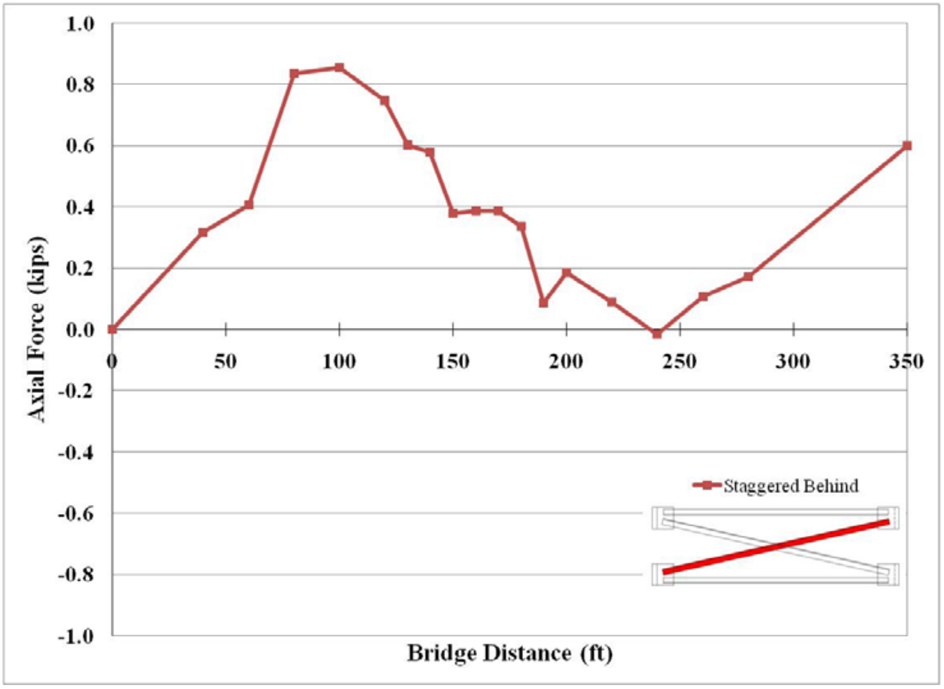


Figure A.10 Axial Force versus Bridge Distance for Bottom Diagonal

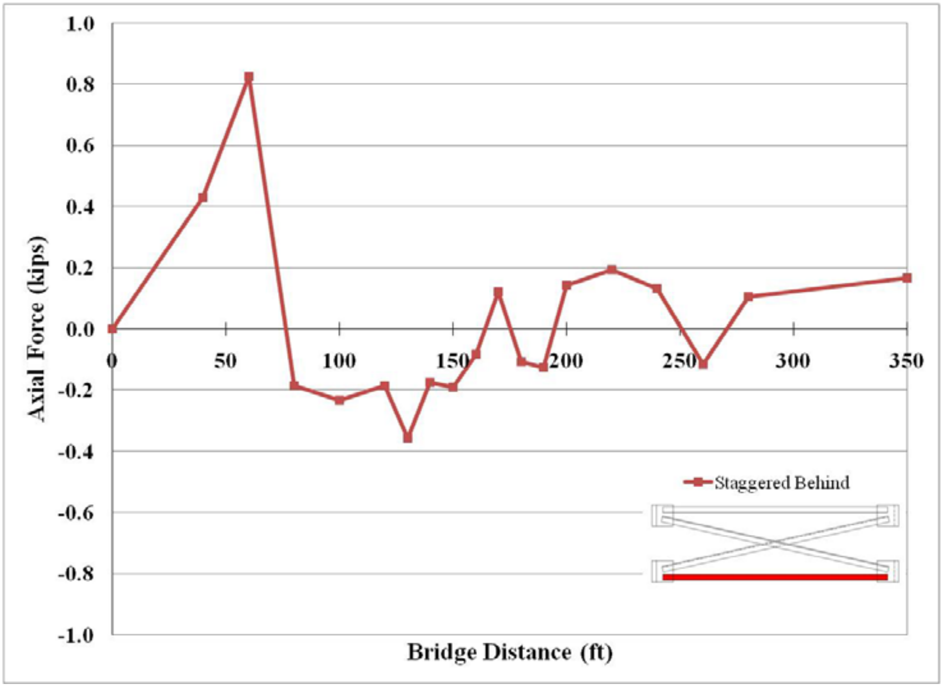


Figure A.11 Axial Force versus Bridge Distance for Bottom Strut

A.5 LIVE LOAD TEST DATA: SIDE BY SIDE (SOUTH)

Figure A.12 Axial Force versus Bridge Distance for Top Strut

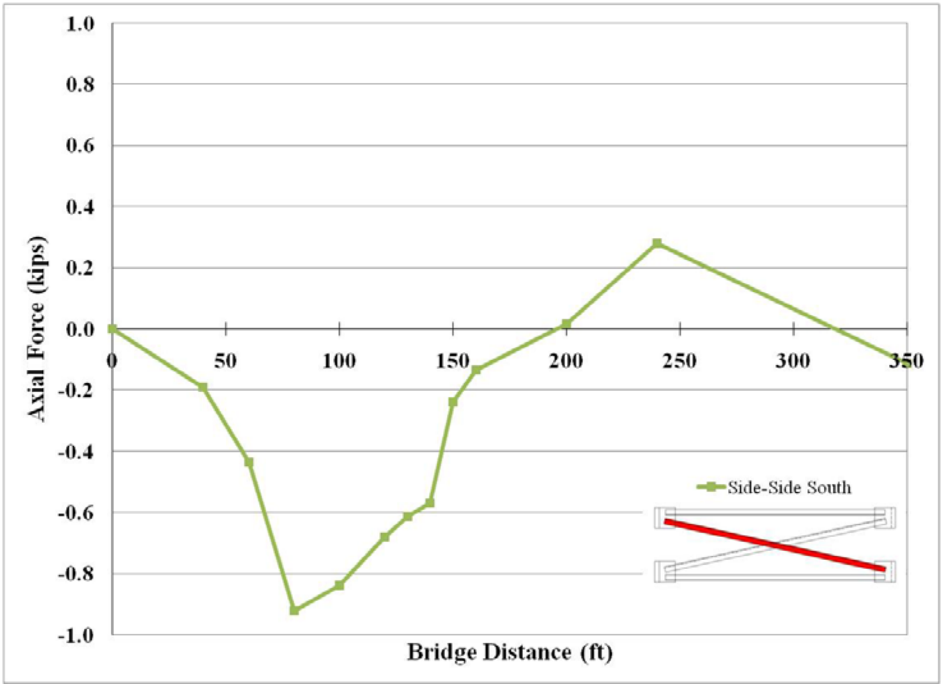


Figure A.13 Axial Force versus Bridge Distance for Top Diagonal

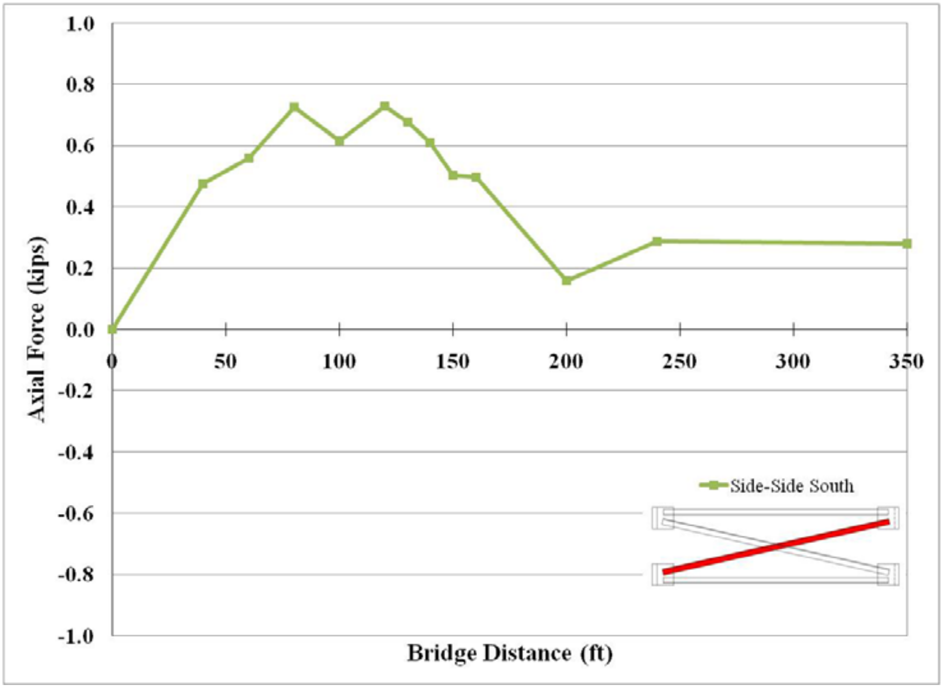


Figure A.14 Axial Force versus Bridge Distance for Bottom Diagonal

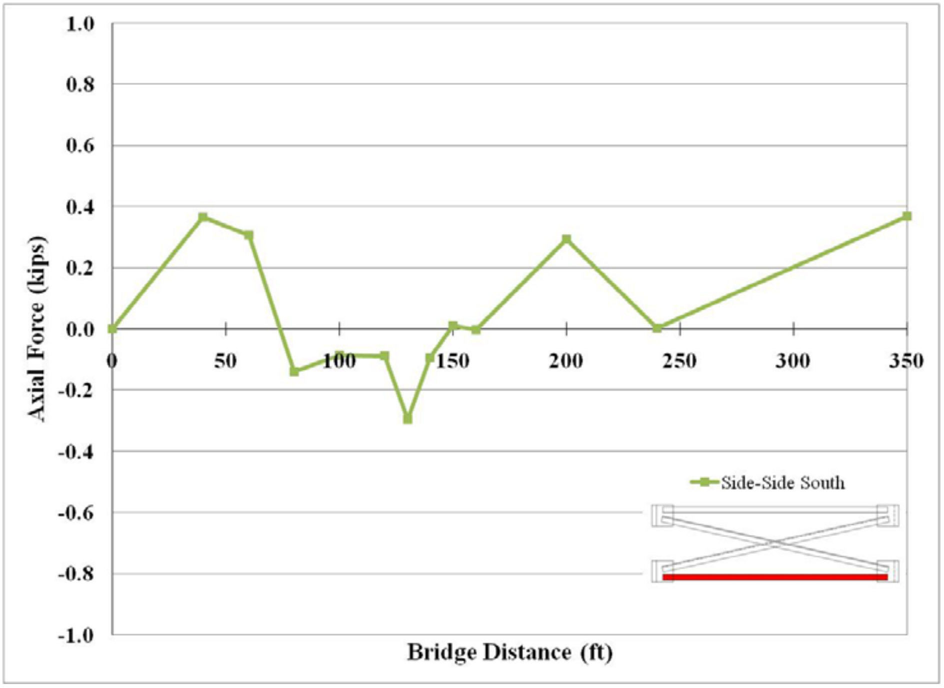


Figure A.15 Axial Force versus Bridge Distance for Bottom Strut

A.6 LIVE LOAD TEST DATA: SIDE BY SIDE (NORTH)

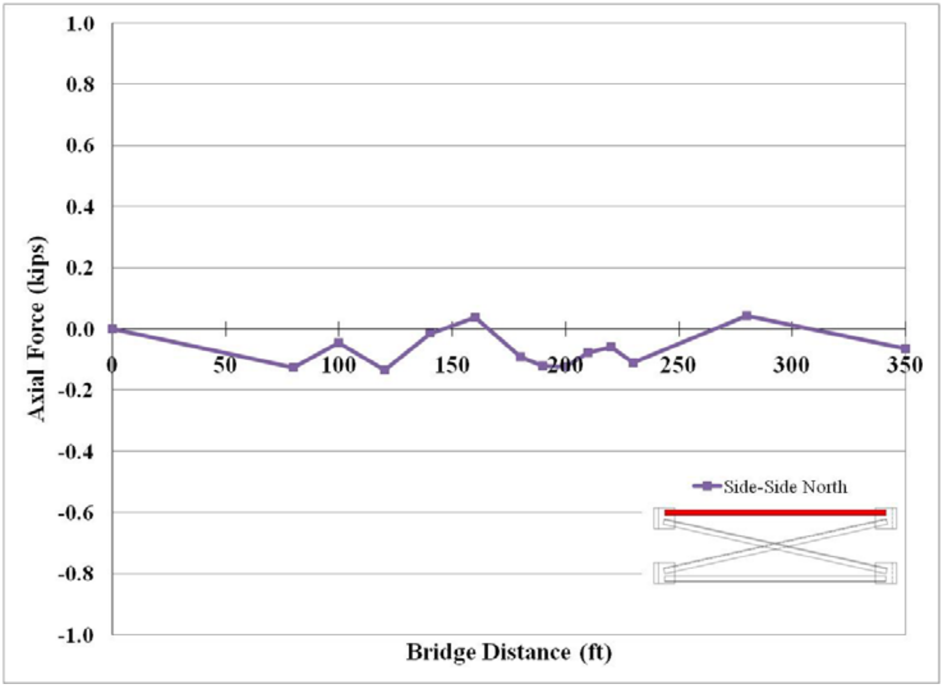


Figure A.16 Axial Force versus Bridge Distance for Top Strut

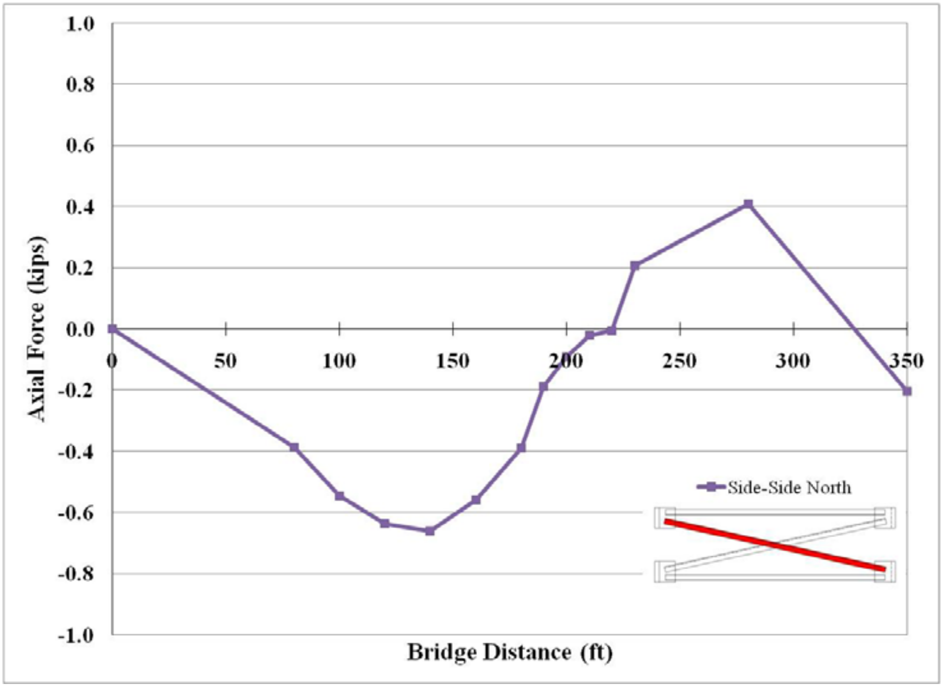


Figure A.17 Axial Force versus Bridge Distance for Top Diagonal

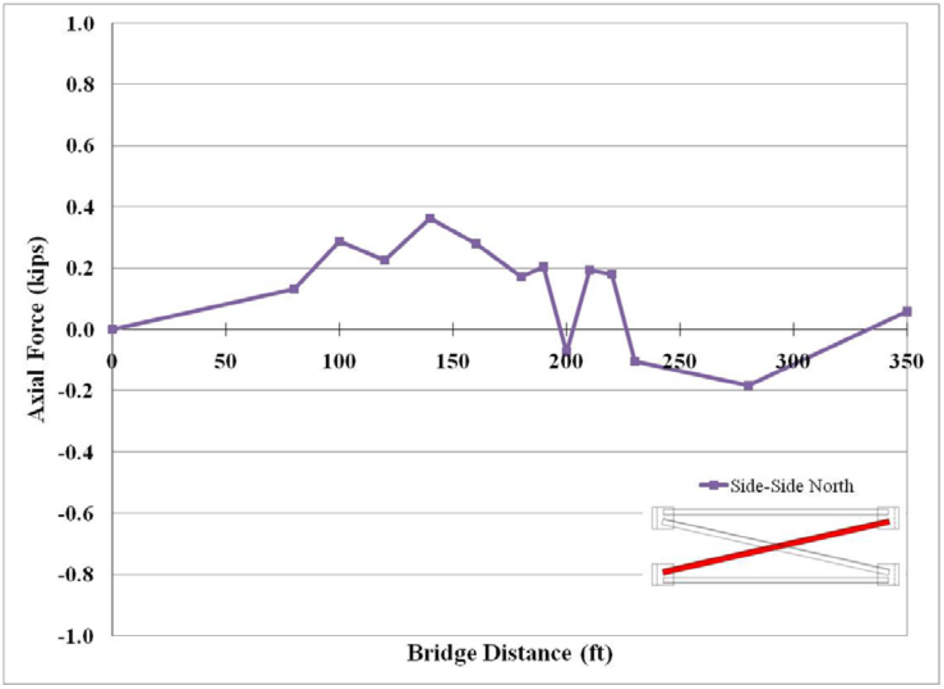


Figure A.18 Axial Force versus Bridge Distance for Bottom Diagonal

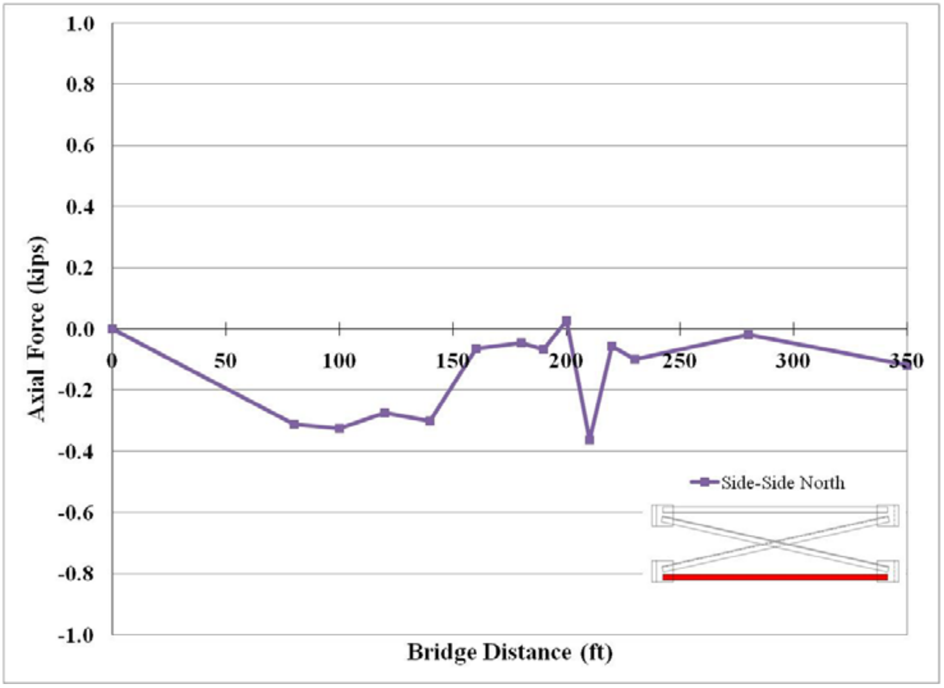


Figure A.19 Axial Force versus Bridge Distance for Bottom Strut

A.7 LIVE LOAD TEST DATA: END TO END (SOUTH)

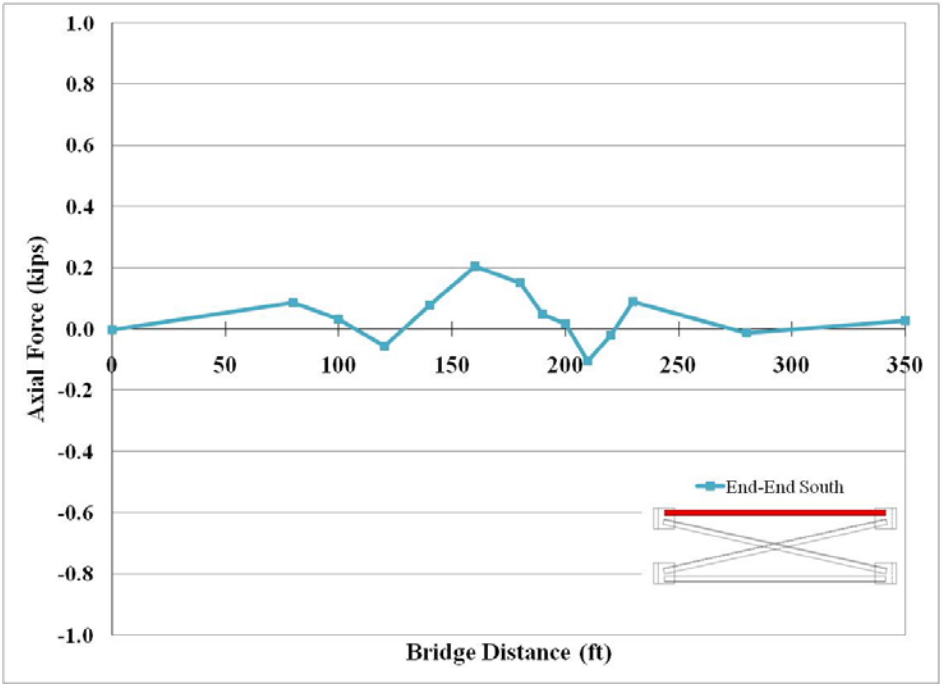


Figure A.20 Axial Force versus Bridge Distance for Top Strut

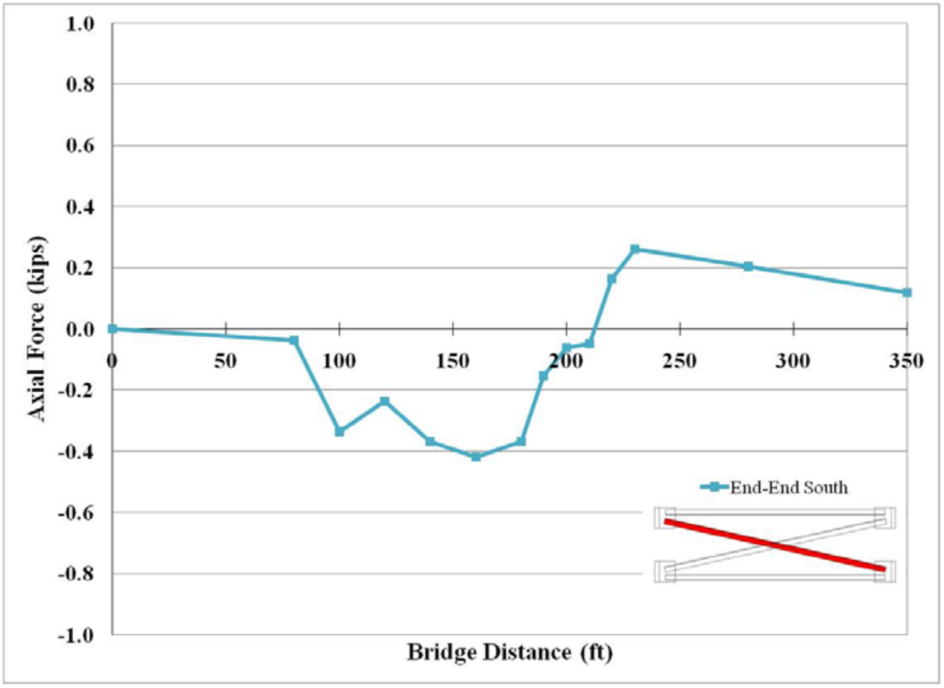


Figure A.21 Axial Force versus Bridge Distance for Top Diagonal

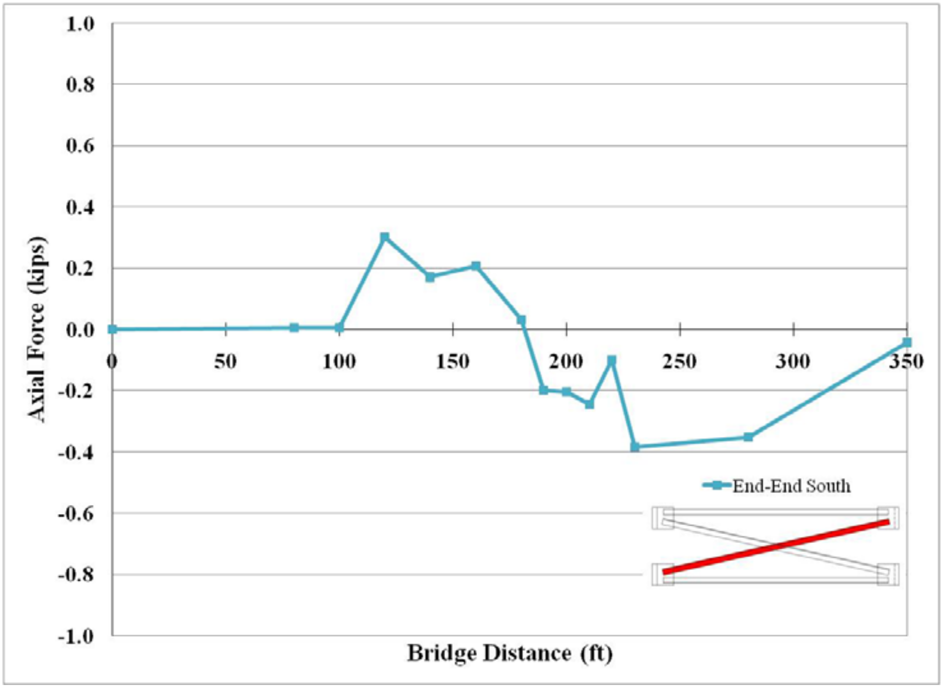


Figure A.22 Axial Force versus Bridge Distance for Bottom Diagonal

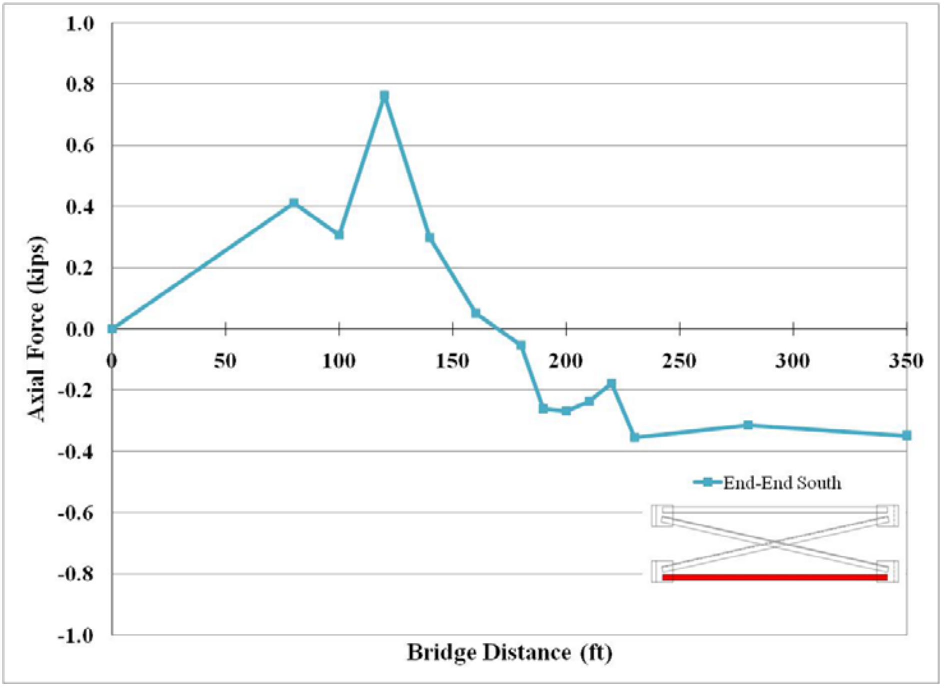


Figure A.23 Axial Force versus Bridge Distance for Bottom Strut

A.8 LIVE LOAD TEST DATA: END TO END (CENTRAL)

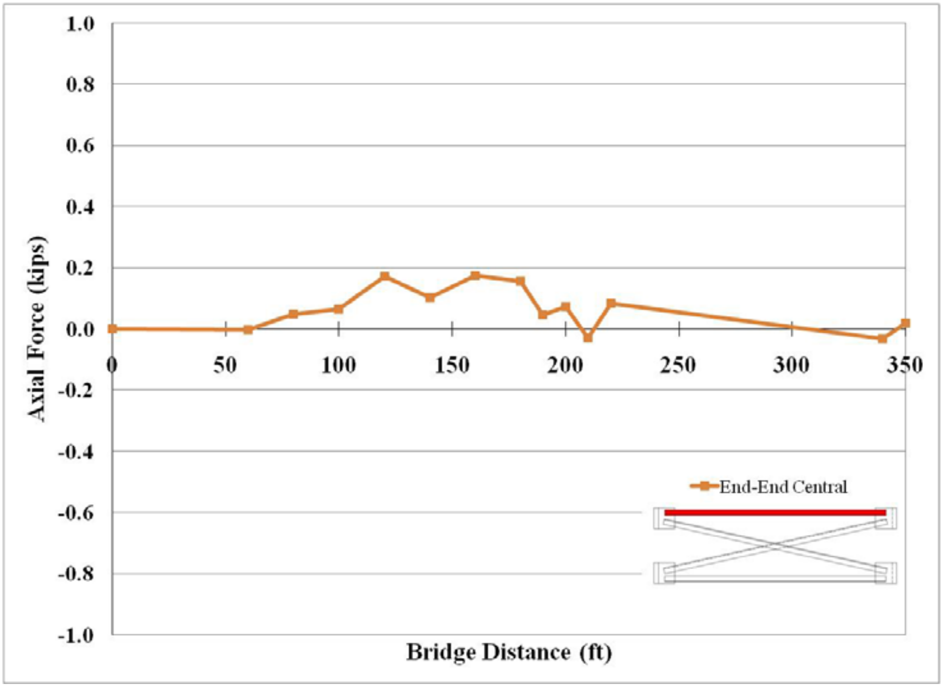


Figure A.24 Axial Force versus Bridge Distance for Top Strut

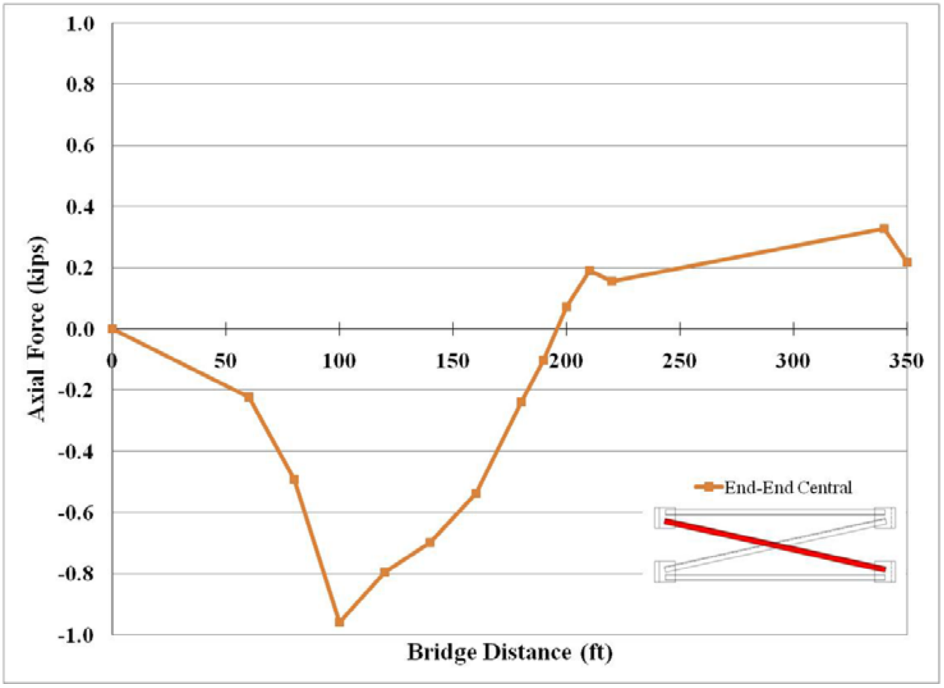


Figure A.25 Axial Force versus Bridge Distance for Top Diagonal

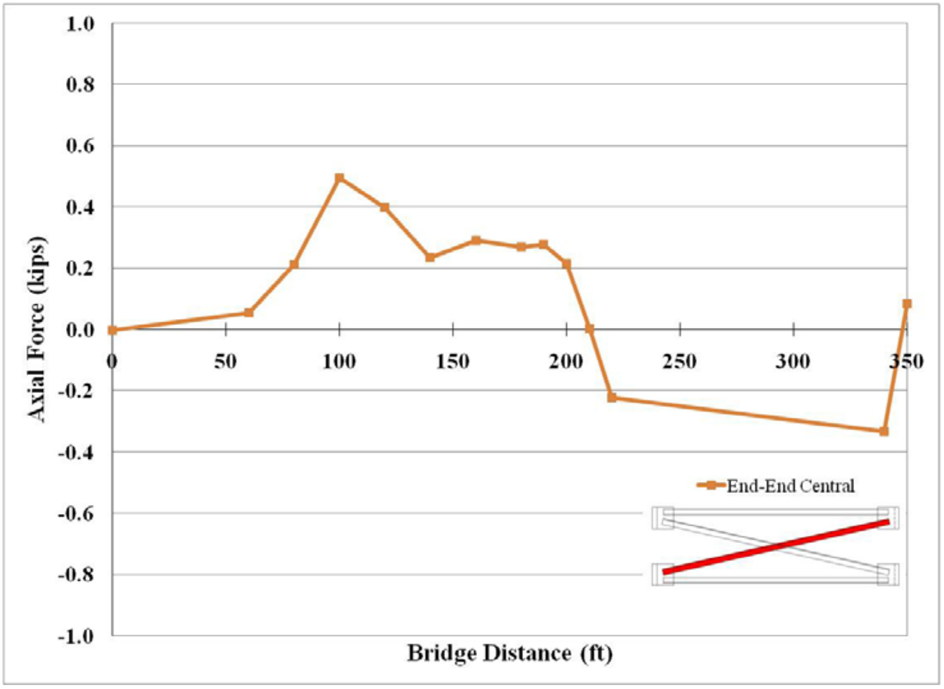


Figure A.26 Axial Force versus Bridge Distance for Bottom Diagonal

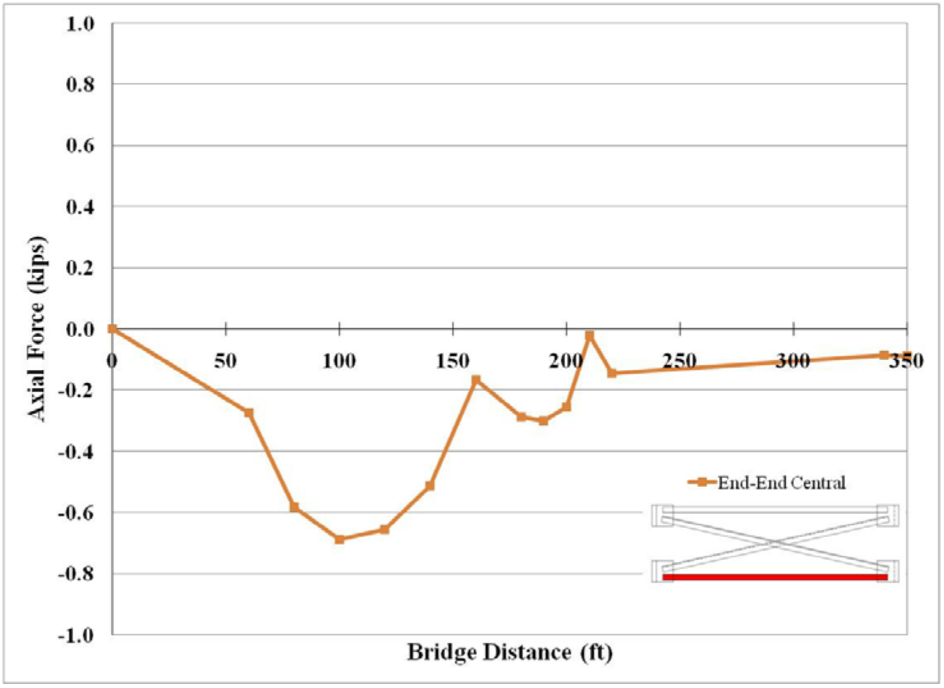


Figure A.27 Axial Force versus Bridge Distance for Bottom Strut

APPENDIX B

Laboratory Testing Results

B.1 BENT PLATE DETAIL: EFFECT OF SKEW ANGLE

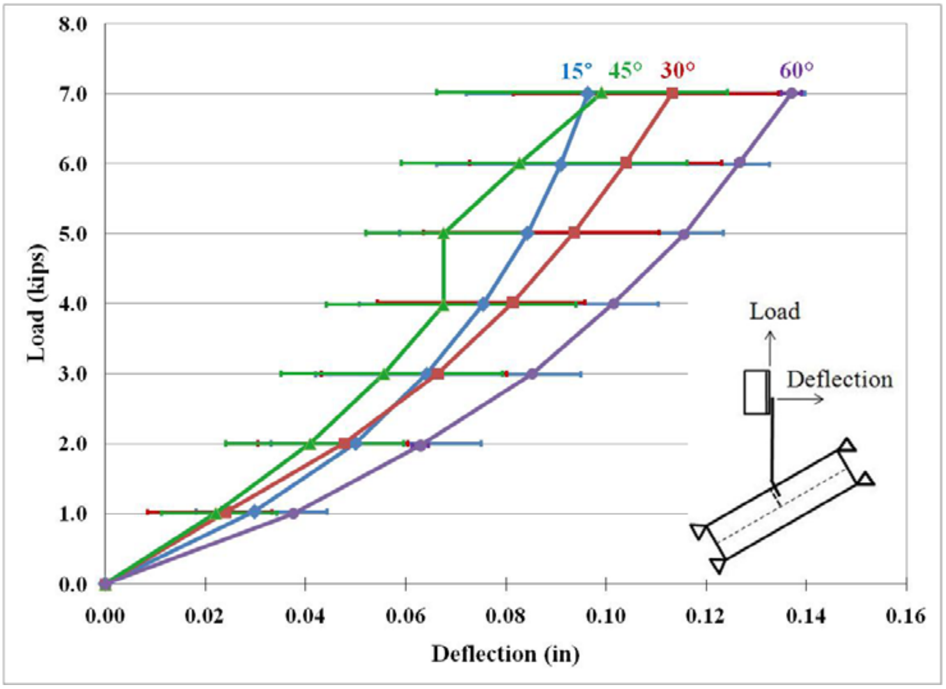


Figure B.1 Horizontal Deflection at the Top of the Bent Plate vs. Load

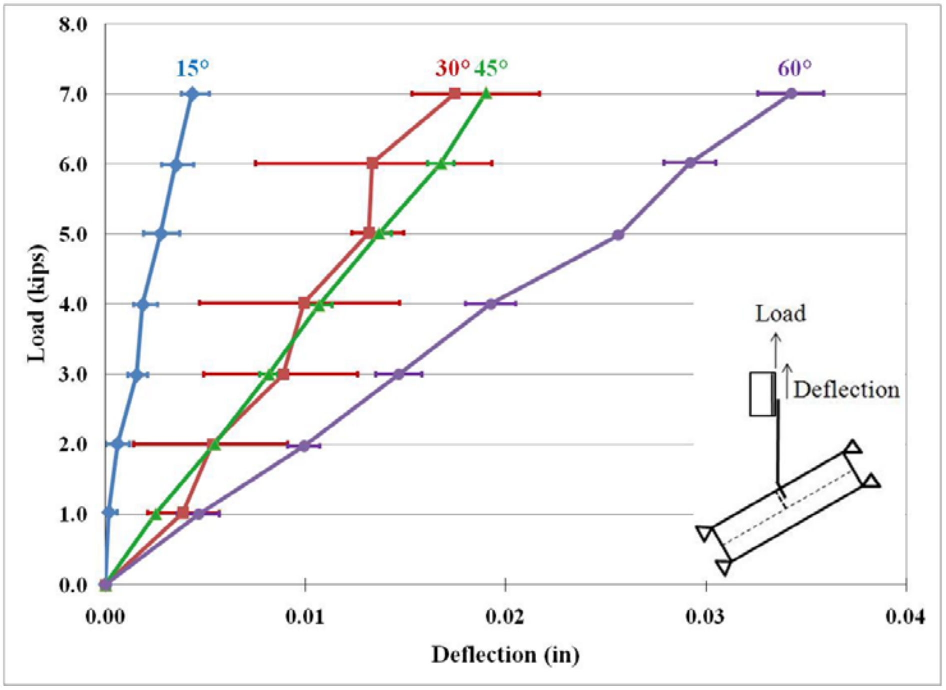


Figure B.2 Vertical Deflection at the Top of the Bent Plate vs. Load

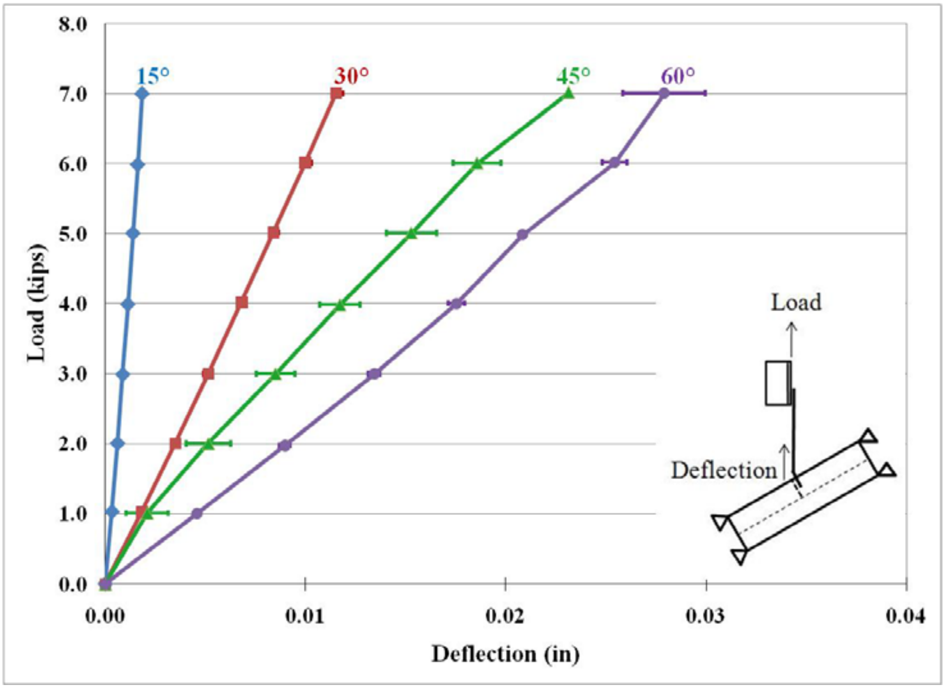


Figure B.3 Vertical Deflection at the Top of the Stiffener vs. Load

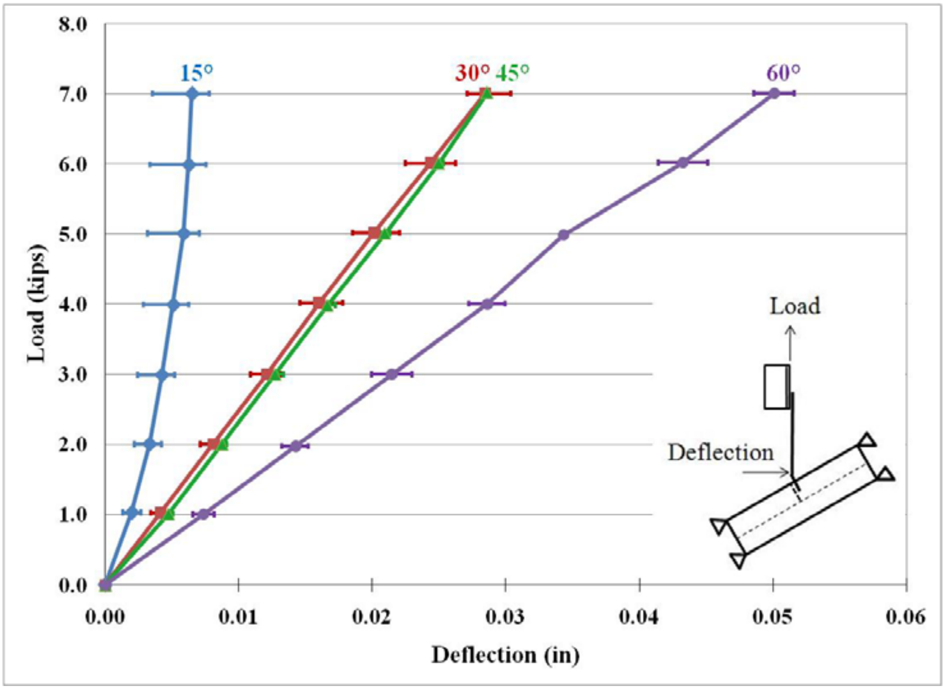


Figure B.4 Horizontal Deflection at the Bottom of the Bent Plate vs. Load

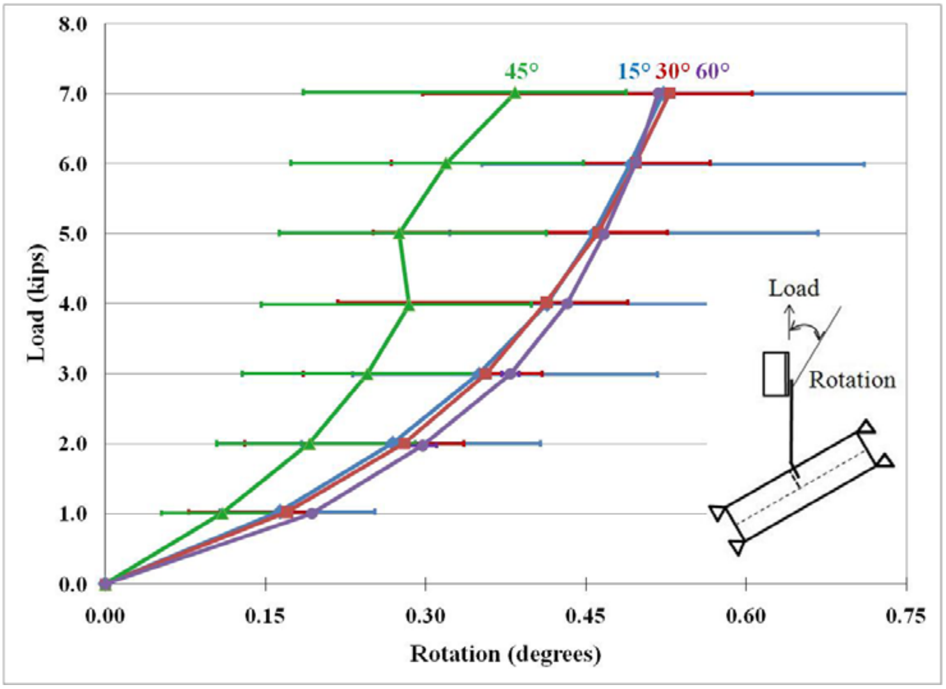


Figure B.5 Rotation at the Top of the Bent Plate vs. Load

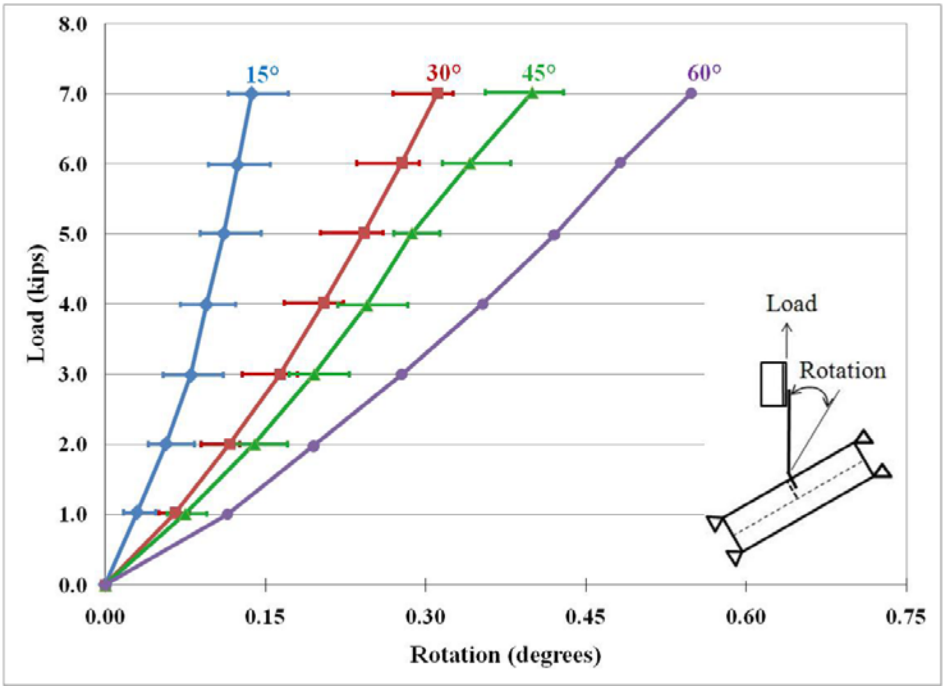


Figure B.6 Rotation at the Bottom of the Bent Plate vs. Load

B.2 BENT PLATE DETAIL: EFFECT OF BEND RADIUS

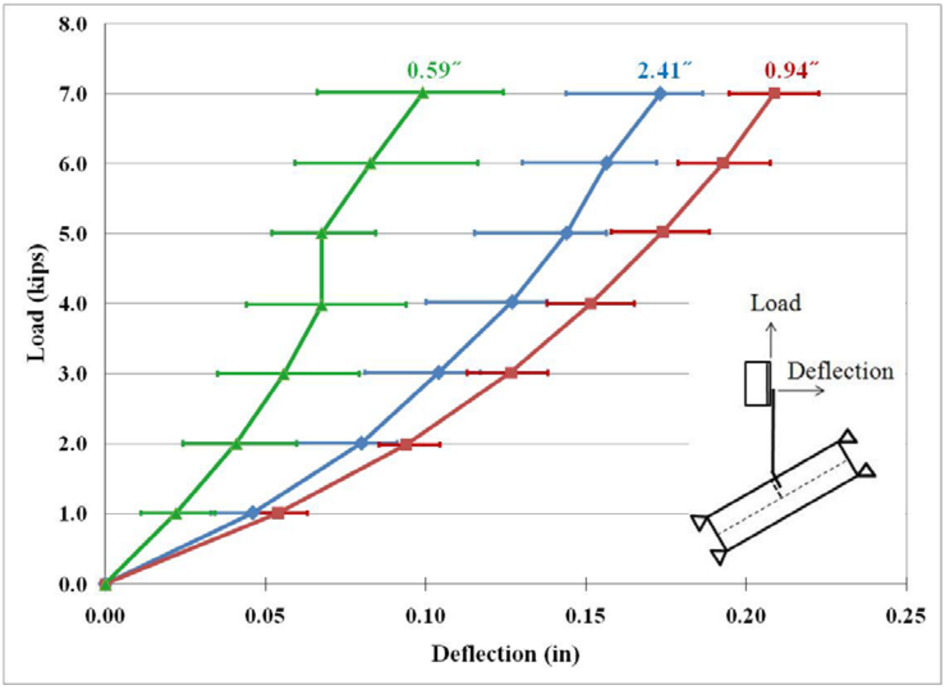


Figure B.7 Horizontal Deflection at the Top of the Bent Plate vs. Load

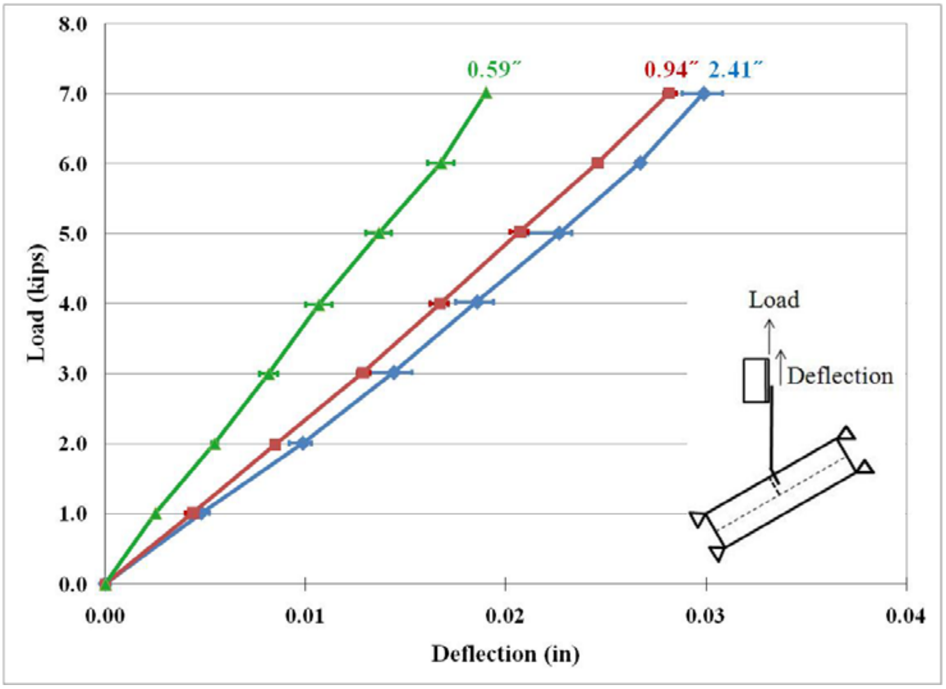


Figure B.8 Vertical Deflection at the Top of the Bent Plate vs. Load

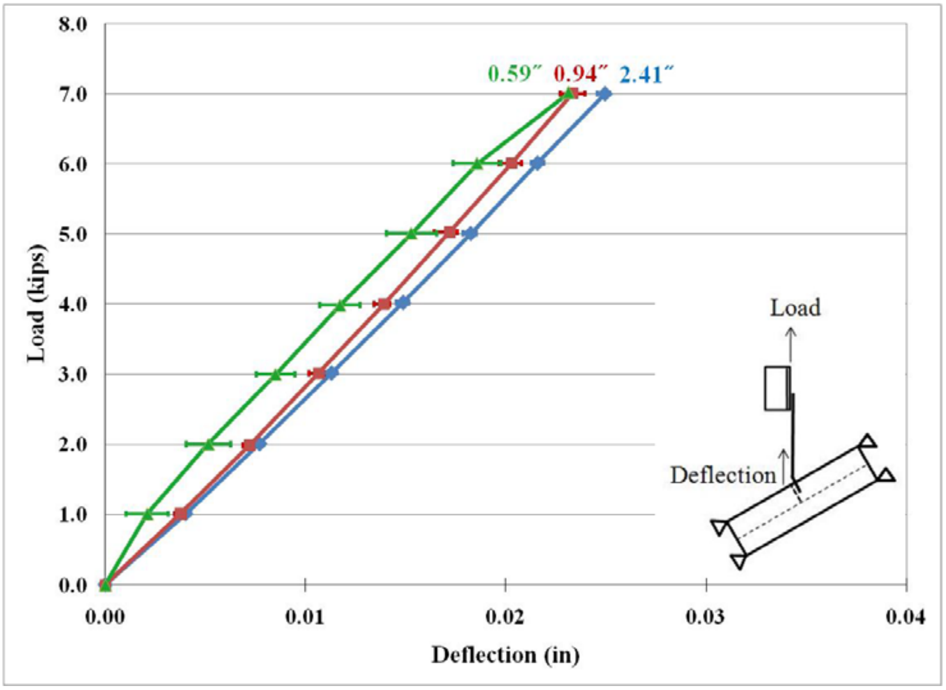


Figure B.9 Vertical Deflection at the Top of the Stiffener vs. Load

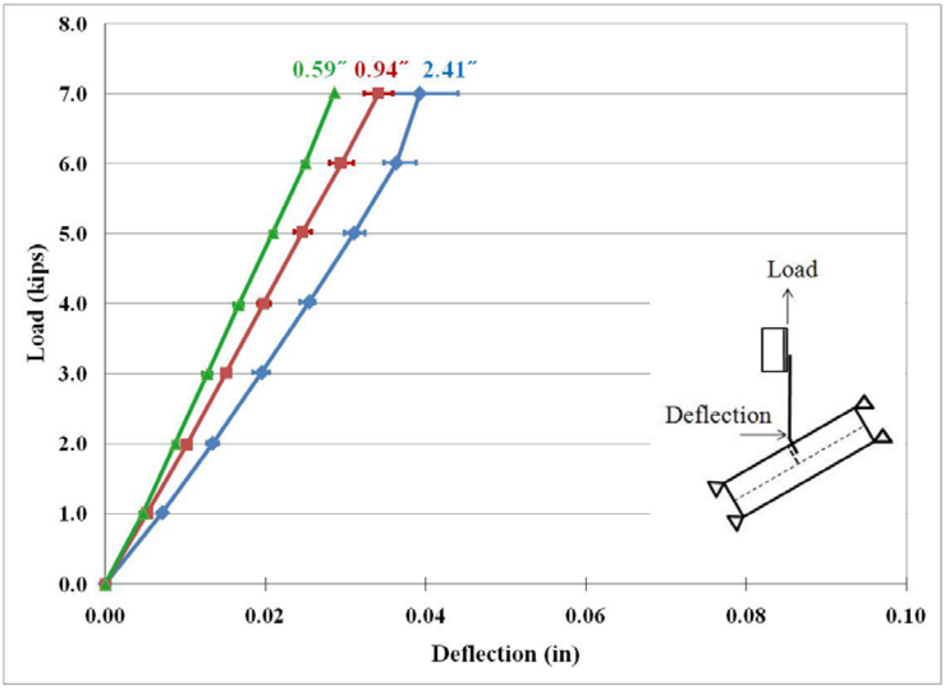


Figure B.10 Horizontal Deflection at the Bottom of the Bent Plate vs. Load

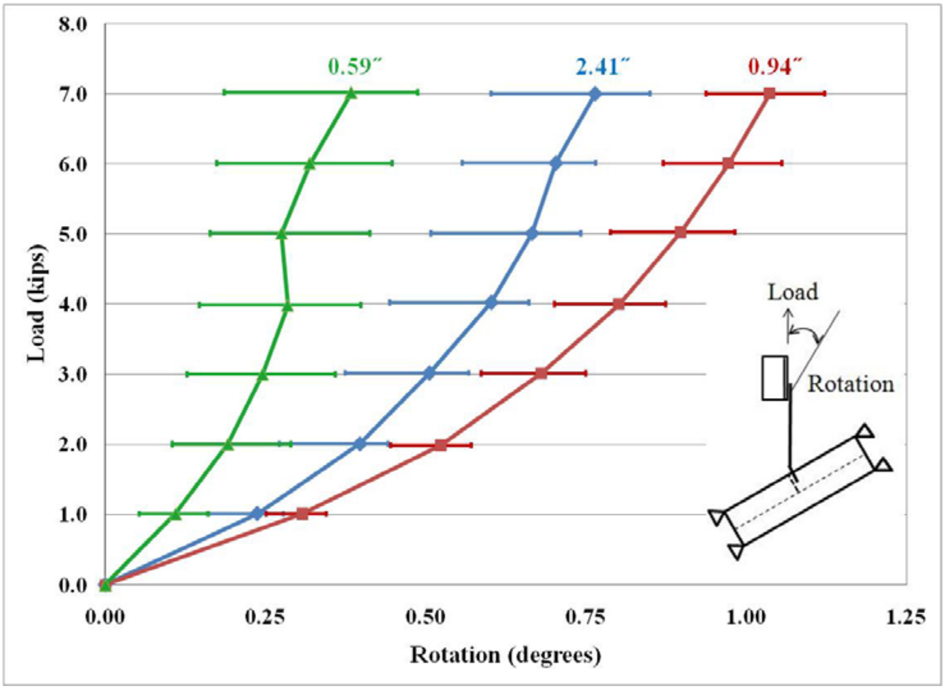


Figure B.11 Rotation at the Top of the Bent Plate vs. Load

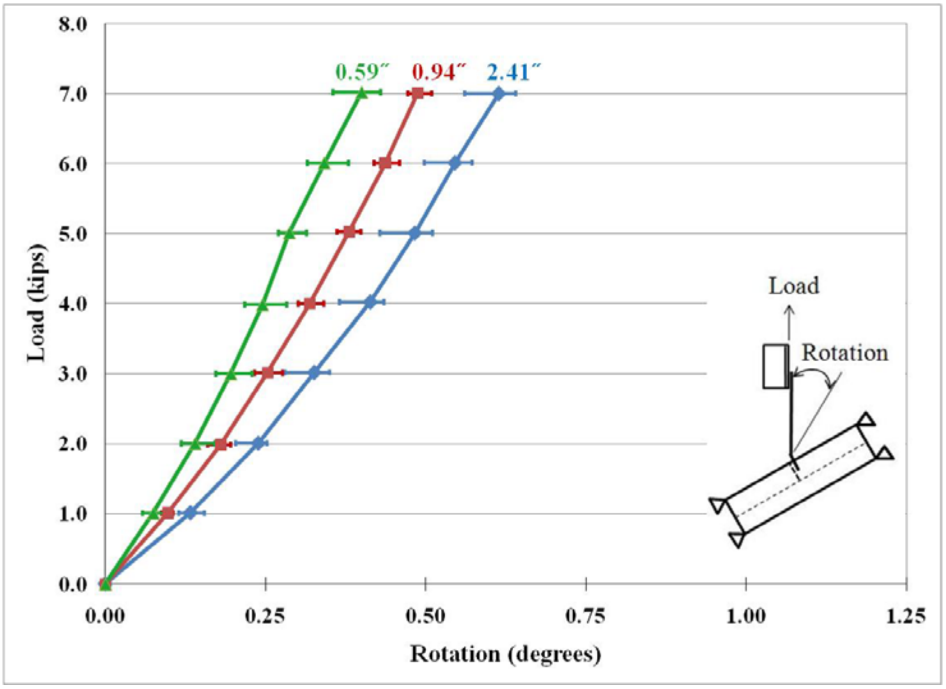


Figure B.12 Rotation at the Bottom of the Bent Plate vs. Load

B.3 BENT PLATE DETAIL: EFFECT OF BOLTED AND WELDED CONSTRUCTION

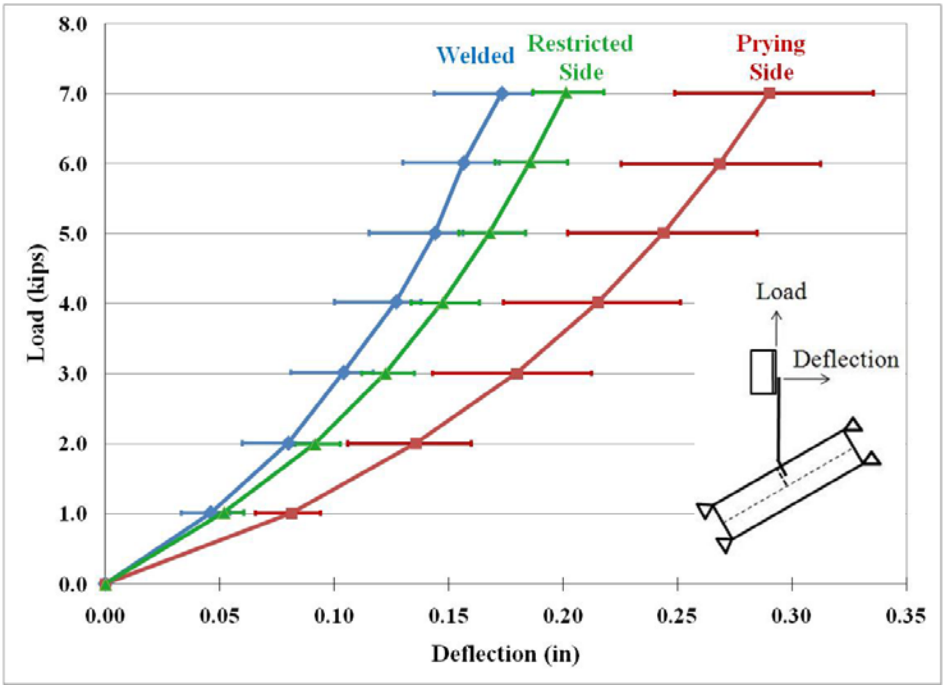


Figure B.13 Horizontal Deflection at the Top of the Bent Plate vs. Load

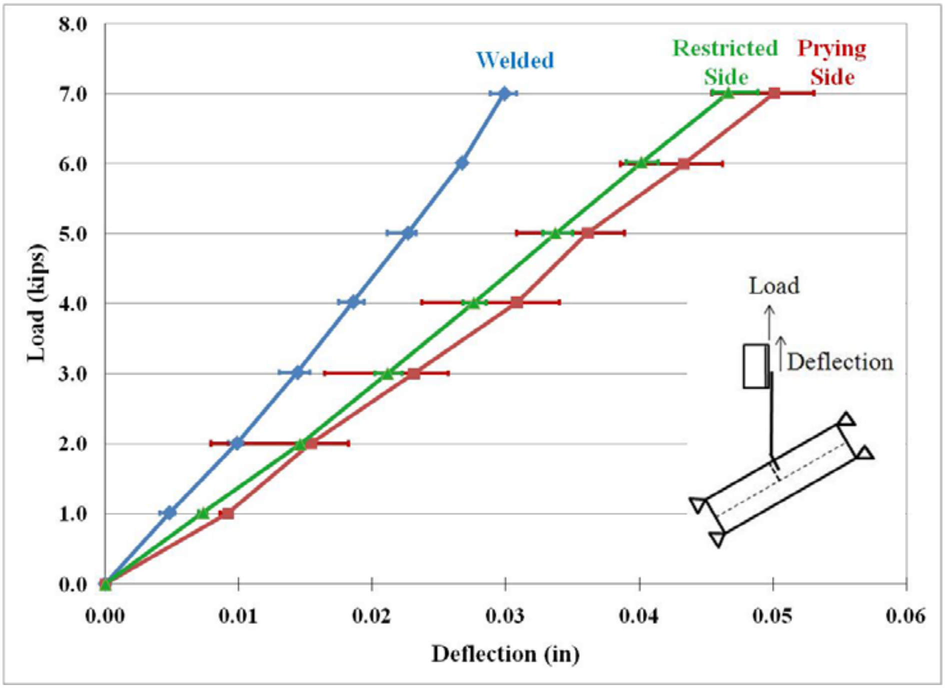


Figure B.14 Vertical Deflection at the Top of the Bent Plate vs. Load

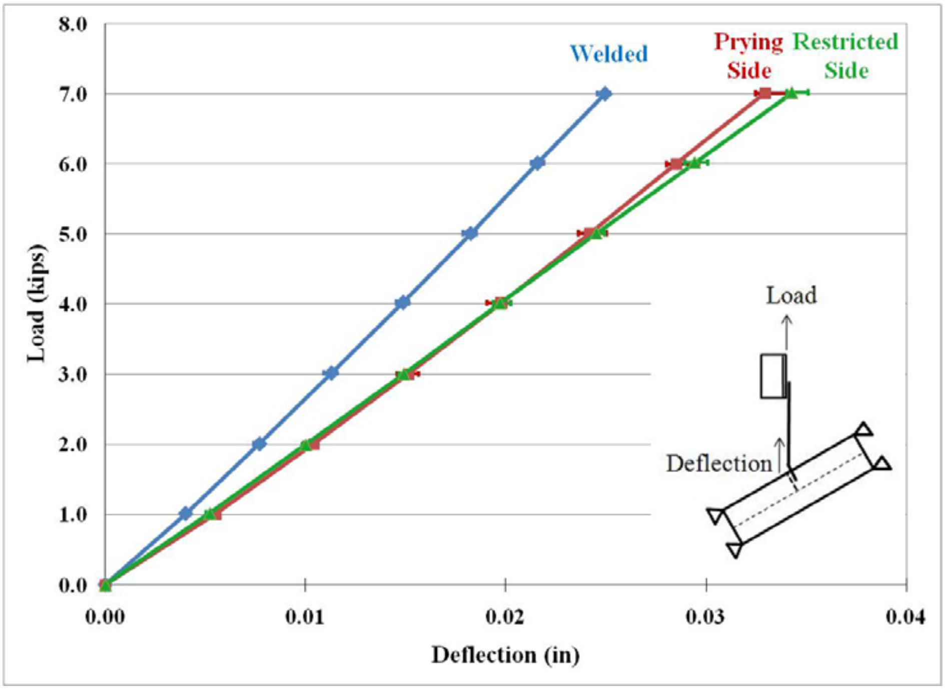


Figure B.15 Vertical Deflection at the Top of the Stiffener vs. Load

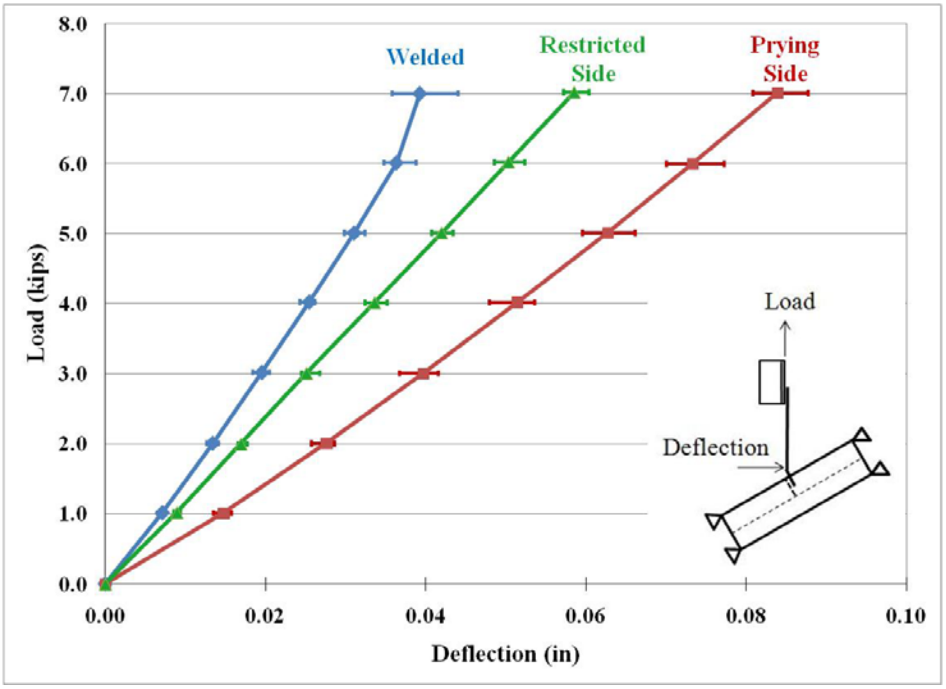


Figure B.16 Horizontal Deflection at the Bottom of the Bent Plate vs. Load

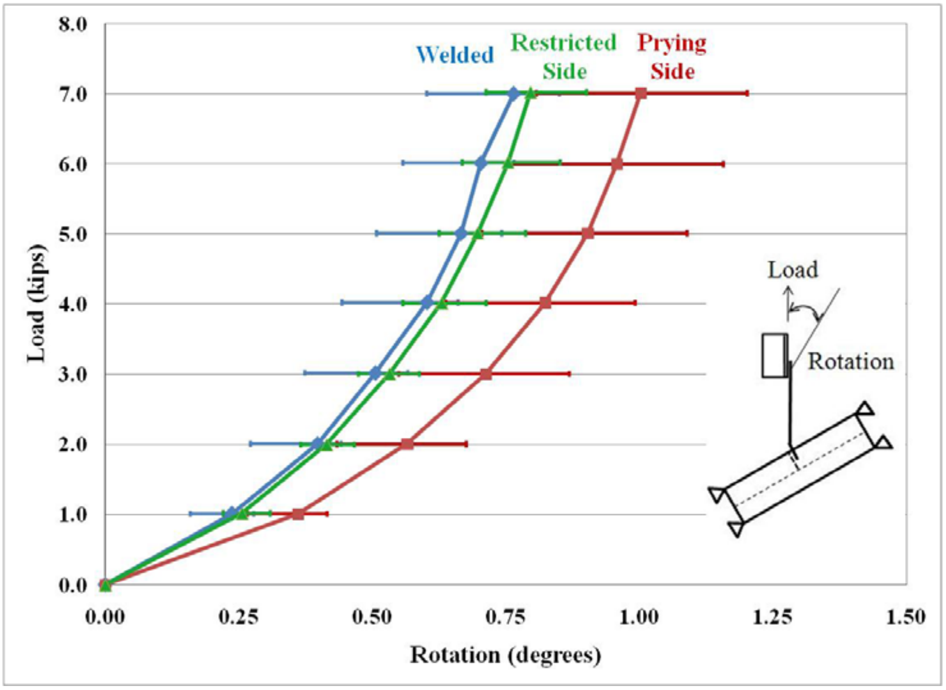


Figure B.17 Rotation at the Top of the Bent Plate vs. Load

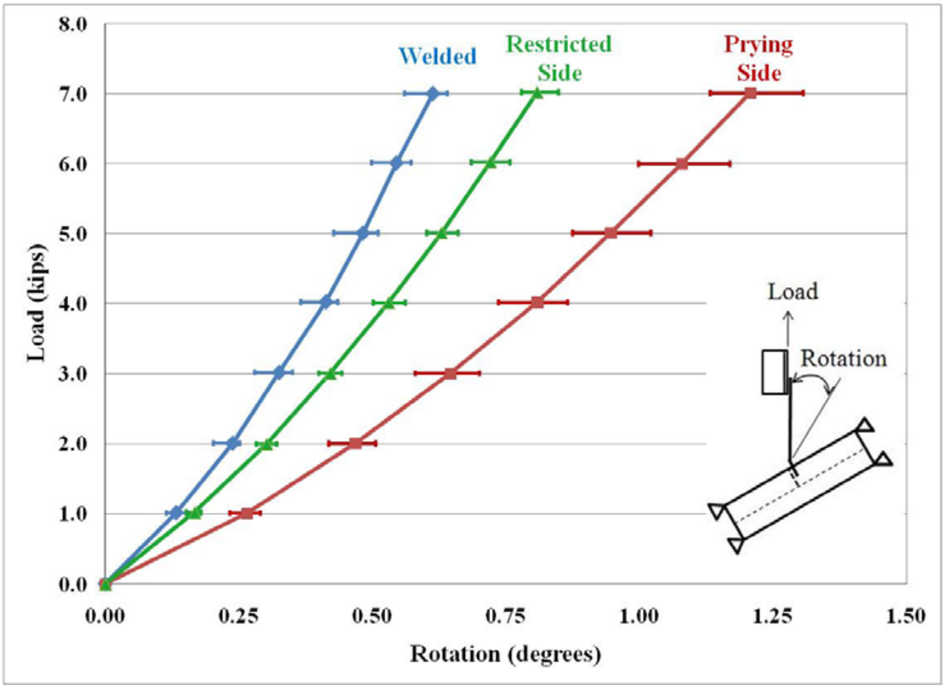


Figure B.18 Rotation at the Bottom of the Bent Plate vs. Load

B.4 HALF PIPE STIFFENER DETAIL: EFFECT OF SKEW ANGLE

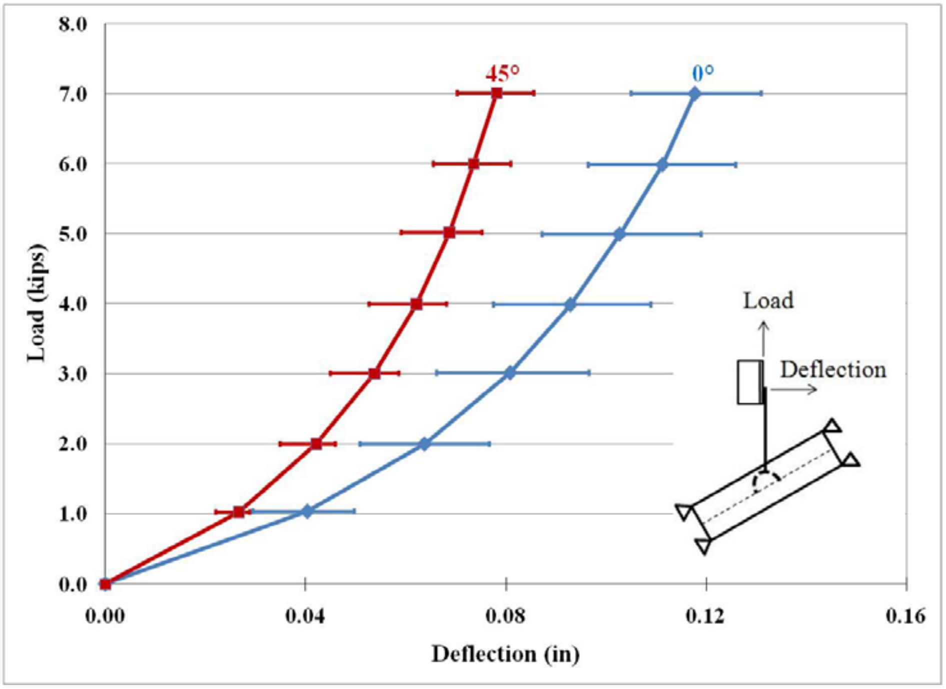


Figure B.19 Horizontal Deflection at the Top of the Plate vs. Load

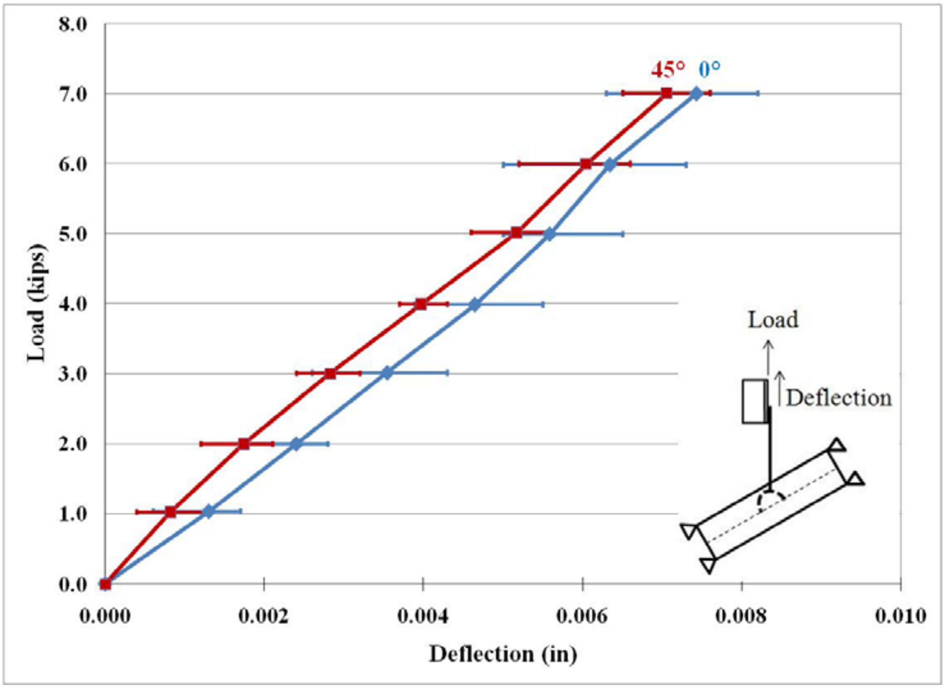


Figure B.20 Vertical Deflection at the Top of the Plate vs. Load

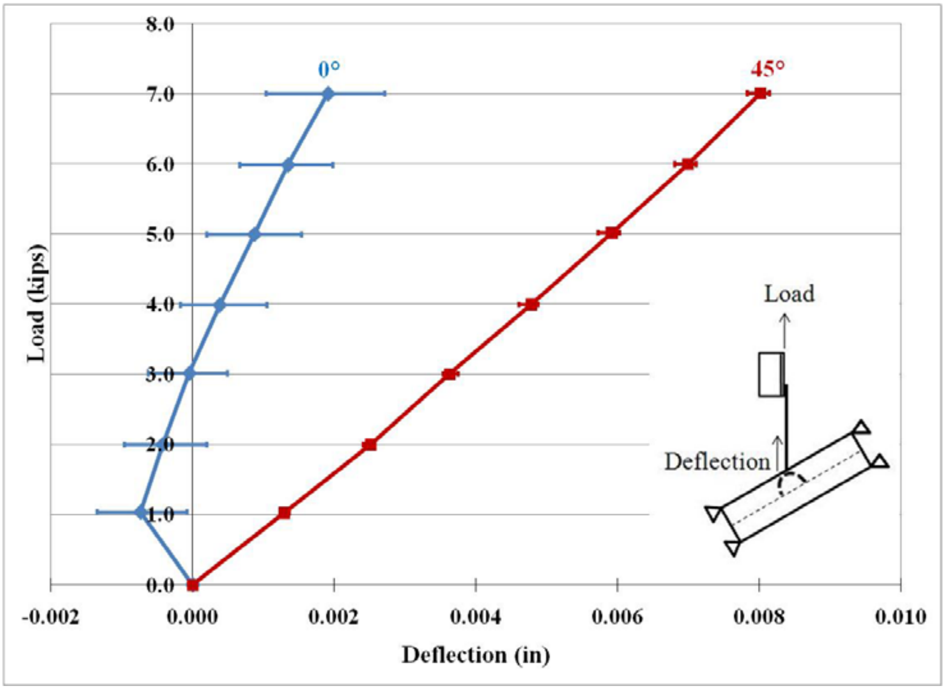


Figure B.21 Vertical Deflection at the Top of the Stiffener vs. Load

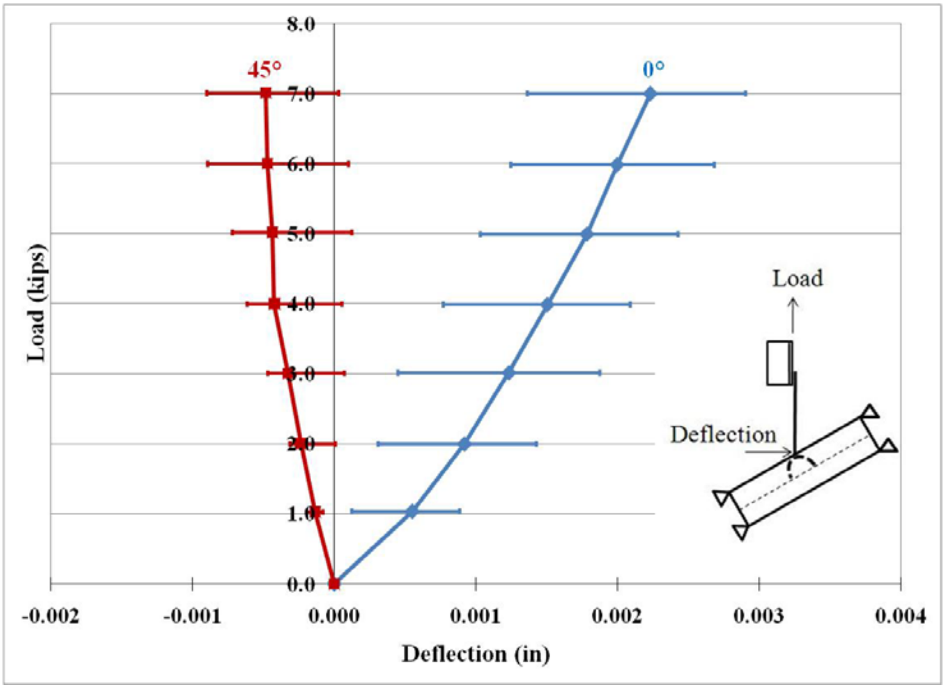


Figure B.22 Horizontal Deflection at the Bottom of the Plate vs. Load

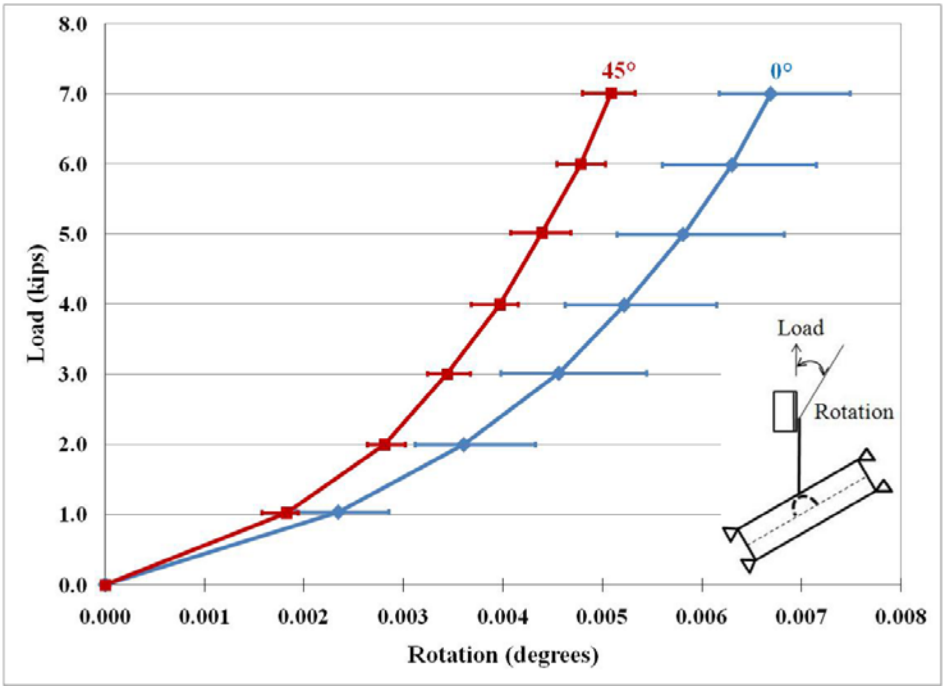


Figure B.23 Rotation at the Top of the Plate vs. Load

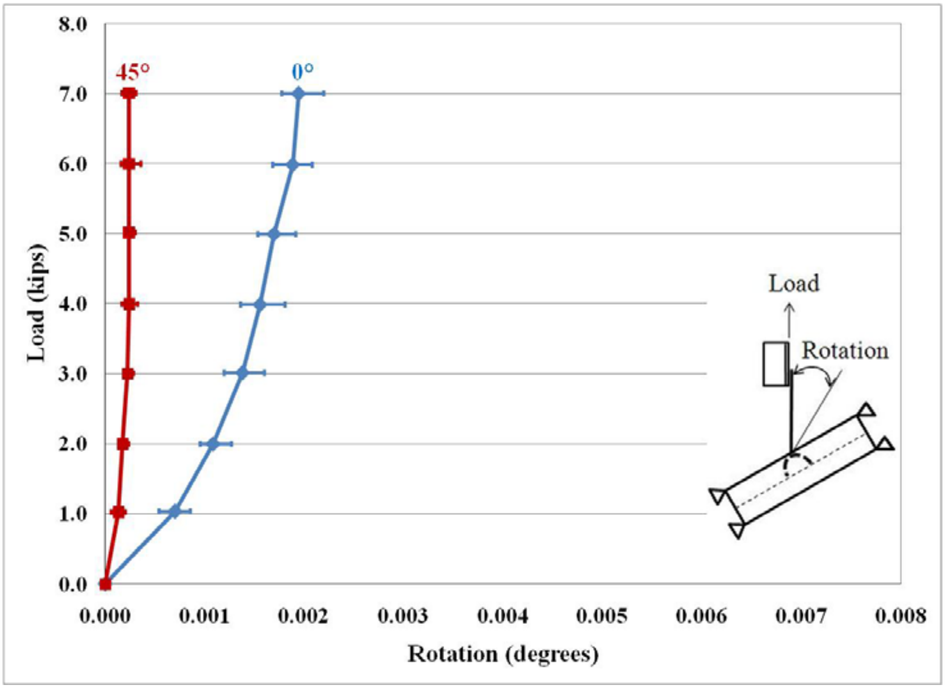


Figure B.24 Rotation at the Bottom of the Plate vs. Load

B.5 COMPARISON OF BENT PLATE AND HALF PIPE STIFFENER DETAILS

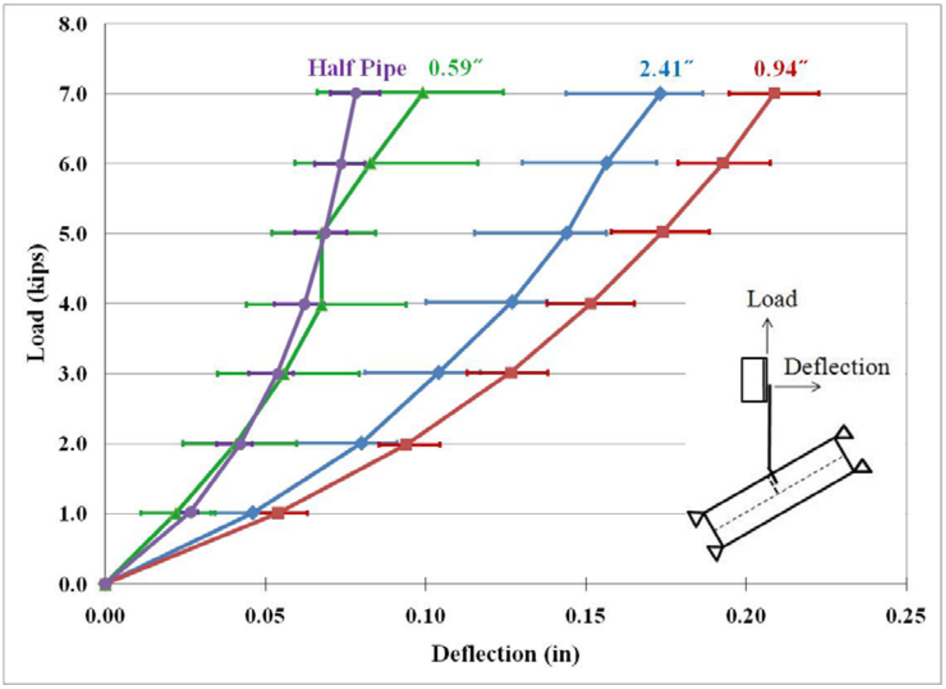


Figure B.25 Horizontal Deflection at the Top of the Plate vs. Load

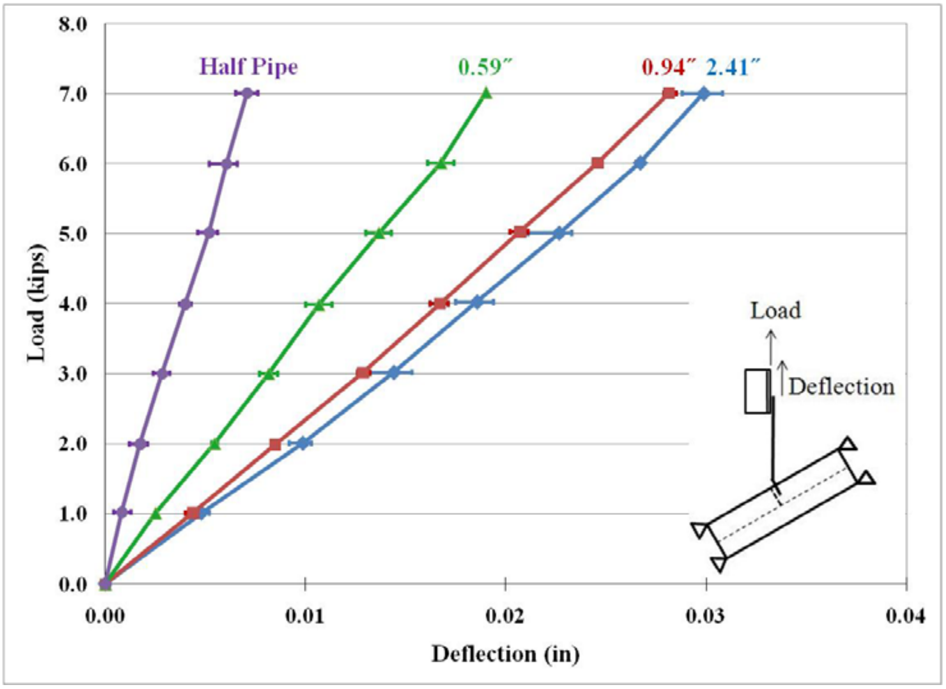


Figure B.26 Vertical Deflection at the Top of the Plate vs. Load

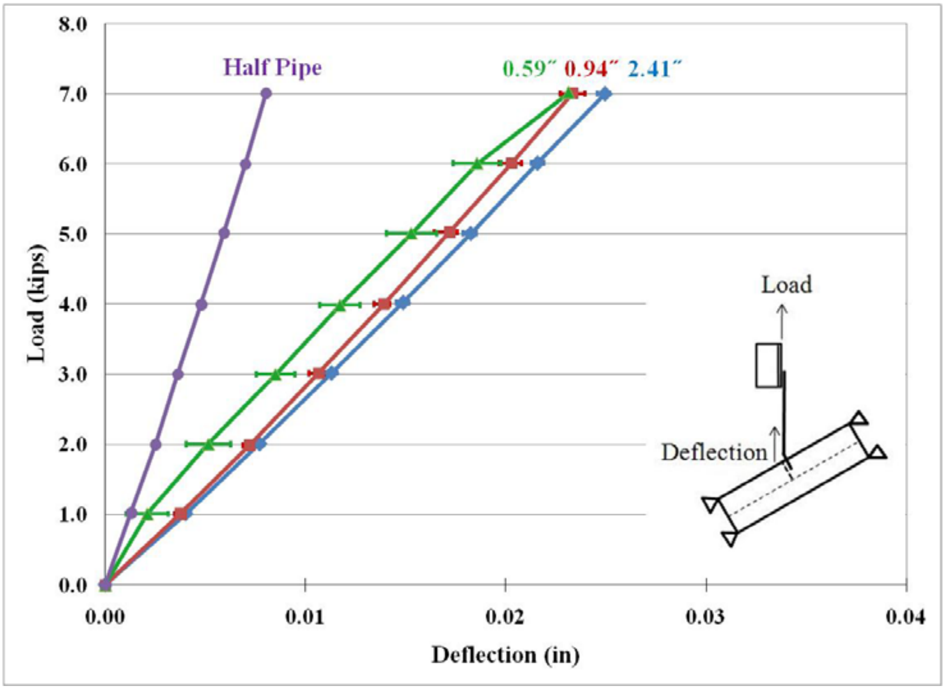


Figure B.27 Vertical Deflection at the Top of the Stiffener vs. Load

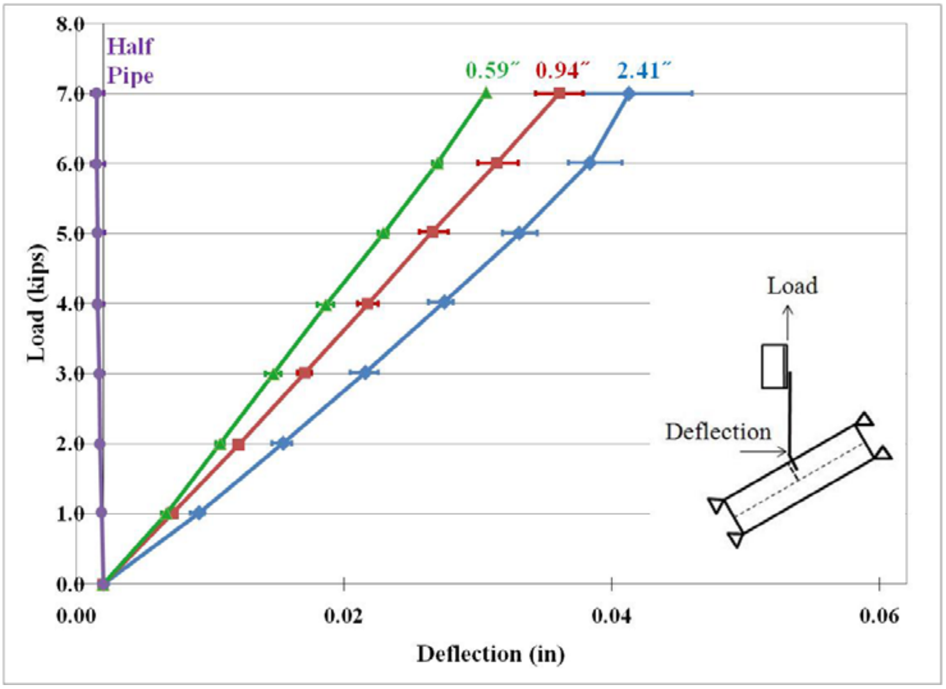


Figure B.28 Horizontal Deflection at the Bottom of the Plate vs. Load

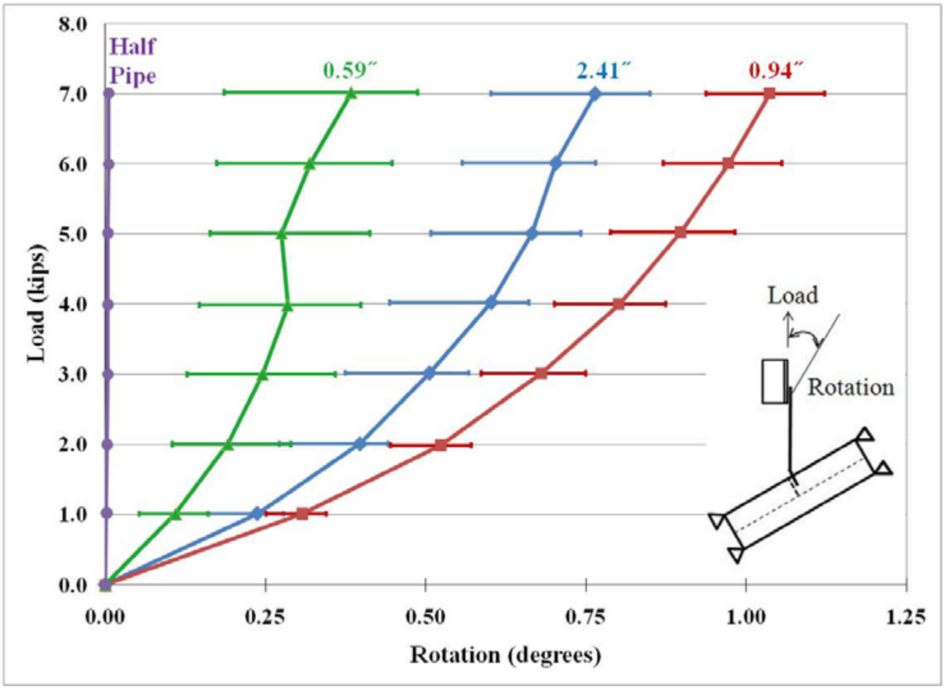


Figure B.29 Rotation at the Top of the Plate vs. Load

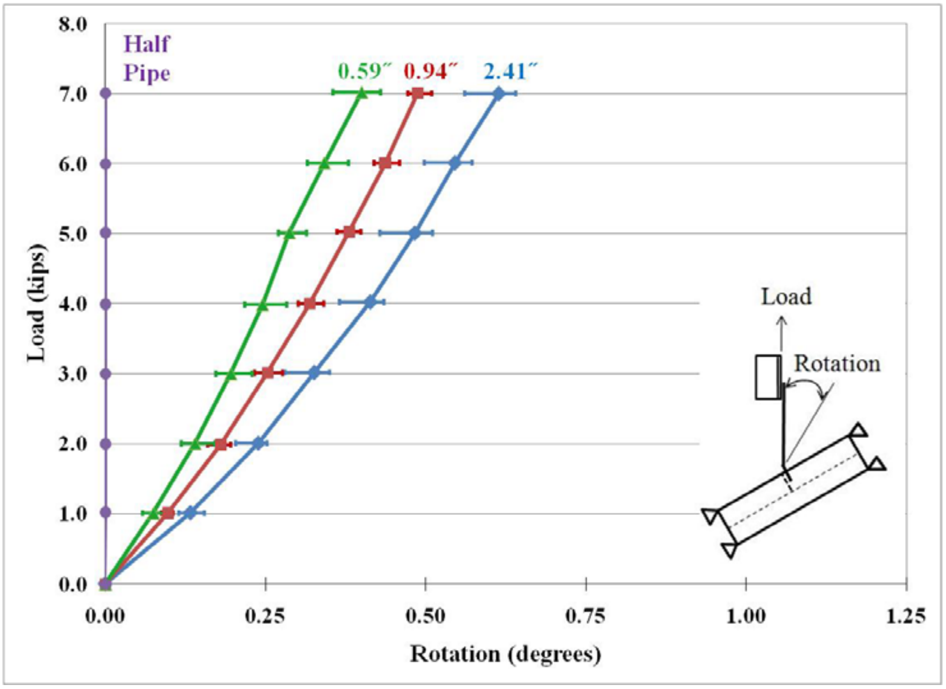


Figure B.30 Rotation at the Bottom of the Plate vs. Load

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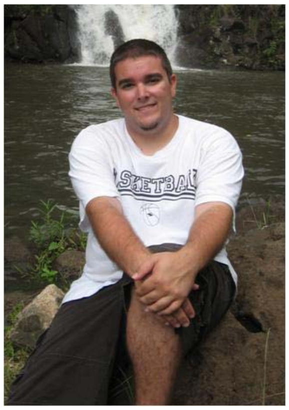

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