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# Effect of Imperfection on X-Type Cross Frame Forces in Two-Span Continuous Steel I Girder Bridge Systems

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**Abstract**

Cross frames are used in steel bridges to improve the stability of the girder by providing lateral and torsional restraint at discrete points along the girder length. To establish the strength requirements for the cross frame members, large displacement analyses on imperfect systems can be performed. The selection of the imperfection magnitude and shape can significantly impact the forces developed in the braces.

To maximize the cross frame forces, previous research on simply supported spans suggested applying the critical imperfection at the brace nearest to the location of the maximum moment, with zero twist at the adjacent brace points. The recommended imperfection shape was a pure twist, where the bottom flange remains perfectly straight while the top flange displaces laterally. However, in two-span continuous girders, the location of maximum moment typically occurs at the center support, a location which is not likely to have the critical imperfection. In addition, in the negative moment region, the compression flange will correspond to the bottom flange instead of the top flange, potentially changing the critical shape.

In order to provide guidance on maximizing cross frame forces in two-span continuous steel I-girder bridge systems, various imperfection locations and magnitudes will be studied using a three-dimensional finite element analysis program. Preliminary results of cross frame forces for both straight and skewed bridge layouts are provided.

## 1. Introduction

To increase the resistance of steel I girder bridge systems to lateral torsional buckling, cross frames are typically provided along the length. To be an effective brace, the cross frame must provide adequate stiffness and strength (Winter 1958). The X-type cross frame is frequently used to provide both lateral and torsional restraint at the cross frame location. As the load on one girder approaches its buckling capacity, the cross section will begin to twist. By inserting X-type

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cross frames that connect to adjacent girders, the girder attempting to buckle will be restrained by the adjacent girders which will not want to twist. An example of an X-type cross frame is shown in Fig. 1.

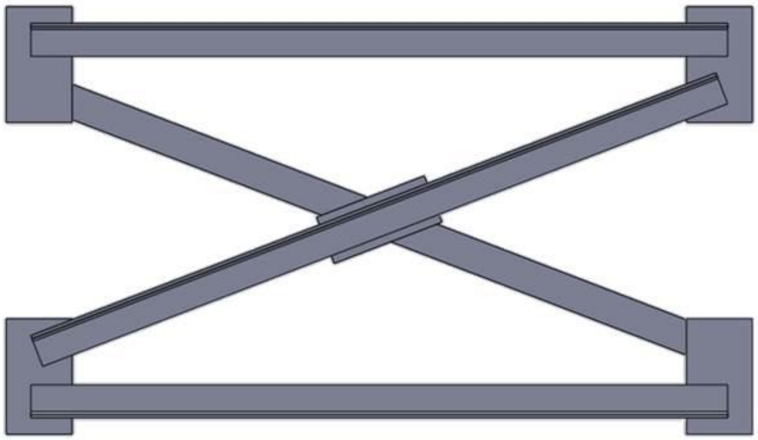

Figure 1: Typical X-Type Cross Frame with Steel Angles

To determine the stiffness requirements for cross frames, an eigenvalue analysis is often performed, which will provide the minimum stiffness necessary for the brace so that the predominant buckling mode will result in beam buckling between the brace points. This minimum stiffness is referred to as the *ideal brace stiffness*. Previous research has established that only using the ideal stiffness may result in very large deflections and subsequently large brace forces (Yura 2001). Therefore, it is recommended that the brace stiffness provided be at least twice the ideal stiffness to improve the behavior of the system.

When performing the eigenvalue analysis, the geometry of the girder does not have a significant impact on determining the brace stiffness requirements. The analysis is usually done on an assumed perfectly straight member. However, determining the magnitude of the brace forces generally requires a large displacement analysis on an imperfect member. Since both the magnitude and shape of the imperfection can have a significant impact on the resulting forces, deciding which imperfection to use can be difficult. The following paper summarizes some pertinent information regarding the choice of imperfection for single span girders and begins to establish guidance on selecting the critical shape of the imperfection for two-span continuous systems. Preliminary results from the study are also presented.

## 2. Background

Computational analyses performed by Wang and Helwig (2005) helped to establish guidance on choosing the critical shape of the imperfection for single span systems. The *critical imperfection* is defined as the shape of the imperfection that maximizes the stability brace forces. For a given girder system and loading, the two main factors which affect the magnitude of the brace forces are the shape of the cross sectional imperfection and the distribution along the length (Wang and Helwig 2005). In order to define the critical imperfection, both lateral sweep and twist of the girders were considered.

The finite element study examined six different critical imperfections for three different sizes of cross sections. Each imperfection had different magnitudes of lateral sweep and/or cross sectional twist. The analysis considered a twin I girder simply-supported system with a point load applied at midspan and a singular brace at midspan. It was determined from the study that the critical imperfection consists of a lateral sweep of the compression flange of the girder, while the tension flange remains perfectly straight. The results further recommend that the magnitude of the sweep be $L_b/500$, where $L_b$ is the length between brace points (Wang and Helwig 2005). The magnitude is consistent with the AISC Code of Standard Practice (2010).

The study further went on to examine simply-supported twin girder systems with multiple brace locations and load conditions (uniform moment, distributed load, and point load at midspan). In each case, the brace forces were maximized by applying the suggested imperfection at the brace nearest the location of the largest static moment from the applied load, while keeping the cross sections at the other brace locations perfectly straight (Wang and Helwig 2005). The maximum brace forces for the entire system would occur at the location of the imperfection.

Lastly, Wang and Helwig (2005) observed that the brace forces were generally linear with the magnitude of the applied sweep to the compression flange. For instance, if an imperfection of $L_b/250$ is used rather than the suggested $L_b/500$, the measured brace forces will be twice as large. Being able to scale the forces is useful for engineers if there is reason to believe a different imperfection magnitude exists.

## 3. Finite Element Model and Analysis Procedures

Before discussing the preliminary results of the analysis, the following sections will describe in detail the model used for the current analytical study and the procedures used to model the critical imperfections. Particularly, the study hopes to address some specific difficulties faced when choosing the critical imperfection shape for a two-span continuous system.

### *3.1 Finite Element Model Basics*

The three dimensional finite element program ANSYS (Academic Research) was used to create computational models of the test experiments and further examine cross frame behavior. To determine the typical magnitude of force in the cross frame members, a previously developed computer code was employed. Quadrato (2010) details the development of this model, as well as its validation with experimental test data. The computer code uses the ANSYS Parametric Design Language (APDL) to allow the user to vary the geometry and placement of the structural components on a steel bridge.

The computer model uses shell elements to make up the cross section of the girders for the bridge model and uses truss elements to model the cross frames. The shell elements for the cross section are 8-noded shell elements (ANSYS SHELL93), where each node contains six degrees of freedom (ANSYS 2011). As previously discussed in this research, the shell elements are able to capture out-of-plane bending effects, and in the past, have been used successfully in girder buckling research (Helwig 1994; Wang 2002; Quadrato 2010; Wongjeeraphat 2011; Wang 2013).

The steel shell elements for the girder webs and flanges were meshed to have coincident nodes along the interfaces. Shell elements were also used to construct the cross frame connection plates at each brace location. The placement of these connection plates was input, and if the nodes did not align with the mesh at a given location, constraint equations were used to enforce displacement compatibility with the nearest nodes on the girder. Lastly, the cross frames were modeled using line elements (ANSYS LINK8). In order to account for the flexibility introduced by the eccentricity of the angle connection and the subsequent lower stiffness of the brace, a reduction factor *R* was used (Wang 2013). This reduction factor will help the brace forces be more accurately modeled (Battistini 2014). Fig. 2 shows the completed finite element model for one of the straight, two-span continuous bridge geometries considered within this study.

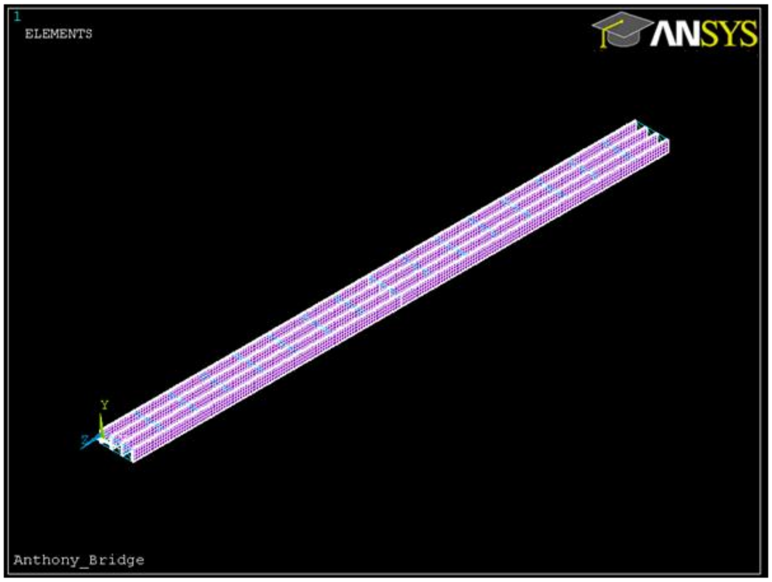

Figure 2: Finite Element Model Used for Study

*3.2 Large Displacement Analysis*

To determine the maximum brace forces anticipated in a typical steel bridge cross frame, a geometrically nonlinear analysis was conducted. The analysis was performed to capture both the statically induced forces in the braces, as well as the stability induced forces due to the application of a uniformly distributed dead load.

Statically induced forces arise from the application of the vertical load causing relative displacement within a brace. For skewed and curved bridges, a uniform dead load will cause these forces as the braces will most likely be connected to the girders at different locations along the respective girder lengths. However, in a perfectly straight bridge with normal supports, a uniform dead load essentially causes both sides to deflect equally, and therefore no internal forces develop in the brace.

While the analysis of a perfectly straight bridge will not result in brace forces, in reality, all structures possess initial imperfections that will induce forces in the braces that become a maximum as stability limits are approached. Stability induced forces are present in both "straight" girder systems (that possess an imperfection), as well as skewed and curved systems. By applying a vertical load, the girder will begin to twist at the location of the imperfection. If the load continues to increase, the girder will eventually reach a critical moment capacity and lateral torsional buckling of the girder will occur. Obtaining a measure of the stability induced forces requires a geometrically nonlinear analysis. This type of analysis method performs a series of static analyses in which the applied load is gradually increased to the target value. After each load step, the geometry of the structure is updated to capture destabilizing effects that may arise from the current geometry. As the girders approach the critical buckling moment, the displacements and forces from the analysis significantly increase and solution convergence becomes more difficult.

*3.3 Girder Imperfection*

In order to analyze the total force in the cross frame member, an imperfection magnitude and location was selected to maximize the stability induced forces. As previously discussed, Wang and Helwig (2005) observed the worst case imperfection was a lateral sweep of the compression flange while keeping the tension flange perfectly straight at the cross frame nearest the location of maximum static moment.

To create this imperfection in the finite element study, displacement boundary conditions were applied at the compression flange nodes at a specified location to create the desired imperfection prior to application of the vertical loads. Due to the indeterminate nature of the girder systems, the determination of the specified displacement often requires an iterative approach. The preliminary analysis did not include the restraint of the cross frames around the desired imperfection location, so that forces were not induced in the cross frames. The restraint of the cross frames were removed using element birth and death. In this process the cross frame elements are first selected and “killed” by the program by assigning a very small stiffness to the members. After the analysis step to achieve the desired imperfection is complete the elements are brought “alive” by assigning the proper stiffness in subsequent load steps.

The magnitude of the imperfection was chosen to be 1/500 of the unbraced length at the location of the critical imperfection ($L_b/500$).

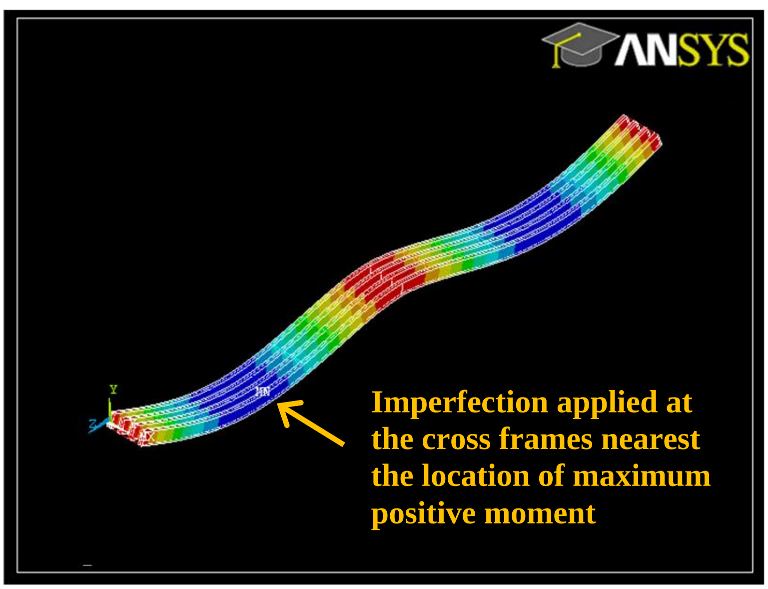


Figure 3: Static Analysis of Two-Span Continuous Bridge to Identify Location of Maximum Moment

In order to determine the location of the maximum static moment (and therefore the location of the girder imperfection), a preliminary analysis in the finite element program was performed. To date, the study has examined two span continuous bridge geometries with equal span lengths subjected to a vertically applied uniform load. For this scenario, under a uniform distributed load the maximum positive bending moment occurs at 3/8*$L$ from the end support, where $L$ is the span length. As expected, the analysis confirmed the location of this maximum moment. The vertically displaced shape of the structure subjected to uniform loading is shown in Fig. 3, as well as the location of the applied imperfection. The magnitude of the deflections and stresses obtained in the analysis shown in Fig. 3 were compared with analytical solutions to further validate the use of the finite element model.

It is important to note that in a two-span continuous system, the maximum absolute value of moment occurs at the center support. However, it does not intuitively make sense to place the imperfection at this location since the erector will plumb the girders at the support locations. Therefore the location shown in Fig. 3 corresponds to the second highest absolute value of moment. Further study will be completed to determine if this selection maximizes the overall brace forces, or if locating the imperfection at some other location will maximize the forces (i.e. the cross frame line adjacent to the center pier).

### *3.4 Analysis Steps*

The analysis procedure used throughout the parametric analysis is summarized as follows:

- Use a static analysis of the bridge subjected to uniform load to determine the location of the maximum moment.
- Identify the critical brace nearest the maximum girder moment.
- Apply an imperfection equal to $L_b$/500 to the compression flange only on each girder at the critical brace line. During this analysis, the cross frames are forced to have near-zero stiffness using the element birth and death option.
- Any forces developed in the bridge system are erased prior to further analysis. The displaced geometry is saved. Cross frame member stiffnesses are restored.
- A geometrically nonlinear analysis of the displaced geometry is performed until the target load is achieved or the analysis diverges.
- Record the final brace forces in each member for each brace.

## 4. Finite Element Study Parameters

In order to perform the parametric study, a baseline bridge geometry was selected and certain variables identified for examination. The following subsections document the details analyzed.

### *4.1 Cross Sections*

Five plate girder cross sections were used in this study, ranging from web depths of 48 in to 96 in. The cross sections were similar to those used in previous studies by Quadrato (2010), but a flange-to-depth ratio of 1/4 was utilized. The use of the 1/4 flange to depth ratio was used to provide more realistic cross section dimensions based upon a survey of bridge plans provide by TxDOT as well as based upon previous research Stith (2010). The cross sections used in this study are shown in Fig. 4.

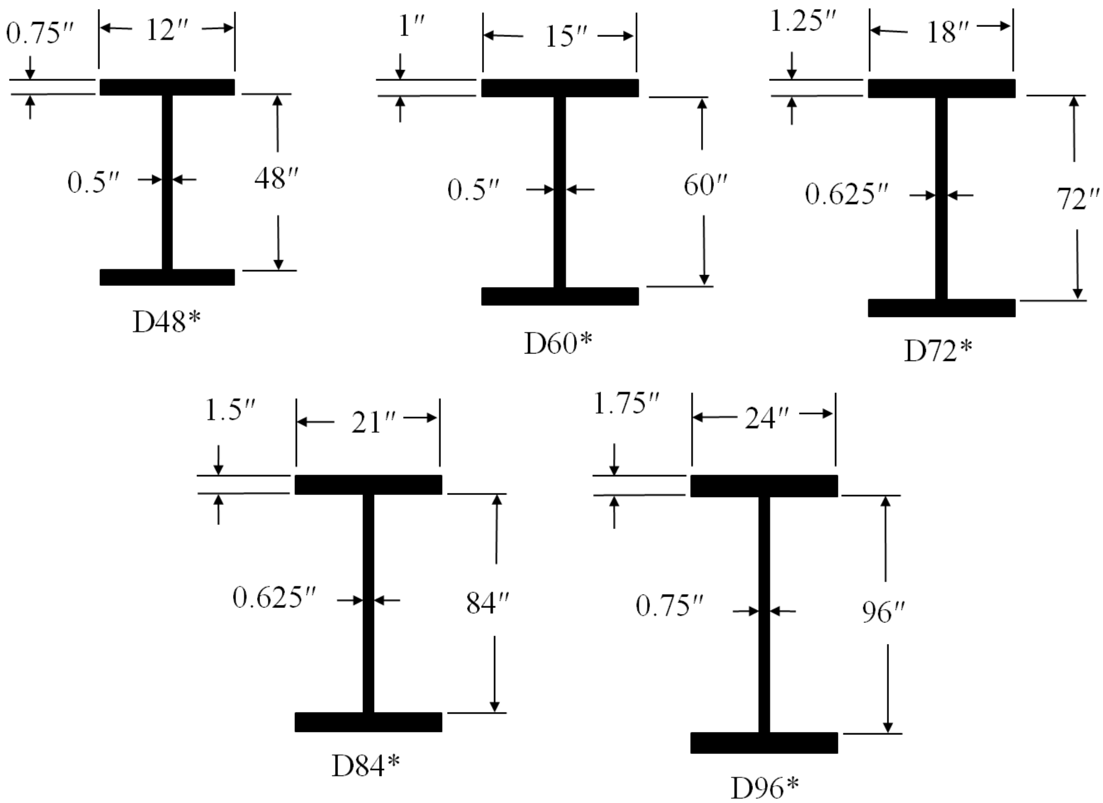


Figure 4: Cross Sections Used in Parametric Study

The cross sections were kept constant along the girder length to limit the introduction of an additional variable. Although typical two-span continuous bridge geometries would have larger sections in the negative moment region, the increased girder stiffness should reduce the forces transmitted to the cross frames. Therefore, assuming a constant cross section should result in larger cross frame forces, providing some conservatism in the approximation of maximum cross frame forces.

*4.2 Bridge Layout*

The study evaluated two-span continuous systems with equal length spans. The bridge layout considered both straight girder bridges as well as skewed bridges, where the end abutments and center pier are not normal to the girder cross section. The skew angle was varied in 15˚ increments from 0˚ (no skew) to 60˚ (extreme skew). Fig. 5 shows the basic bridge geometry, identifying the skew angle as α.

The study looked at 4 girder steel bridge systems, as many examples provided by TxDOT in associated research seemed to indicate this as a frequent geometry constructed. The individual span lengths evaluated were 100 ft for the D48* and D60* cross sections, and 200 ft for the D72*, D84*, and the D96* cross sections.

Lastly, three girder spacings were selected for analysis: 6 ft, 8 ft, and 10 ft. Based upon a review of numerous bridge plans and experience, these values represent the minimum and maximum of typical steel bridge girder spacings.

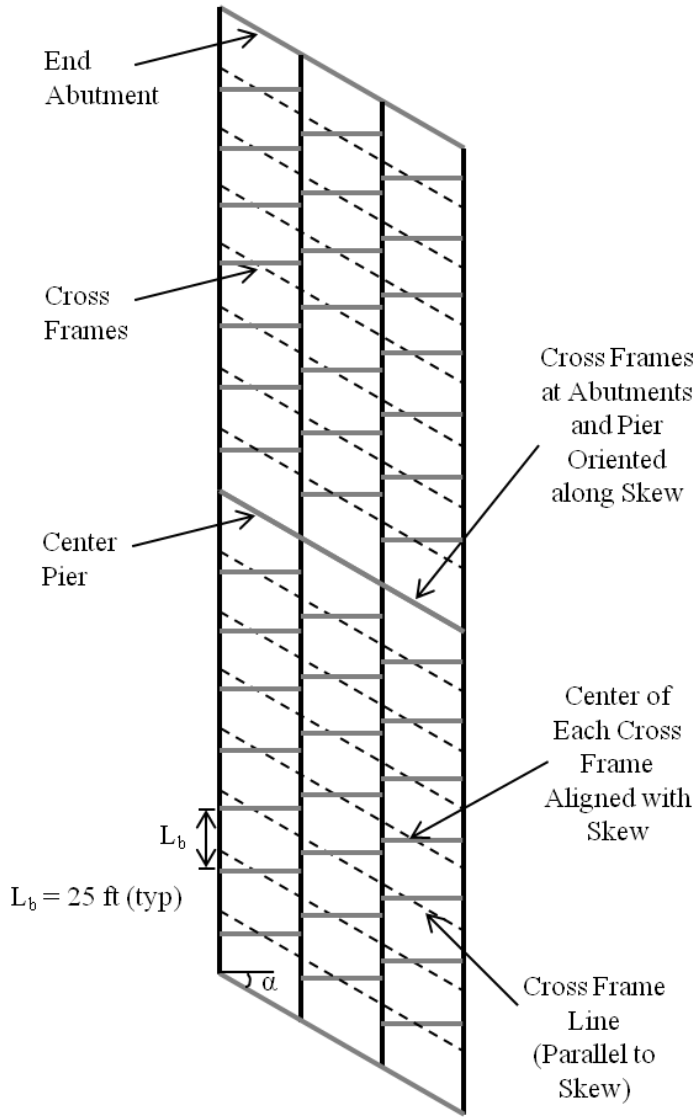


Figure 5: Bridge Layout Used in Study

*4.3 Cross Frame Size*

As previously discussed, the cross frames were modeled in this study using line elements to reduce computational time and to minimize the changes to the existing validated finite element model. Two cross frame member areas were selected for the analysis. The first area was 2.86 in$^2$, which corresponds to an L4x4x3/8 member, the member size identified by the TxDOT XF1 Cross Frame Detail (2006). The second area was $R$*2.86 in$^2$, where $R$ is the reduction factor presented by Wang (2013) that reduces the member stiffness to account for the eccentricity of the connection. The equation for the $R$ factor for X-type cross frames is given by the following:

$$R_{est-SX} = 1.063 - 0.087\frac{S}{h_b} - 0.159\,\bar{y} - 0.403t \qquad (1)$$

where $S/h_b$ is the ratio of girder spacing to height of brace, $\bar{y}$ is the member eccentricity, and $t$ is the thickness of the leg of the connected angle. The $R$ factor varied from case to case depending upon the analyzed geometry, with a range of 0.51 to 0.67 for the study.

*4.4 Cross Frame Layout*

Cross frames were placed in the bridge at a 25 ft spacing. Although a larger spacing would often be viable, the 25 ft spacing matches the former maximum allowed by the AASHTO LRFD Bridge Specification (2004) and aligns with the spacing that is often utilized based on discussions with TxDOT engineers and evaluation of numerous bridge drawings.

For the skewed bridge systems, the braces were placed in a staggered layout, as indicated in Fig. 5. The staggered layout is one option designers have when engineering skewed bridges. A second option is orienting both the end and intermediate braces parallel to the skew, but this can only be done when the skew angle is less than 20˚ (AASHTO 2013). A third commonly used arrangement is to use a normal layout, where each cross frame line would be normal to the girder lines and continuous across the width. This option was not considered in the current study.

*4.5 Support Conditions*

At the end support locations on each girder, roller type supports were provided, preventing translation in the vertical direction and transverse direction. Pin type supports were provided at the center pier, preventing vertical, transverse, and longitudinal translations. Fig. 6 shows a schematic of these described boundary conditions.

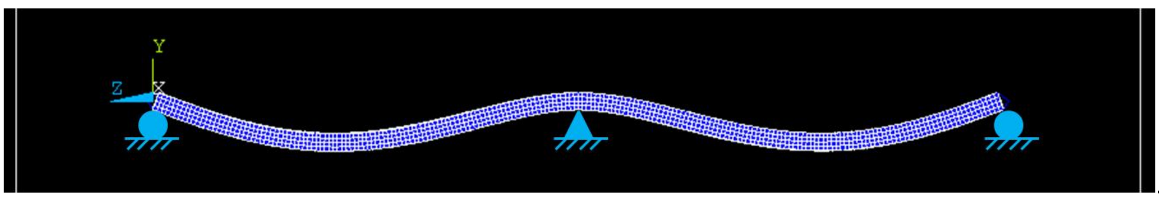


Figure 6: Schematic of Support Reactions

*4.6 Load Application*

The girders for each bridge geometry considered were subjected to a uniform load of 1 kip/ft along the length for analysis. The load was applied to the nodes along the top flange. The self-weight of the girders is assumed to be part of the applied uniform load.

When the girders begin to twist, loads applied to the top flange will have a destabilizing effect on the cross section, increasing the demand on the braces. The concrete deck and construction loads naturally act on the top flange of the girder; however, the steel self-weight would be distributed throughout the web and flanges, and could be considered to act at the mid-depth of the cross section. In terms of the cross frame forces, applying the entire load to the top flange will result in higher forces in the cross frame members. Also, with respect to the concrete dead load, the contribution of the steel dead load to the cross frame forces will be smaller, and most likely would not significantly lower the observed forces in the cross frames if applied at mid-depth.

The magnitude of the uniform loading is representative of the steel dead weight, the dead weight of a tributary section of the concrete deck, as well as the majority of construction loads acting on the beams without load factors. The critical stage for stability of these girders is during construction, when the full weight of the concrete deck and associated construction loads will act on the noncomposite steel section. Table 1 summarizes the calculated steel dead weight for each of the cross sections studied and Table 2 lists the dead weight per unit length of a tributary width of an 8 in concrete deck. Calculations in these tables assume a density of steel of 490 lb/ft$^3$ and a density of normal weight concrete of 150 lb/ft$^3$.

Table 1: Steel Dead Load Calculations

| Cross Section | Area [in$^2$] | Dead Weight of Steel [lb/ft] |
|---|---|---|
| D48* 12″ 0.75″ 0.5″ 48″ | 42 | 142.9 |
| D60* 15″ 1″ 0.5″ 60″ | 60 | 204.2 |
| D72* 18″ 1.25″ 0.625″ 72″ | 90 | 306.3 |
| D84* 21″ 1.5″ 0.625″ 84″ | 115.5 | 393.0 |
| D96* 24″ 1.75″ 0.75″ 96″ | 156 | 530.8 |

Table 2: Concrete Deck Dead Load Calculations Using Tributary Area

| Girder Spacing (Tributary Width) | Dead Weight of Concrete [lb/ft] |
|---|---|
| 6 ft 72″ 8″ | 600 |
| 8 ft 96″ 8″ | 800 |
| 10 ft 120″ 8″ | 1000 |

## 5. Preliminary Results

To help facilitate prediction of cross frame forces for various loads, the first stage of the study sought to determine if the results for cross frame forces were scalable. In general, when performing a geometrically nonlinear analysis, the results cannot be scaled as the effect of the large displacements can greatly increase the computationally measured forces. However, numerous representative cases were performed and a comparison showed the error caused by scaling the results were typically within a few percentage points. Table 3 summarizes one such case.

Table 3: Verification of Scaling Cross Frame Member Forces

| Description | Cross Frame Member Forces [k]<br>(+) tension (-) compression | | | |
|---|---|---|---|---|
| | Diagonal 1 | Diagonal 2 | Bottom Strut | Top Strut |
| Case 1: Maximum Cross Frame Forces<br>w = 1 kip/ft | -12.07 | 6.684 | -7.511 | 10.35 |
| Case 2: Maximum Cross Frame Forces<br>w = 2 kip/ft | -24.80 | 13.44 | -16.16 | 21.22 |
| Approximation Using Scaling<br>2*(Case 1) | -24.12 | 13.37 | -15.02 | 20.69 |
| Percent Error | 2.71% | 0.51% | 7.02% | 2.49% |

Table 3 shows a comparison of the forces in a typical intermediate/end cross frame. The forces were obtained when the girders were each subjected to a uniform load of 1 kip/ft and then 2 kip/ft and analyzed allowing large deflections and accounting for the nonlinear geometrical effects. As viewed in the table, the forces obtained from scaling a 1 kip/ft load versus applying a 2 kip/ft load results in some errors. In this case, the expected force in one of the diagonals could be off by approximately 7%.

Reviewing numerous results of varying cross sections, skew angles, girder spacings, and cross frame member areas, it was determined the percentage difference in *the braces with the maximum forces* was typically between 0-10%. The forces in braces with lesser load sometimes exceeded this percent error, especially when the member forces were close to zero. But since the maximum forces in the braces were the primary concern of this study, it was deemed that scaling would provide an acceptable level of error. In reviewing Table 1 and Table 2, it is noted the loads of 1 kip/ft and 2 kip/ft provide a reasonable bound of the dead load forces acting on the girders.

Further results of this study are ongoing. Particularly, the author is examining the effect moving the location of the imperfection has on maximum brace forces. At the present time, even though the imperfection is located at the location of maximum positive moment for the two-span continuous system, the maximum brace forces are still occurring at the center support. This result suggests that an imperfection closer to the center support may have an even larger effect on the maximum recovered brace forces.

## 6. Conclusions

When trying to determine the stability-induced forces in cross frames expected from the erection and construction stages of a steel bridge, a large displacement nonlinear analysis must be performed. When performing the analysis, an initial imperfection must be given to the girders. Selecting this imperfection for multiple span continuous girder systems is difficult. Previous research on simple span systems suggests that applying the imperfection to the girders at the cross frame location nearest the maximum static moment will, in turn, maximize the brace forces obtained. Those brace forces occur at the critical imperfection location. However, the maximum absolute value of the static moment in a continuous system occurs at the center pier, a location which is unlikely to have an imperfection due to typical construction practices.

The research herein attempted to provide guidance on selecting the location of the imperfection that maximizes the brace forces. To date, the study has only been able to observe the effect of applying the imperfection to the girder at the cross frame location nearest the second largest absolute value of moment. When applying this imperfection, the maximum brace forces are still occurring at the center pier location; therefore, the research will next examine locating the imperfection at the brace line adjacent to the center pier to determine if that further increases the brace forces obtained.

To aid in the computation of various two-span continuous bridge geometries, the results have shown that although performing a nonlinear analysis, the maximum obtained brace forces seem to scale linearly within a few percent error. This result was consistent with previous research on simply-supported spans (Wang and Helwig 2005). Being able to scale the results will be used to facilitate the analysis of the study and can help increase the applicability of the computationally measured results.

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