A New Perspective on Lifting Wood Trusses

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Metal plate wood trusses are popular framing options for residential and light commercial work. They are extremely unstable and flexible out of plane during erection. This instability jeopardizes site safety and often leads to damaged trusses that require repair or replacement. The Wood Truss Council of America and the Truss Plate Institute have developed recommended guidelines for lifting trusses. These recommendations are based on field trials and experience of what has worked well. This study evaluates the recommendations using simple statics and current National Design Specification requirements for wood construction. Specifically, the slenderness ratio o6f compression chords as well as the maximum stress in the top and bottom chords are considered. The results indicate relatively low stresses in top and bottom chord members during lifting. Slenderness ratios are exceeded under current lifting guidelines. Further study of slenderness ratios is recommended considering an effective length factor in the analysis. Recommendations to equalize slenderness ratios for top and bottom chord compression members as well as to limit the maximum stress in members is made for longer trusses where lateral buckling is especially critical.

Key Words: Wood trusses, lifting, setting trusses, residential construction, safety

Introduction

Since the inception of wood trusses in the early 1950's, contractors have recognized the advantages offered. Metal plate connected wood trusses offer several advantages over traditional 2x framing including quicker framing time, less skilled labor required, faster closure against the weather, and the ability to span long distances (Smulski, 1994). Trusses can be configured in a variety of profiles, reducing complexity of field construction. Members can be erected with traditional field labor and lifted into place by a variety of methods.

Recent studies indicate that approximately 75% of all new houses in the United States use metal plate connected wood trusses for their roof systems (Moore, 2005). Floor trusses compose approximately 10.4% of the new home market nationwide while some markets have higher preferences for wood floor trusses (International Trade Commission (ITC) 332 Report Summary, 2003). Sales of new one-family homes in September of 2008 were at a seasonally adjusted annual rate of 464,000 (U.S. Census Bureau News, 2008). Based on these numbers, approximately 350,000 homes sold in the United States this year will contain wood trusses. Wood trusses are also popular options for light frame commercial structures.

Many truss advantages are also their disadvantages. Trusses are often long and slender having almost no resistance to out-of-plane bending. Without adequate lateral bracing, they may buckle. This can be an issue during lifting of the trusses to the floor or roof elevation as trusses can buckle under their own self-weight.

This study examines the current guidelines for lifting a simple, 30 foot (ft.) long box truss. Existing recommendations for lifting are detailed. These recommendations appear simple and relatively easy to apply. However, lifting provisions are based on crude rules of thumb and what worked well in previous practice. In addition, these guidelines serve only as recommendations. An analysis of the current Building Component Safety Information (BCSI) recommendations is done based on statics to confirm the existing approach. Results indicate some problems with the existing truss lifting recommendations. The author summarizes these issues and proposes a more detailed review for longer length trusses. The study also suggests that modifications to the lifting method may be warranted and a more detailed approach to lifting of trusses may be worthwhile.

Background

A truss is a “structural form which is used in the same way as a beam, but because it is made of a web-like assembly of smaller members it can be made longer, deeper, and therefore, stronger than a beam or girder while being lighter than a beam of similar dimensions”(PGH Bridges, 2008). A truss is made up of a series of triangles created by the chords and webs. The triangle is a stable geometric shape, and it is the basis of the truss’ strength. “In fact, you can’t change the shape of a triangle unless you change the length of one of its three legs” (Smulski, 1994). The different pieces of the truss are securely fastened to each other, and all of the pieces must work together; when loads are imposed on the truss, some of the pieces are put in compression while other pieces are put in tension resulting in a “stable, self-balancing structure”(Smulski, 1994). If any component of the truss is damaged, the entire integrity of the truss is compromised.

The different pieces of a truss are typically held together by metal plate connectors which transfer the stress between the members (Figure 1). The metal plate connectors typically have eight teeth per square inch which grip the wood truss, and it is the integrity of these connectors which impact the strength and integrity of the truss (truss-frame.com, 2003). Metal plate connected engineered wood trusses were invented in 1952 by A. Carroll Sanford, founder of Sanford Industries in Pompano Beach, Florida. Metal plate connected wood trusses allowed for short and long-span trusses to be prefabricated off-site in an efficient manner (Moore, 2005).

Figure 1: Metal plate connected wood truss

Although the trusses are strong in a vertical position, “trusses have very little lateral strength or resistance to lateral loading”, and it is for this reason that great care must be taken when lifting trusses to the roof of a house (Workplace Safety and Health Division (WSHD), 2007). The most common reasons for the failure of a roof truss system are improper handling during delivery and during installation (truss-frame.com).

OSHA’s (Occupational Safety and Health Administration’s) safety guidelines for truss erection in residential construction are found in Standard (STD) 3-0.1A (29 CFR 1926 OSHA Construction Industry Regulations, 2007). STD 3-0.1A requires that for any wall up to eight feet, interior scaffolds must be installed along the interior wall, below the area where the trusses will be located. If a wall is over eight feet, the first two trusses must be set from ladders. After the first two trusses have been set, the framers can stand on the interior top plate to secure the peaks of the trusses. Workers should stand on the exterior top plate.

Common methods for lifting trusses include crane, forklift, and hand installation. In crane installation, three groups of workers are employed. One or two workers are used on the ground to secure the lifting straps to the top chord of the truss. They also will often attach a tag line that helps the ground crew guide the truss into position. A crane operator is used to lift the truss to the appropriate building elevation. A framing crew receives the truss from the ground and secures it into position. The crane approach to lifting trusses has significant advantages. A crane can lift heavy trusses and can lift multiple trusses in one lift. The wide reach of the crane often is advantageous to picking them up where they have been dropped and placing them where needed. Less lifting by the workers is required thereby reducing worker fatigue. The major drawback to cranes is the high cost of renting or owning the crane. Since many home builders work on a tight schedule, a delayed or cancelled crane delivery can cause substantial delays.

A forklift is sometimes substituted for a crane. The chief benefit for the building is that a forklift is cheaper than a crane. The forklift has many of the same drawbacks as a crane. In addition, it does not have the same reach as a crane and often cannot place trusses where they are required.

The final method for erecting trusses is to lift the trusses by hand. It is cheaper than either of the two methods. However, it can damage the truss and cause significant worker fatigue. Trusses are routinely lifted into place manually by having a ground crew secure the truss with ropes and another crew of men on the roof pulling the truss up (Figure 1). This approach is a violation of OSHA and should not be performed.

Installation is the responsibility of the General Contractor. Often, truss installation would be sub-contracted to a framing or carpentry contractor. As the truss industry evolved, there were no guidelines for truss erection and each contractor developed methods based upon practical experience and intuition. However, many truss toppling accidents occurred, and the industry recognized that installations were beyond the intuition of the average contractor (Meeks, 1987). The Truss Plate Institute responded with the publication of "Bracing Wood Trusses: Commentary and Recommendations" (Truss Plate Institute, 1976). Over time, this set of guidelines has evolved and remains the industry standard currently updated as BCSI (Wood Truss Council of America and Truss Plate Institute, 2008).

The guidelines regarding the handling and erection of trusses can be found in the BCSI Manual. The guidelines cover the rules and methods that should be followed to ensure that trusses are not damaged while being lifted into place. The guidelines should be followed regardless of which method is chosen to lift trusses. The recommendations for truss erection state that a truss should be lifted into place without excessive lateral deflection. Previous Truss Plate Institute (TPI) publications have defined this as three inches within a ten ft. span (Truss Plate Institute, 1991). Excessive lateral deflection produces a strain in the metal connector plates which weakens the joints of the truss. Proper lateral support of the truss is critical during the installation process. For trusses that span 30 ft. or less, two pick up points must be used at points up to ½ the length of the truss (Figure 2). "The angle between the two cables should be 60 degrees or less to reduce the tendency for the truss to buckle laterally during the lift" (WSHD).

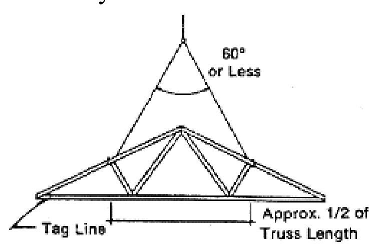

Figure 2: Trusses 30' and less in length

The guidelines have worked well. No known cases of failure are documented where the procedures of BCSI were carefully followed. However, the implementation of the BCSI standards is often not followed closely. Lifting regulations are not dictated by law and remain "recommendations" based primarily on field experience of truss erection. Almost anyone who has worked with wood trusses realizes that they bend during lifting and installation (Figure 3). Trusses buckle and sometimes break during lifting requiring costly repairs or replacement. Truss plates can be damaged if the lateral buckling deflection of trusses is large enough compromising the integrity of the trusses. In wood construction, trusses often have a significant role in the building's ability to support rain, snow, wind, roof dead load, and earthquakes. Their important role in the completed building and their ability to support loads must be compared to their vulnerability to out-of-plane bending and deflection during installation. How trusses are lifted directly affects the structural integrity of the overall structure.

Figure 3: Lifting a truss by hand on a two story building showing lateral bending in truss.

Methodology

No documented structural analysis of the lifting of trusses was found in the literature. As a result, a quantitative approach based on simple statics was used. A 30 ft. long box truss, three feet in depth (Figure 4) was used since most industry professionals indicate that this span falls within the standard range for residential and light commercial structures. The box truss was selected since the length of the top chord is exactly the same as the bottom chord. Using a sloping “A” truss would be more representative of the industry; however, the top chord length complicates the analysis since the sloping top chord has a longer length than the bottom chord. If a problem exists with a box truss, it will only be magnified as the top chord length increases. Future studies should consider an “A” shaped truss.

The truss was assumed to be lifted from the top chord at varying points along the truss. Lifting devices were assumed to be connected to the truss top chord with a closed-loop attachment utilizing materials such as slings, chains, cables, nylon strapping, etc. of sufficient strength to carry the weight of the truss. Out of plane bending was assumed as the primary failure mode when lifting the truss. Only the weight of the truss was included in the analysis. Truss weight was assumed to be equal to 2.7 pounds per linear ft. which is equivalent to the truss shown below with 2x4 Southern Yellow Pine (SYP) chord and web members.

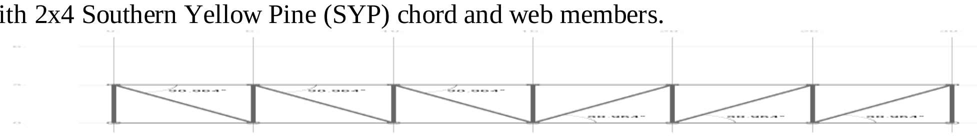

Figure 4: 30’ long, 3’ deep Box Truss Analyzed.

Depending on the location of the pick points, either the top or bottom chord will be in compression. The other chord will be in tension. As pick points are spread out and approach the ends of the truss, the entire top chord is in compression. As pick points move closer together, the cantilevered portion of the truss generates tension in the top chord and compression in the bottom chord. It is the compression in either the top or bottom chord that leads directly to out of plane bending. Where we lift the truss directly affects which chords are in compression and what length those compression members have.

Euler buckling of trusses during lifting is likely the primary mode of failure during a lifting operation. Current requirements specify distances between the two pick points in an effort to limit the amount of compression that is placed on the truss component (Halbert, 2007).

In wood construction, the slenderness ratio of a compression member is defined as the unbraced length of the member divided by its least width, l/d. For clarity of notation within this document, l/d has been set equal to the variable “SR”. SR is typically limited to a maximum value of 50 (American Wood Council, 2005). Larger values of SR tend to yield an elastic buckling failure. This approach is unique in wood design since the length of the member is taken as the unbraced length for design. In other design approaches, a support condition factor, often referred to as K, is multiplied by the length to account for support conditions. A K of one can often be justified in wood construction since members are almost always pinned at each end of the member.

The SR is composed of the length of the chord in compression, l, and the least cross sectional dimension of the wood truss, d. For the top and bottom chords, d was 1.5” assuming the use of 2x4 top and bottom chord members. The truss was analyzed in the program MDSolids to determine maximum member forces and length of compression top and bottom chord members (Philpot, 2007). Truss cantilever lengths from zero ft. to 14.5 ft. were considered in 0.5 ft. increments. These cantilever lengths corresponded with distances between pick points from one ft. to 30 ft.. At a distance between pick points of 16 ft., the bottom chord compression length was 11.1 ft. on each end of the truss. Once the length of the compression chord was known, calculation of l/d was straightforward. For the truss with 16 ft. between lift points, l/d for the bottom chord was 11.1 ft./1.5 inches which equaled 89. Similarly, the 16 ft. distance between lift points put the top chord in compression for a distance 7.7 ft.. Calculation of l/d for the truss top chord yielded a value equal to 61.9. An analysis of the SR value for the top and bottom chord of a truss as the lifting points are varied is shown as Figure 5.

Figure 5 indicates that at small distances between lift points, the entire bottom chord is in compression and has maximum SR value. Zero SR is shown for the top chord since it remains in tension until the pick points are at least 15 ft. apart. As the pick points approach 17’-0” apart, SR values for the top chord (in compression in the center of the truss) and bottom chord (in compression on the cantilever ends of the truss) are approximately equal. At currently recommended pick point locations of 15 ft. between lift points, the bottom chord is in compression for the full length of the truss, and SR equals the maximum value of 240. This SR value exceeds the recommended maximum ratio as required by the wood National Design Specification (NDS) of 50 (American Wood Council, 2005). Based on the graph, it would be impossible to achieve SR less than 50 for both trusses.

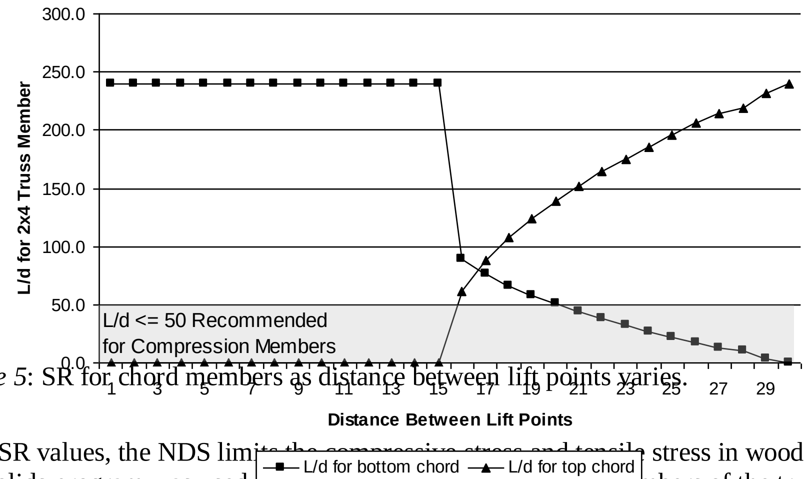

Figure 5: SR for chord members as distance between lift points varies.

In addition to the SR values, the NDS limits the compressive stress and tensile stress in wood members to empirical values. The MDSolids program was used to analyze the force in the chord members of the truss at various locations. Once the force in each individual member was known, the stress in each member could be found by dividing that force by the cross sectional area of a 2x4 member. At 16 ft. between pick points, the stress was determined to be 24.4 lbs./(3.5 in. * 1.5 in.) which equaled 4.64 psi.

Figure 6 details the stresses in the top and bottom chord of the truss based on the location of the pick points for the truss. All of these values indicate stress levels below 22 pounds per square inch (psi). For tension members using #2 SYP 2x4 members, the allowable stress is 875 psi (American Wood Council, 2005). Obviously, there is no danger of exceeding this stress for members in tension. For compression members, the allowable critical stress varies with the unbraced length of the members. Using current NDS design parameters and an unbraced length equal to the full 30 ft. of the truss yielded an allowable compressive stress of 45 psi which is approximately twice the maximum chord stress. Current lifting recommendations correspond to a maximum stress of approximately five psi well below any limiting stress values in the wood.

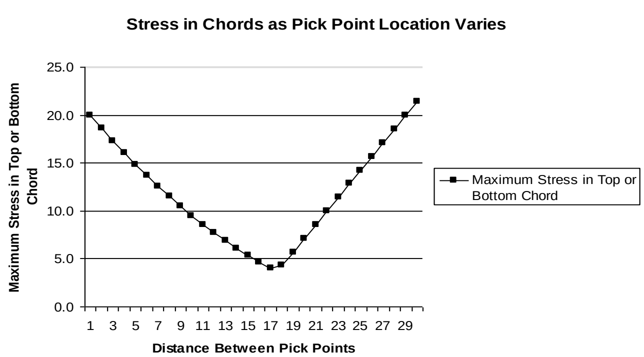

Figure 6: Stress in top and bottom chords as pick point location varies.

Author's Analysis and Conclusions

Current industry standards for lifting a 30 ft. truss indicate a distance of approximately 15 ft. between pick points. No known cases of failure were identified when these recommended guidelines were followed. However, industry experts recognize that there is substantial lateral deflection of trusses during erection. This deflection has a potential to split truss chords and damage connections so that the load capacity may be compromised in the finished structure.

This study has focused on a detailed analysis of this lifting guideline for a 30 ft. truss. Results indicate that top and bottom chord stresses are substantially below limiting allowable design stresses. However, results do indicate that NDS required SR ratios are exceeded for the top chord with this guideline if 15 ft. between pick points is used. In fact, the truss bottom chord is in compression for the full length of the truss with pick point spacing of 15 ft.. As the distance between pick points increases slightly over 15 ft., positive bending occurs in the center of the truss, and the bottom chord experiences tension for the middle portion of the span. This substantially improves the SR ratio for the bottom chord; however, existing limiting values of SR are exceeded for both the top and bottom chords in this condition. These values indicate a propensity of the truss to buckle. The author recommends that it may be prudent to devise a lifting strategy for trusses where SR is balanced for both top and bottom chords. Such an approach is not addressed in the current literature. Further study is needed in this area to determine if an SR value of 50 is appropriate or if a higher value could be tolerated for erection.

A major issue in this analysis is the use of the NDS defined SR value without a modifier for end supports. This approach works well in wood construction since almost all post and beam construction has columns with pinned ends. Pinned ends yield an effective length factor (K) of one. Thus, K*SR = SR for most wood compression members. If an effective length factor for the top and bottom chord of a truss during lifting was used, it appears reasonable that it would be greater than one. This is especially true for the cantilevered end of the truss where K would essentially be two. Higher K values would magnify SR values that are already out of line based on NDS criteria. This could be particularly troublesome as truss length becomes longer than 30 ft.. A detailed study of this is recommended.

If a K factor is added, one possibility is that it may offer an opportunity to improve the effectiveness of truss lifting. For example, K is less than one for a fixed condition. If a mechanism could be developed that attached to the truss and lifting sling and essentially provided a fixed condition, the effective slenderness ratio for the truss could be reduced. Such a device may essentially clamp the truss at the point of lifting to prevent out of plane buckling at that location. This would limit the propensity to buckle and improve safety on the job site.

The author recommends that this analysis approach be extended to longer span trusses where lateral buckling is more likely. Consideration should be given to setting pick point locations so that slenderness ratios of the top chord and bottom chord compression elements are balanced.

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