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STABILITY BRACING REQUIREMENTS OF TRUSSES

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Abstract. *The evaluation of the global buckling capacity of structural members and systems plays a critical role in ensuring a safe structure. The buckling capacity is improved by incorporating bracing to reduce the unsupported length of the members. This paper highlights the results of an investigation targeted to improve the understanding of the bracing behavior for truss systems. The study included laboratory testing and parametric finite element analyses and considers the effects of truss and bracing geometry, connection flexibility, as well as the types of bracing systems. The tests have considered the impact of the number and stiffness of the braces as well as the location on the truss cross section. According to the test results, it was found that the effect of load height exists in trusses, but to a lesser degree compared to beams. Proper selections of the brace stiffness value and brace location are important in improving buckling capacity of the truss.*

1 INTRODUCTION

The evaluation of the global buckling capacity of structural members and systems plays a critical role in ensuring a safe structure. Failure to consider certain stability modes can lead to catastrophic problems during construction or in-service. Several types of structural systems have members that act as the bracing for the main members. However, these members are usually secondary members and brace forces add an additional force demand on these members, which may or may not be considered in design. For the under-designed secondary elements that carry the extra force due to the bracing effect, these forces might cause the element to become unstable and may lead to problems in the finished structure.

While there have been several past bracing studies that have led to a good understanding of the bracing requirements of columns, beams, and frames, very little work has been focused towards the study of bracing behavior for truss systems. The AISC Specification [1] provides requirements for the bracing of beam and column systems. With some conditions, AISC [1] allows the design of bracing systems for trusses by using beam provisions. Although engineers often rely on solutions that have been developed for columns and beams, the factors that affect bracing for trusses can be quite different. Since trusses are generally flexural systems composed of a collection of axially loaded members, there are a variety of failure modes that complicate the bracing requirements. Establishing a clear understanding of the bracing requirements to control the variety of instabilities that can occur in truss systems is vital to a proper design. Unfortunately, the current knowledge base on the bracing behavior in trusses is generally inadequate.

2 BACKGROUND

Several types of trusses have been developed to maximize the load carrying capacity, aesthetic appeal, and span length for use in bridges, buildings, and stadiums. However, bracing requirements for trusses have not been well developed. The most developed bracing design recommendation was for the half through truss (pony truss). A summary of the design recommendations for the half through truss can be found in Galambos [2]. AASHTO [3] also specifies the requirement for the design of half through trusses. In contrast, beam and column bracing requirements have been well developed. There are 2 types of bracing that are used to improve the buckling capacity of beams and columns: lateral and torsional bracing systems. Several factors have been included in the requirements for beam bracing, such as the load height effect, type of loads, stiffness of the brace, connection type, and beam cross section. Effective bracing must satisfy both stiffness and strength requirements. Historically, many designers have used rules of thumb such as sizing the brace for 2% of the compression force in the member being braced. While this may provide sufficient strength, such an approach may often possess insufficient stiffness. May bracing provisions are often a function of the "ideal stiffness" which is the stiffness required so a perfectly straight member buckles between brace points. However, the ideal stiffness usually results in very large displacements and brace forces and therefore providing at least twice the ideal brace stiffness is often required [4].

Bracing requirements for trusses are not well documented, however, recommendations have been provided. With some conditions, AISC [1] allows a truss to be designed by using the beam bracing provisions. In Europe, the bracing requirements for trusses can be found in the Polish steel design code [5]. According to the Polish code [5], the strength requirement for the brace is:

$$F = 0.01N \quad \text{and} \quad F \geq 0.005A_s f_y \tag{1}$$

Where N is the axial force in the compression chord, A_s is the cross sectional area of the compression chord, and f_y is the steel's yield stress. The Polish code also limits the maximum displacement of the brace to 1/200 of the unbraced length.

In recent study of trusses, Iwicki [6] found that the buckling capacity increases with an increase in the stiffness of the brace and decreases with an increase in the angle of the brace. When the angle of the brace reached 30 and 45 degrees, the horizontal displacement was greater than the limit set by the Polish code, which is $L_b/200$. Also, the brace force ranged from 0.25% to 3.0% of the compression force on top chord. Also of note: from the sensitivity analysis, it was found that attaching the brace at some locations might decrease the buckling capacity by up to 10%.

3 EXPERIMENTAL PROGRAM

3.1 Truss and brace designs

Trusses are complex structures, the behavior of which can be affected by several factors. In particular, factors such as the connection types, cross sections of the chord and web elements, end conditions, alignment of diagonal members, all have an impact on the buckling behavior. In this study, tests were conducted on twin trusses that were designed to minimize the number of unknowns by keeping the model symmetrical. The same size members were used for the chords and the vertical and diagonal members of the truss. Twin trusses with a depth of 4 ft. and a maximum span of 72-ft were fabricated. Tests were conducted with both torsional and lateral bracing. The trusses were designed to buckle in the elastic range. Truss supports were designed to allow the truss to warp freely, but the twist was prevented. The details of truss supports are shown in Figure 1(without the truss). The thrust washers and the rounded threaded rods minimized warping restraint.

The vertical loads were applied at one third and two thirds of the span using gravity load simulators. Details of the loading apparatus were discussed in Wongjeeraphat and Helwig [7]. For the purposes of discussing the results, the individual trusses are referred to as the East or West truss. The spacing between the trusses was set at 10 feet to accommodate the gravity load simulator placement. The lateral deflections of the tests were limited to approximately 3 inches.

3.2 Truss setup with lateral bracing

The lateral braces used in the tests were composed of either an aluminum bar or various HSS steel sections. The lateral bracing was provided by the flexural stiffness of the brace with one end of the brace attached to the ground and another support point on the brace that could be adjusted to vary the stiffness.

The aluminum bar that was used for the brace is shown in Figure 2a. At the contact point between the top chord of the truss and the brace, two Teflon contact surfaces were used to provide low friction contact, so that lateral movement could be prevented, while still allowing the truss to deflect vertically. A Teflon pad on the brace was connected through a 1″ diameter threaded rod to allow lateral adjustments to account for imperfections in the truss.

Lateral braces were positioned either at mid-span or at the third points of the truss. The design stiffness values were 0.2, 0.5 and 0.8 kip/in, based upon the elastic deflection equations for an overhanging beam. The actual stiffness of the braces varied since the trusses deflected vertically, thereby changing the contact point. Although the actual stiffness varied, in the remainder of this paper, the design stiffness will be referred to when discussing the behavior.

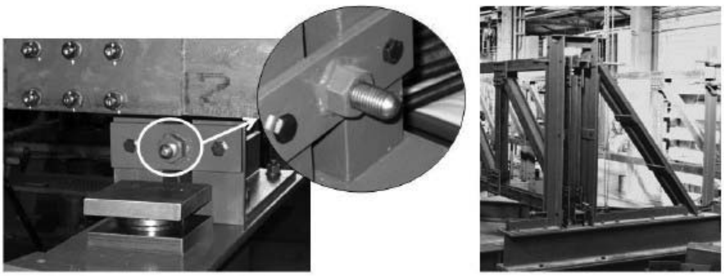

Figure 1: Support conditions a) Thrust bearing at support with rounded threaded rod b) Support frame.

3.3 Truss setup with torsional bracing

Two torsional stiffness values were used for the tests of the trusses with torsional bracing. The braces were placed at 24, 36 and 48 ft from the North support for the bottom chord loading case. The braces could not be placed at the 24 and 48 ft locations for the top chord loading case, due to the positioning of the load beam. Therefore, the braces were each shifted 1 joint in the outside direction to 20 and 52 ft locations. The torsional braces that were used in the tests were HSS 3″x2½″x1/4″ and HSS 5″x2½″x1/4″. The torsional braces were placed with their major axis in the out-of-plane direction of the trusses. Therefore, the major axis was acting to prevent the rotation of the trusses. Figures 2b, 2c, and 2d show the torsional braces and connection details. For the torsional braces placed at the third points, due to the unsymmetrical bending at the brace points and the trusses both bent into the same half sine curve, the torsional braces resisted this rotation and created the warping restraint on the minor axis of the braces. Figure 2 shows the details of lateral and torsional braces.

4 RESULTS AND DISCUSSIONS

The results presented in the paper were from the West truss; however similar behavior was observed for the East truss. For the top chord loading case, the loads were applied at the third points at the truss joint. However, when referring to the bottom chord loading case, the load was offset 10 inches towards the supports from the third points. “Total load” refers to the total load applied to the twin trusses.

The testing program demonstrated that several factors had a significant impact on the buckling behavior. Some of these factors include the magnitude and shape of the initial imperfection, load position, cross-sectional distortion, as well as the stiffness and location of the bracing. These factors are being considered in the parametric finite element analyses that are currently underway.

4.1 Buckling capacity of trusses without bracing

For all of the buckling test results without bracing, the trusses deflected laterally to the same side with almost the same deflection in the half sine shape. Due to the difference in the initial imperfections between the adjacent trusses, there was a lean-on effect imposing some axial force on the loading beams; however, this did not have a significant impact on the test results. The Southwell plotting technique [8] was used to estimate the buckling capacities of the trusses. The Southwell technique [8] uses a graph of the lateral deflection versus the ratio of lateral deflection to the applied load, to obtain a linear relationship. The inverse of the slope of the line is the estimated buckling capacity. The X-intercept is the estimated initial imperfection. Figure 3 shows the result of Southwell plot at mid span top chord of 72-ft span truss with top chord loading. It can be seen that Southwell plot has very good agreement with the test result with correlation coefficient (R_2) equal to 1.0. The Southwell plot produced a linear relationship in nearly all of the tests without intermediate braces. However, for the cases with bracing, the braces themselves contribute some effect to the buckling behavior of the truss. Therefore, the Southwell plot of the case with bracing was not used in cases with bracing. The estimated buckling capacity and initial imperfection for top chord and bottom chord loading cases were 7.5 kips and 1.54 inch, and 8.6 kips and 1.33 inch, respectively.

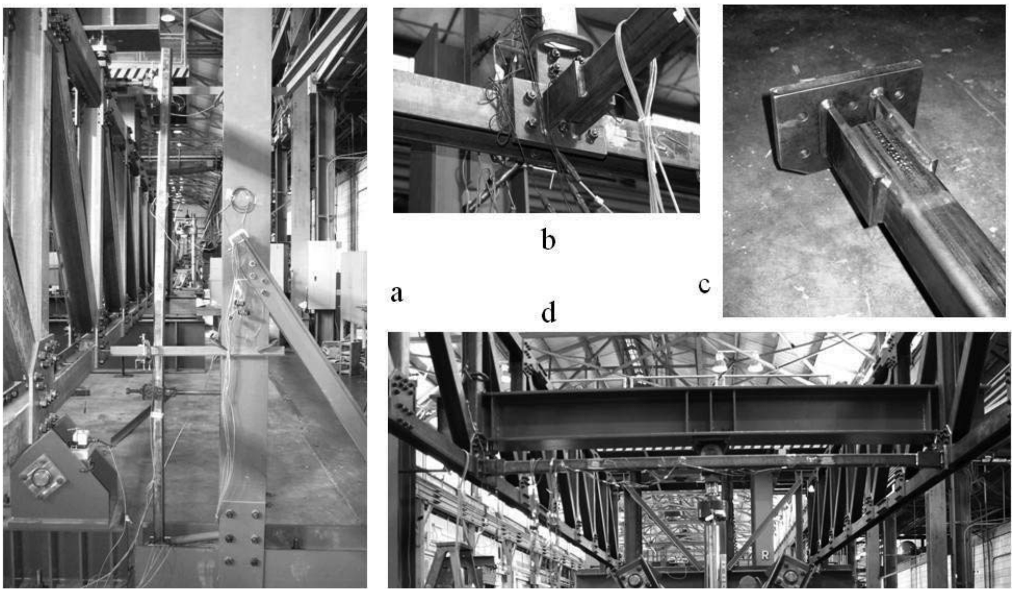

Figure 2: Brace details a) Lateral brace b, c, d) Torsional brace.

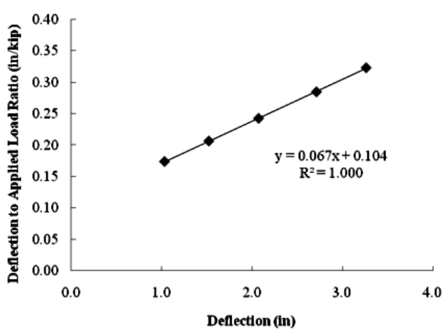

Figure 3: Southwell plot at mid span top chord of 72-ft span truss with top chord loading.

According to the Southwell plot, the estimated buckling capacity of the top chord loading case is different from the bottom chord loading case. The ratio of the buckling capacity of the bottom chord loading case to the top chord loading is about 1.16. This indicates the possibility of a load height effect, which has been observed for with beams. For the load height effect of a beam with loads at third points, the load height effect can be calculated by using the following equations [2]:

$$C_b = AB^{2y/h} \tag{2}$$

Where y = Distance from the mid height to the point of load application
h = Depth of beam
A = 1.111 for third points loading

$B = 1 - 0.465W^2 + 1.636W$ for third points loading

$$W = \frac{\pi}{L}\sqrt{\frac{EC_w}{GJ}}$$

For a typical wide flange section, W is low for a long, slender beam and is high for a short, stocky beam. The ratio of the load height effect of bottom chord to top chord loading versus a range of possible W values is shown in Figure 4. The range of the W was from 0.1 to 2.5, which covers a wide range of spans. The load height ratio ranged from 1.34 at W = 0.1 to a maximum of 5.8 at W = 2.0. Comparing the ratio for beams to the tested truss, the truss's load height effect ratio is still lower than the beam's, even at the W of 0.1. Therefore, it could be said that even though the load height effect exist in trusses, the effect of load height on trusses is lower than on beams. The further parametric study of finite element models will be done to clarify the impact of load position on the truss behavior.

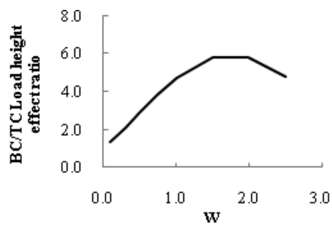

Figure 4: Bottom chord to top chord load height effect ratio of beam with load at third points

4.2 Effect of lateral bracing on buckling capacity

Figure 5 shows the relationship of the applied load and relative deflections at the locations limited by the braces. For the case without bracing and cases with 1 brace at mid span, the relative lateral deflections were the deflection at mid span relative to support. For the cases with 2 braces, the plots were the maximum deflection of 1) the deflection at 24 ft relative to support at 0 ft, 2) the lower of the deflections at 24 or 48 ft relative to deflection at 36 ft, and 3) the deflection at 48 ft relative to the support at 72 ft. For the case with stiffness values (K) of 0.2 and 0.5 kip/in, the maximum relative deflections were taken between 48 and 72 ft. The relative deflections between 24 and 36 ft was taken for the case with K = 0.8 kip/in. If the maximum lateral deflection of the trusses were limited by the maximum initial imperfection allowed by the AISC code of standard practice [9], which is $L_b/500$, where L_b is unbraced length, the maximum deflections are 1.73, 0.86 and 0.58 inch for trusses without bracing, with 1 brace at mid span, and with 2 braces at third points, respectively. The maximum load at the limit of deflection for truss without bracing was 8 kips. The maximum loads for the cases with 1 brace at mid span were 22, 45 and 55 kips for the cases with the brace stiffness values of 0.2, 0.5 and 0.8 kip/in respectively. The maximum loads for the cases with 2 braces at 24 and 48 ft were 26, 50 and 59 kips for the cases with the brace stiffness values of 0.2, 0.5 and 0.8 kip/in respectively. By limiting the lateral deflection to the $L_b/500$, the test showed that changing the brace from 1 brace to 2 braces helped improve the load carrying capacity, even though the load deflection at mid span was the same for the case with brace stiffness of 0.8 kip/in, graph was not shown here. However, with the stiffness in the test range, 0.2 to 0.8 kip/in, the improvement of the buckling capacity seems to be the same, about 5 kips, for every stiffness increment.

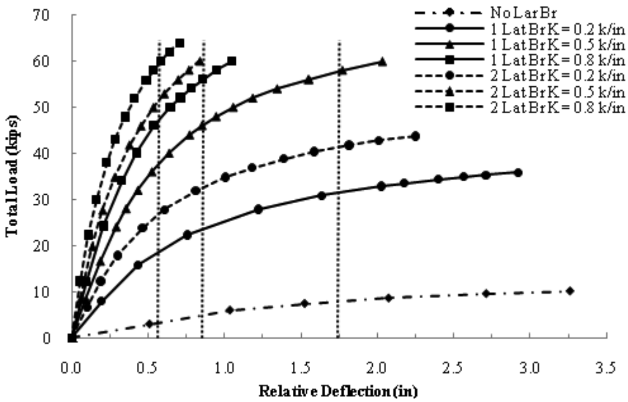

Figure 5: Relative maximum lateral deflection of truss with and without lateral bracing.

4.3 Effect of torsional bracing on the buckling capacity

The twin trusses were tested with torsional bracing in several configurations, including braces at the top chord, braces at the bottom chord (with lateral restraints on both top and bottom chords at the ends) and as a pony truss (torsional bracing along the bottom chord only – no lateral restraint at the top chord at ends). Only the cases with braces at top and bottom chord are discussed in this paper.

The maximum deflection point was always at mid span of the top chord whether the braces were attached at top or bottom chords. Therefore, the deflections of the top chord at mid span were the points that were compared in this setup. The results of the test with 2 and 3 torsional braces with the load applied at the braced chord are shown in Figure 6 for the setup with small torsional bracing and Figure 7 for the setup with large torsional bracing. The results were for the lateral deflection at mid span of the top chord of the West truss on both graphs. There was one exception where the maximum deflection was not at the mid span. This was the case where the trusses snapped from half sine mode to full sine mode, in the trial test of the case with 3 large torsional braces at the top chord. All subsequent buckling tests with the same setup following the change in mode shape buckled in the full sine shape. The lateral deflections at both 20 and 36 ft locations of this case are shown in the graph. In practice, there is usually more than one brace attached to an actual structure; therefore, the results of the cases with 1 torsional brace were not shown here. In comparing the top and bottom chord loading cases in Figures 6 and 7, it can be seen that for a given brace size (and number) the top chord always deflected more for cases with bottom chord loading than top chord loading.

In order to compare the cases between top and bottom chord, the truss should have the braces at the same locations. However, the braces were not at the same locations between top and bottom chord due to conflicts with the loading apparatus. The braces for the top chord were placed at 20, 36 and 52 ft, and the brace at the bottom chord were placed at 24, 36 and 48 ft. Thus, it might be difficult to compare the results between the cases with braces at top and braces at bottom chord. Figure 8 shows the preliminary FEA results of the lateral deflection at mid span of the trusses with torsional braces at the top chord at various location and loads applied at the top chord with half sine initial imperfections at top chord and straight bottom chord. For the case with 2 braces, attaching torsional braces at 20 and 52 ft slightly decreased the buckling capacity (for the case with low stiffness braces) compared to attaching braces at

24 and 48 ft. For the cases with 3 braces, attaching torsional braces at 20, 36 and 52 ft meant the braces were uniformly distributed, resulted in a higher buckling capacity than the case with braces at 24, 36 and 48 ft. It can be seen in both cases that a more uniform distribution of braces leads to the improvement of the buckling capacity. Therefore, equally distributed braces provide a better bracing effect for the truss, which is similar to beam and column behavior. The stiffness of the brace is also a factor in this effect.

Combining the results of Figure 8 on the brace locations with Figure 6 and 7 with the same brace configurations, it can be seen that the effect of the brace location, between 20 and 52 ft and 24 and 48 ft, was still lower than the effect of the top chord/bottom chord loading. If the test results were reduced by the effect of the change in brace locations within the same setup configuration, the buckling capacities of the top chord loading cases were still higher than the cases with bottom chord loading. This means the braces were more effective in the top chord loading case than the bottom chord loading case. In other words, to obtain the same buckling capacity, the required bracing stiffness for the bottom chord loading case is higher than for the top chord loading case.

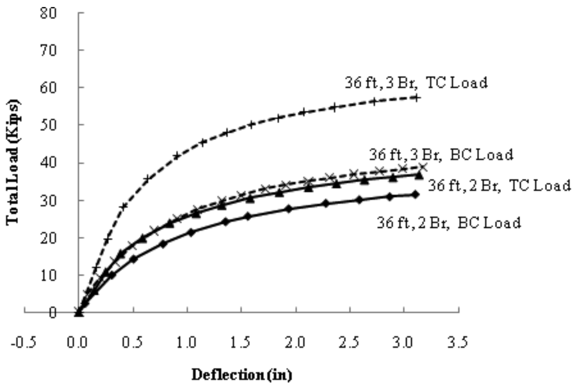

Figure 6: Top chord lateral deflection of truss with small torsional bracing.

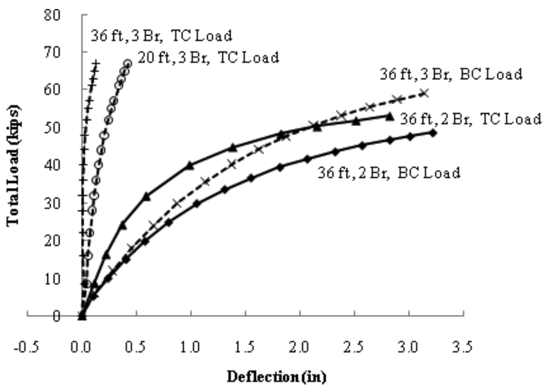

Figure 7: Top chord lateral deflection of truss with large torsional bracing.

5 CONCLUSIONS

The test results demonstrated that load position on the cross section was important in truss systems, but the impact was not as significant as has been observed in beams. Adding the proper lateral bracing stiffness as well as the proper number and location of braces is necessary to improve the buckling capacity of a truss. As would be expected, the effectiveness of adding a lateral brace decreases with an increase in the number of the braces since the buckling capacity is a function of the unbraced length squared. Adding torsional braces is more effective in top chord loading cases than in bottom chord loading cases. In other words, to obtain the same buckling capacity, the required bracing stiffness for bottom chord loading cases is higher than for top chord loading cases.

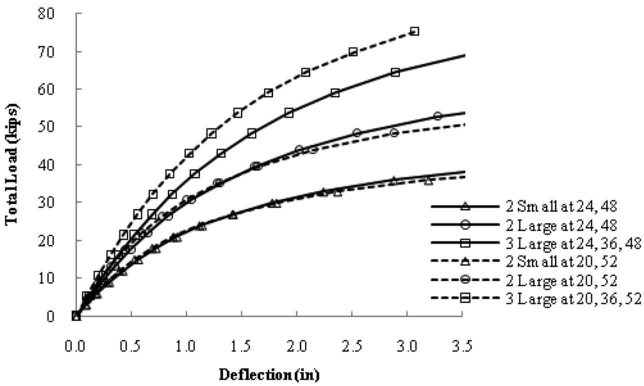

Figure 8: Effect of size and location of braces on lateral deflection of top chord loaded truss with torsional braces at top chord by FEA model.

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