Permanent Bracing Design for
MPC Wood Roof Truss Webs and Chords

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Biological Systems Engineering

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March, 2000
Blacksburg, Virginia

Keywords: Truss, Bracing, Wood, Roofs, Construction, Residential

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(ABSTRACT)

The objectives of this research were to determine the required net lateral restraining force to brace j-webs or j-chords braced by one or more continuous lateral braces (CLB's), and to develop a methodology for permanent bracing design using a combination of lateral and diagonal braces.

SAP2000 (CSI, 1995), a finite element analysis program, was used to analyze structural analogs for three sets of truss chords braced by n-CLB's and one or two diagonals, one web braced by one and two CLB's, and j-truss chords braced by n-CLB's.

System analogs used to model five eight-foot truss chords braced by three CLB's and one diagonal, six twenty-foot truss chords braced by nine CLB's and two diagonals, and eleven twenty-foot truss chords braced by nine CLB's and two diagonals were analyzed. For each of the three cases analyzed, the chord lumber was assumed to be 2x4 No. 2 Southern Pine (S. Pine) braced by 2x4 STUD Spruce-Pine-Fir (SPF). Chord load levels of 10% to 50% of the allowable compression load parallel-to-grain assuming l_e/d of 16 were studied. All wood-to-wood brace connections were assumed to be made with 2-16d Common nails. A nonlinear load-displacement function was used to model the behavior of the nail connections.

Single member analogs were analyzed that represented web members varying in length from four-feet to twelve-feet braced by one and two CLB's. The web and CLB's were assumed to be 2x4 STUD SPF. The web members were also analyzed assuming 2x6 STUD SPF.

Single member analogs were analyzed that represented chord members varying in length from four-feet to forty-feet braced by n-CLB's spaced twenty-four inches on-center. The truss chord was assumed to be No. 2 Southern Pine and the CLB's were assumed to be STUD SPF. The chord size was varied from 2x4 to 2x12 and connections were assumed to consist of 2-16d Common nails. The system analog analysis results were compared to the single member chord analysis results based on the number of truss chords and the diagonal brace configuration.

For the three cases studied involving multiple 2x4 chords braced as a unit (and believed to be representative of typical truss construction), the bracing force from the single member analog analysis was a conservative estimate for bracing design purposes. It was concluded that the single member analysis analog yields approximate bracing forces for chords larger than 2x4 and for typical constructions beyond the three cases studied in this research.

For analysis and design purposes, a ratio R was defined as the net lateral restraining force per web or chord divided by the axial compressive load in the web or chord. For both 2x4 and 2x6 webs braced with one CLB, the R-value was 2.3% for all web lengths studied. For both 2x4 and 2x6 webs braced with two CLB's, the R-value was 2.8% for all web lengths studied. The web and CLB lumber species did not affect the R-values for the braced webs.

Calculated R-values for truss chords, 2x4 up to 2x12, braced by n-CLB's assumed to be spaced two feet on-center for chords four to twelve feet in length ranged from 2.2% to 3.0%, respectively. For chords from sixteen to forty feet in length, R ranged from 3.1% to 2.6%, respectively. The lumber species and grade assumed for the chord and CLB did not affect the R-values for the truss chords.

A step-by-step design procedure was developed for determining the net lateral restraining force required for bracing j-chords based on the results of the single member analogs studied. The required total lateral restraining force for j-compression members in a row can be calculated based on the R-value for or the number of CLB's installed at 2 feet on-center, the design axial compression load in the chord, and number of trusses to be braced.

Acknowledgements

I would like to extend my thanks to Dr. Frank E. Woeste for his everlasting support and confidence in me. I would like to thank Dr. Woeste and Dr. John Perumpral for the financial support and guidance extended to me throughout my stay here at Virginia Tech. In addition, I would like to thank Dr. Dan Dolan and Dr. Seigfried Holzer for serving as my committee and helping me finalize this work.

Additionally, thanks:

To my husband, Casey, who has loved and supported me through it all.

To my father for his support and guidance all these years.

To my mother for her wisdom and excellence in everything she did.

To my brothers, David, John, and James for teaching me how to survive, even in the tough times.

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1. Introduction

The distinction between permanent bracing and temporary bracing has been a gray area in the wood truss industry for many years. Often temporary bracing and permanent bracing elements are the same, but in other cases less overlap in function is evident. It is important to make the distinction between temporary and permanent bracing because different parties are currently responsible for the design and installation. All current truss industry documents state that the responsibility for permanent bracing design lies with the building designer while the responsibility for temporary bracing design lies with the erection contractor.

Code approved ANSI/TPI 1-1995 National Design Standard for Metal Plate Connected Wood Truss Construction (TPI, 1995) defined the responsibilities of the building designer, truss designer, and general contractor. ANSI/TPI 1-1995 and WTCA 1-1995 Standard Responsibilities in the Design Process Involving Metal Plate Connected Wood Trusses (WTCA, 1995) state that permanent bracing for the structure, including trusses, is to be determined by the building designer. The contractor is responsible for installing all permanent bracing details specified by the building designer. In addition, WTCA 1-1995 states the contractor must "determine and install the temporary bracing for the structure, including the Trusses" (WTCA, 1995).

Consideration of permanent and temporary bracing of metal plate connected wood trusses during design and construction is very important in the safety of erecting and maintaining a structure. Trusses are very strong when they are properly installed and braced, but due to the geometrical shape of a truss there is very little resistance to out-of-plane bending. Bracing, whether it be temporary or permanent, is important to help resist the trusses from deflecting laterally causing the trusses to topple over and cause collapse (Kagan, 1993; Vogt and Smith, 1999).

While many factors can cause an erection accident, probably no factor contributes more to erection accidents than a lack of diagonal bracing. Most truss related accidents are related to improper bracing during construction. Either the temporary bracing was not adequate, the permanent bracing was not adequate, or possibly either type was never installed (Kagan, 1993; Woeste, 1998).

Permanent truss bracing can include several different components, but are typically designed using one of two options:

- continuous lateral braces with diagonals
- sheathing such as plywood or OSB

If carefully designed, the temporary bracing can serve dual roles and be used as permanent bracing also. However, the building designer must take precautions since there are currently limited design guidelines for permanent bracing design.

Objectives

The objectives of this research were to determine the required net lateral restraining force to brace j-webs or j-chords braced by one or more continuous lateral braces (CLB's), and to develop a methodology for permanent bracing design using a combination of lateral and diagonal braces.

Three diagonal bracing systems were addressed in this research. Case I anticipated a web braced with either one or two CLB's. The one CLB case is depicted in Figure 1.1. Case II anticipated one diagonal brace connected to the bottom side of a top compression chord of trusses that extends across the entire width of the chord as depicted in Figure 1.2. The third case consisted of two diagonal braces forming a V-shape spanning half of the width of the compression chord as illustrated in Figure 1.3. Both Case II and Case III assume the continuous lateral braces are equally spaced. The angle theta (θ), in Figure 1.2 and Figure 1.3, represents the angle between the diagonal brace and the CLB. Ideally, theta (θ) should approximately equal 45°. In practice, theta depends on the number of chords

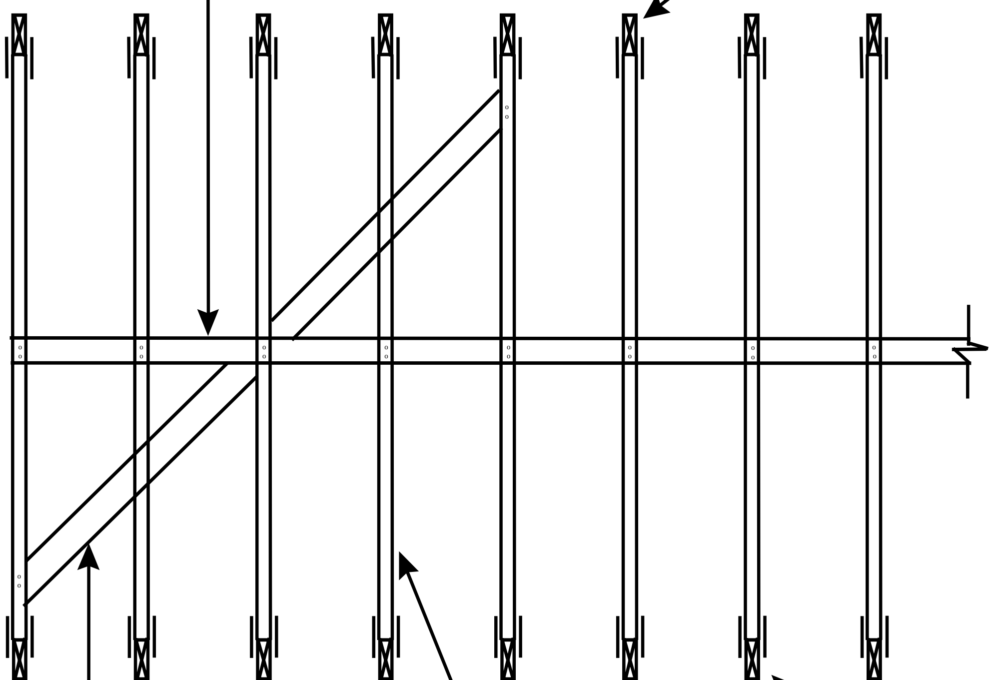


Figure 1.1. j-truss webs are braced with one CLB and one diagonal that crosses the truss webs.

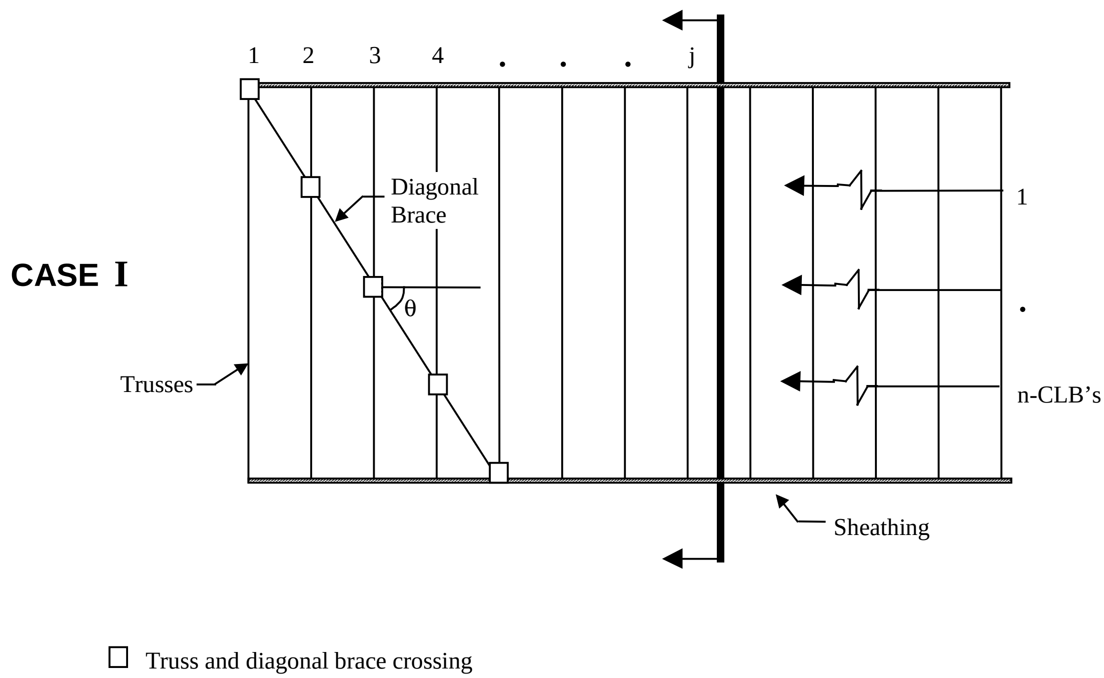


Figure 1. 2. j-truss chords are braced using one diagonal that crosses trusses.

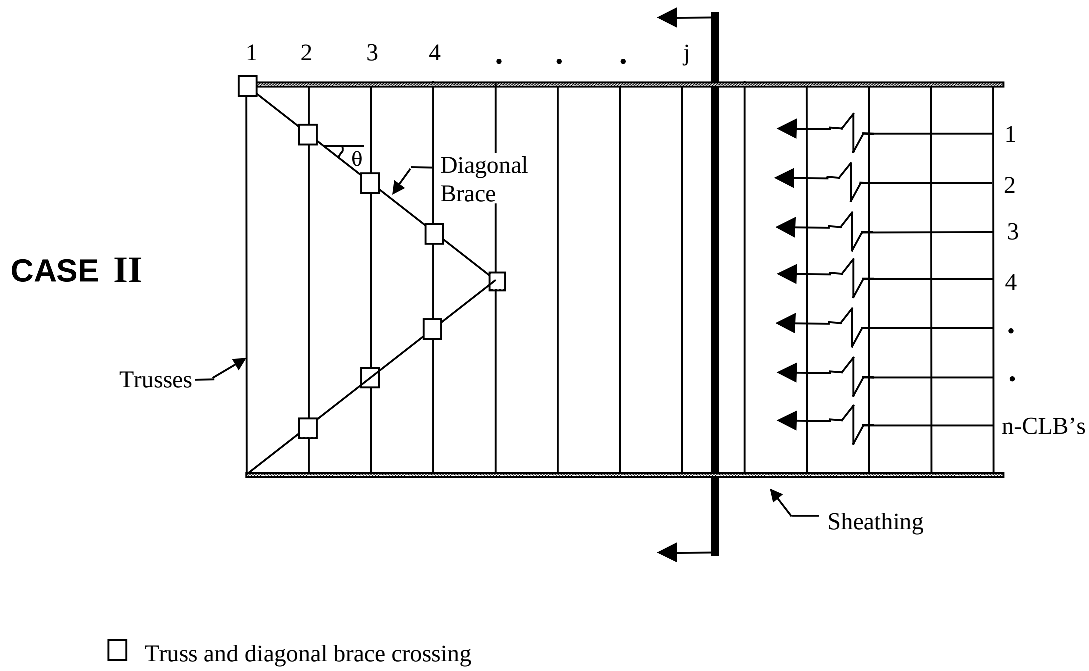


Figure 1. 3. j-truss chords are braced with two diagonals in a V-shape

crossed by the diagonal brace and the distance between trusses, it is therefore difficult to obtain an angle of exactly 45°.

2. Background and Literature Review

2.1 Temporary Bracing Principles

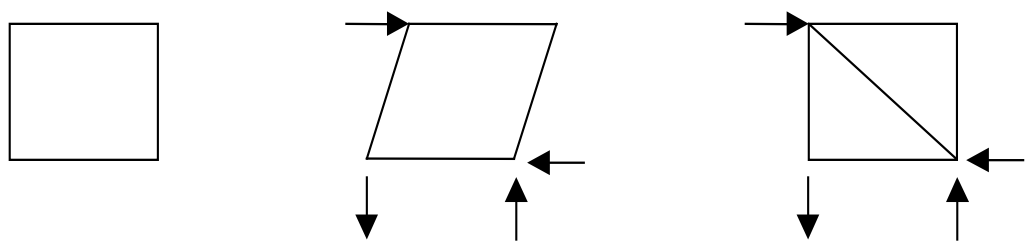
2.1.1 Triangle Theory

The design of truss bracing when using dimension lumber is based on the fact that triangles are structurally stable. Except for the case of a moment resisting frame or box, most shapes, such as squares and rectangles will distort when a force is applied as shown in Figure 2.1 (b).

When a member is added to the square to form two interrelated triangles, as shown in Figure 2.1 (c), the force applied will not allow the structure to collapse unless a connection or member is broken. Meeks (1998) also illustrated this theory by noting that adding a diagonal to an unstable shape, such as a square, adds stiffness and therefore keeps the structure from deforming.

The triangle principle is typically used in designing temporary bracing for a wood truss roof structure. Triangles must be formed between the chords, lateral bracing, and diagonal bracing for a structure to be stable. The chords and lateral bracing form the legs of the triangles at specified intervals. The diagonal braces create the hypotenuse of each triangle.

The following series illustrates the need for triangulation between lateral and diagonal bracing when bracing trusses. In Figure 2.2, line segments AB and CD are analogous to truss top chords in compression. P represents the compression force in the chords and the spring represents a minimum level of support provided by the lateral braces with no diagonal braces. When a spring is shown as part of a structural model, it is assumed that the force is proportional to the displacement of the spring. The loaded structure, as



(a) (b) (c)

Figure 2.1. **(a) A square is structurally unstable.**

(b) When a force is applied, a square will distort.

(c) A member can be added to form two interrelated triangles, which are structurally stable.

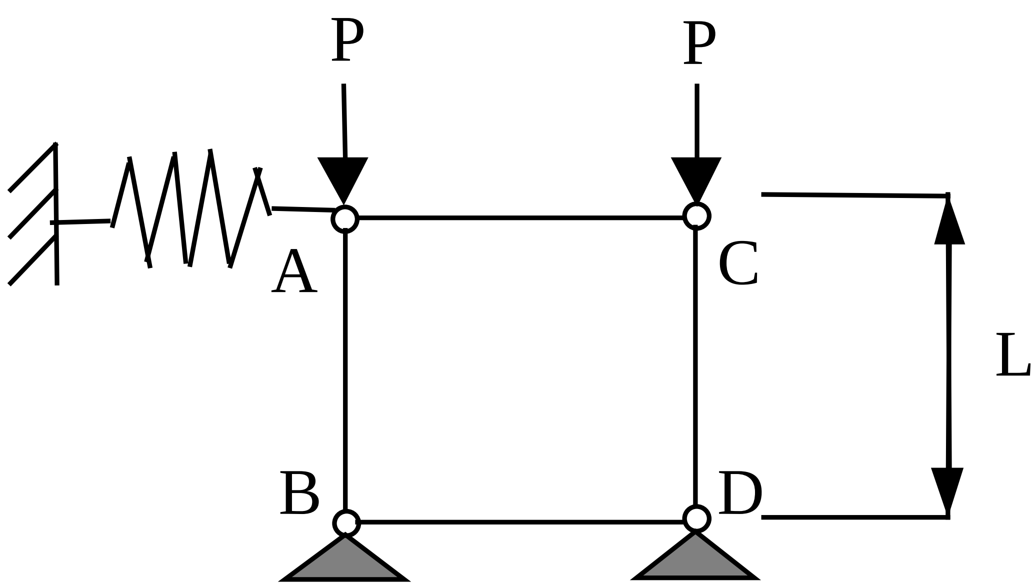


Figure 2.2. Assuming perfectly straight columns that do not produce any lateral forces, the structure is in "unstable equilibrium".

depicted in Figure 2.2, currently in “unstable equilibrium,” is assumed to be composed of perfectly straight columns that do not produce any lateral forces. Under the assumption of perfect columns, the force in the spring is zero. The structure appears to be stable but any change in the environment can cause this structure to displace as shown in Figure 2.3.

Displacement, Δ, in Figure 2.3 is exaggerated, but it represents the structural geometry that is in stable equilibrium. The spring is loaded by a force equal to the spring stiffness, k, times the displacement, Δ. Assuming a linear relationship between the P and Δ, if the load is increased ten percent, the spring force will increase proportionally. Any additional loading in the truss chord depicted by P will cause more force in the spring (the lateral braces). Assuming a small displacement, Δ, the force, F, in the lateral braces can be determined. For the derivation of Equation 2.1, it was assumed that the members are pin connected. Summing the moments about Point B, the result is

$$FL = 2 \times P\Delta \tag{2.1}$$

or

$$F = \frac{2 \times P\Delta}{L} \tag{2.2}$$

If the forces, P, increase, then the deflection, Δ, and the spring force, F, will increase. When F exceeds the ultimate capacity, F^{Σ}, of the spring, the result is collapse as illustrated in Figure 2.4.

The amount of force in the spring, or the lateral moment of the frame, can be minimized by adding a diagonal brace, as illustrated in Figure 2.5. This altered system can safely resist an increased compression force, P. When P is increased, a small deflection, Δ, will occur as illustrated in Figure 2.6. In the case of a braced wood truss system, the small deflection, Δ, is primarily the result of inelastic deformation in the nail connections of the lateral and the diagonal braces (Waltz, 1998).

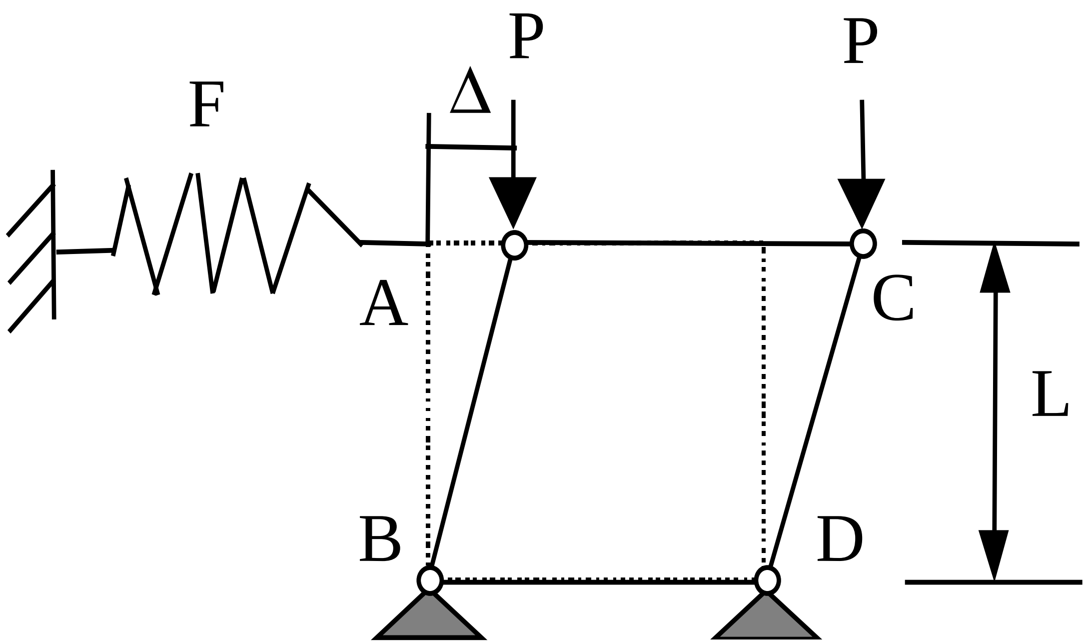


Figure 2.3. A change in the environment will cause the structure to displace. The amount of deflection, Δ, is assumed to be small. The structure is now in stable equilibrium.

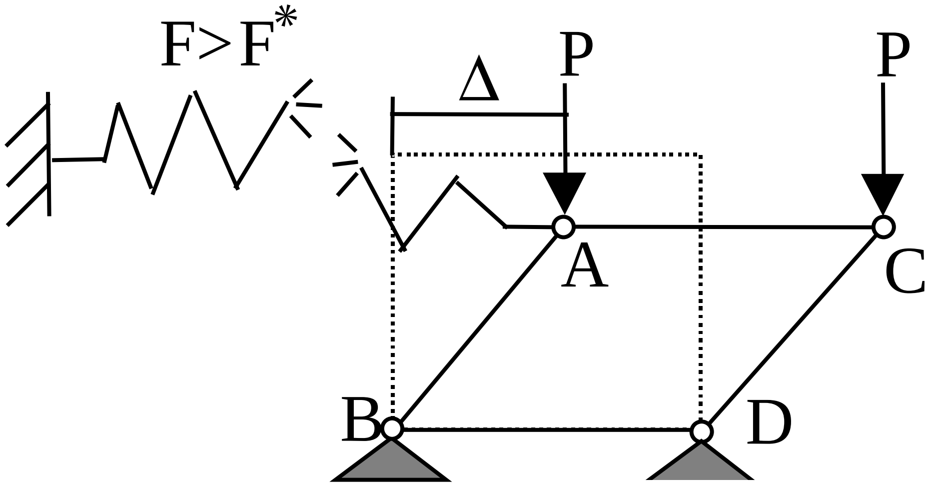


Figure 2.4. When the spring force, F, exceeds the ultimate capacity of the spring, F^*, the result is collapse.

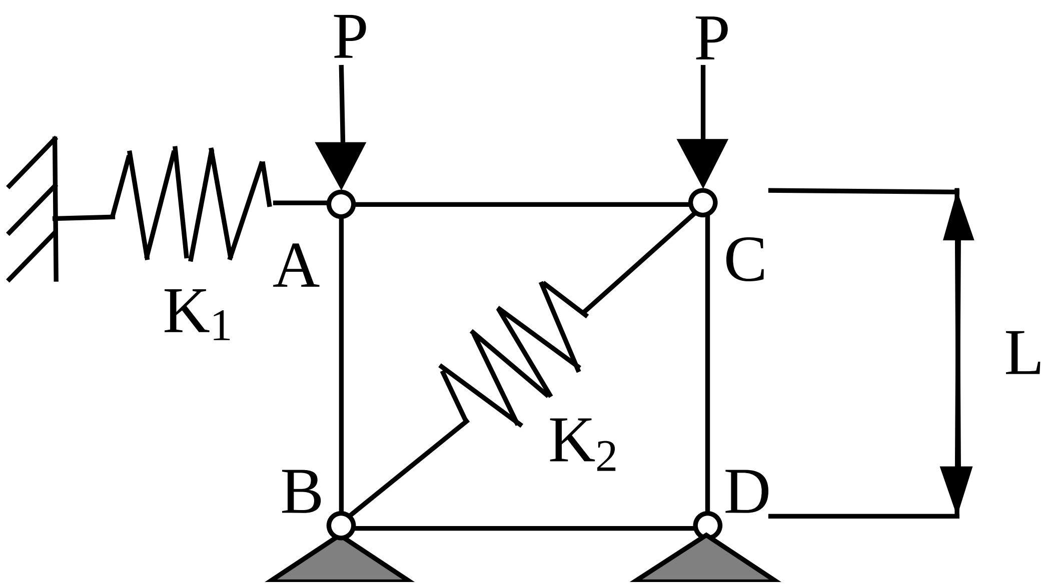


Figure 2.5. The amount of force in the spring can be minimized by adding a diagonal brace. The diagonal braces are represented by a spring.

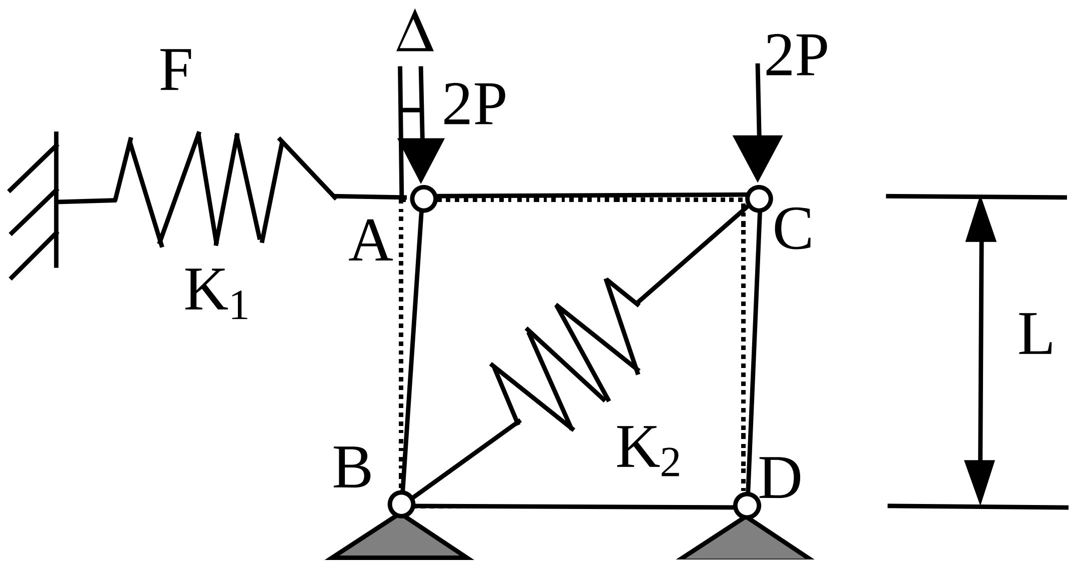


Figure 2.6. The system can hold an increased compression force, represented by 2P. A small deflection, Δ, will occur as a result of the elastic deformation in the nail connections of the laterals and diagonals.

In a braced wood truss system, K_1 represents the stiffness of the lateral braces. K_1 includes the nail slip between the lateral brace and the truss chord, and axial deformation of the lateral brace due to accumulated brace force. Without diagonal braces installed, the stiffness of K_1 is negligible because no positive connection is present to restrain the brace from translation. When the diagonal braces are installed, a triangle is completed. It can not distort without stretching the brace in Figure 2.6 represented by spring K_2. The K_2 spring stiffness includes the slip of the connection between the diagonal brace and the lateral brace, the axial stretch developed in the diagonal due to axial force, and the slip of the connection between the diagonal and the truss chords. A reliable bracing system must include both laterals and diagonals as represented by springs K_1 and K_2.

2.1.2 Temporary Bracing Planes

Temporary bracing is designed to hold trusses in place in a vertical plane until they can be stabilized for in-service conditions by permanent bracing. When considering temporary bracing for a structure, four planes must be considered. The roof plane, traditionally known as the top chord plane, consists of members used to construct the roof. The ceiling plane, traditionally known as the bottom chord plane, consists of members used to construct a ceiling. The web plane is the plane formed by the webs in the truss. The fourth plane to be considered is put in a category classified as "other" planes. This type of plane is neither a roof nor ceiling plane or using traditional terminology can be classified as either top chord or bottom chord planes. A piggyback truss is a good example of a truss having a plane in the "other" category. Figure 2.7 illustrates a piggyback truss with lateral bracing. The top chord of the bottom section and the bottom chord of the top section do not fall into the category of top chord plane and bottom chord plane discussed in ANSI/TPI 1-1995 (TPI, 1995).

2.2 Stability

The top chord member in a truss can be considered a beam-column in design. The top chord is subjected to axial compressive loads and lateral loads, which can cause bending. The combination of loads induces stresses and deformations in the top chord that cannot be analyzed as a beam or a column independently. The bending and axial effects are both

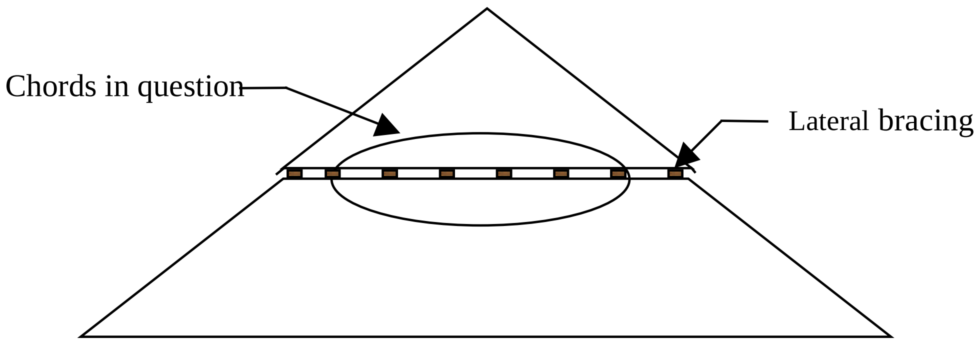


Figure 2.7. **When considering a piggyback truss, it is difficult to classify the top chord of the bottom section and the bottom chord of the top section in terms of "top" or "bottom" chord planes to be considered for temporary bracing.**

significant and therefore must be considered during design. Both the deflection effects in a beam and the stability concerns in a column must be considered (Chen and Lui, 1987).

When analyzing a beam-column as a beam, loading on the beam will cause lateral deflections. Theses lateral deflections and bending moments that result are usually referred to as primary bending moments and deflections. When analyzing the beam-column as a column, the axial forces in the member can cause instability at certain critical values. Since a beam-column combines both the axial and the bending effects, the axial force will produce additional lateral deflections as it is carried through the already deflected beam-column (Chen and Lui, 1987). To distinguish between the effects of both loading cases, the effects due to the bending are considered primary deflection and moment, and the additional effects due to the axial forces are considered secondary deflection and moment.

Stability of the beam columns relies on the geometry of the truss chord, composition of the system, the applied loads, and the material properties of the member. But one difference between beams, columns, and beam-columns is that beam-columns can have a relative translation between the member ends. The relative translation can change the behavior of the beam and must be considered in sway cases (Chen and Lui, 1987).

2.3 Buckling and Bracing

Lateral bracing of columns and beams has been studied for many years. Plaut et al. (1993) focused on lateral bracing forces of columns braced with two unequal spans, Plaut (1993) focused on lateral bracing forces of columns with two spans, and Plaut et al. (1995) focused on columns with 3 equal or unequal spans. Winter (1960) focused on an overall study of lateral bracing of beams and columns. The previously mentioned authors all state that columns can buckle in different shapes or modes. Since columns are not perfectly straight an imperfection in a column can influence the buckling load and mode for any given column. Initial crookedness and out-of-plumbness can be considered imperfections along with material imperfections such as knots and varying modulus of elasticity.

A member can generally buckle in one of two mode shapes. The S-shape and the C-shape mode are illustrated in Figures 2.8a and 2.8b. When designing a member, the designer usually prefers the member to buckle in an S-shape mode. The S-shape is less critical and can be induced with lateral braces. However, if the lateral braces do not have the required stiffness, a C-shape mode will result. The C-shape mode is more critical for brace design as a result of all the bracing forces acting in the same direction. The total required bracing force increases as a result of the C-shape buckling mode. Smith (1991) illustrated the effects of initial crookedness on a member with the C-shape buckling mode. Figures 2.9a and b are from Smith (1991).

2.4 Temporary Bracing Guidelines Available from the Industry

Temporary bracing determination and installation are essential steps for the safe installation of trusses. The purpose of temporary bracing includes positioning and stabilizing trusses until permanent bracing or other building components can be installed.

Four industry documents currently provide recommendations for temporary bracing, and a video on temporary bracing is available from WTCA (Alpine Engineered Products, Inc., 1996). The documents include DSB-89 Recommended Design Specifications for Temporary Bracing of Metal Connected Wood Trusses (TPI, 1989), HIB-91 Commentary and Recommendations for Handling, Installing, and Bracing Metal Plate Connected Wood Trusses (1991) Pocketbook (TPI, 1991a), HIB-91 Summary Sheet (TPI, 1991b), and HIB-98 Summary Sheet (TPI, 1998). The Truss Plate Institute has developed all of the currently available documents.

2.4.1 DSB-89

The target audience of DSB-89 included individuals with a technical background such as licensed engineers, architects of record, and licensed truss design engineers. DSB-89 was developed for typical truss designs, spaced four feet on-center or less. Typical truss

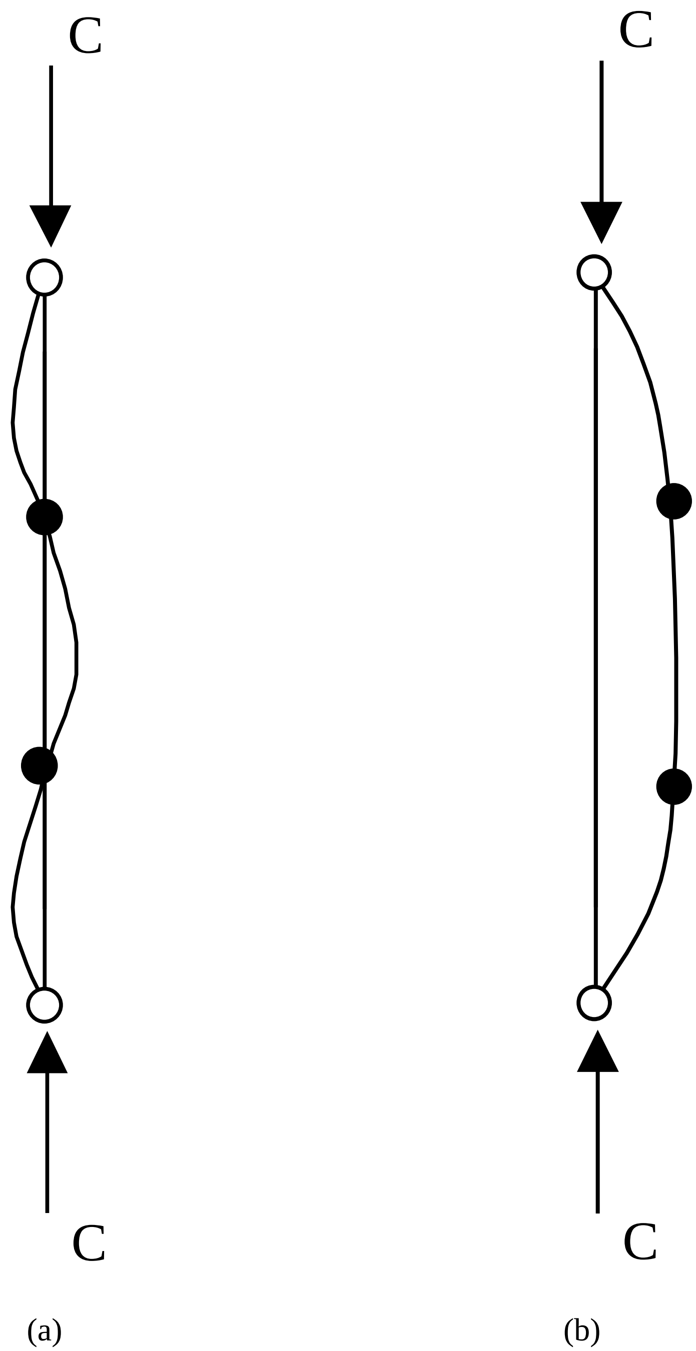
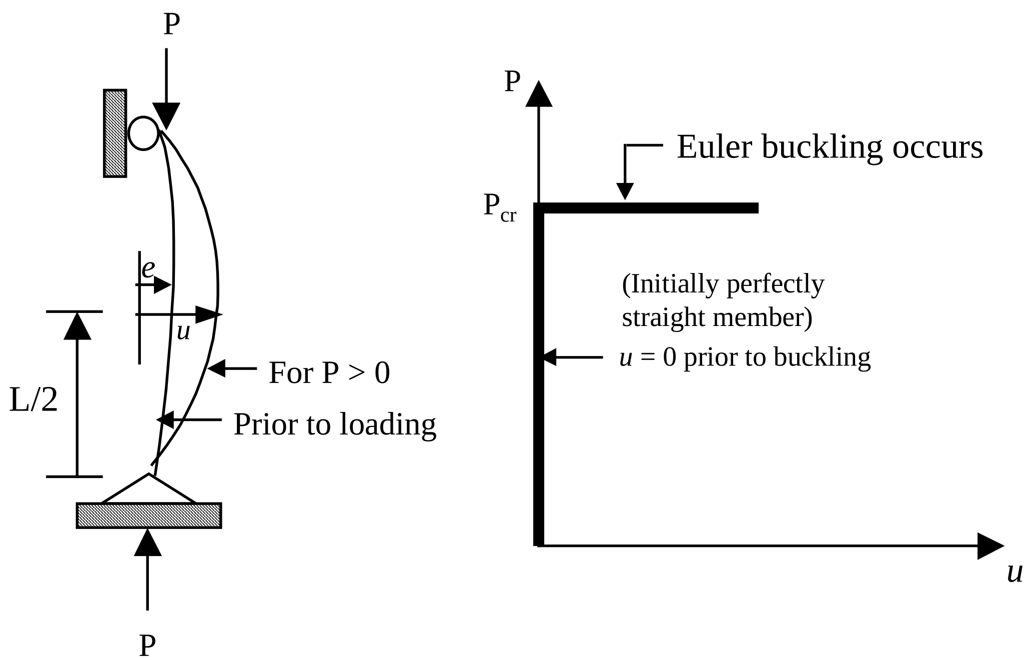


Figure 2.8 **(a) S-shaped buckling mode of a column under an axial load**

(b) C-shaped buckling mode of a column under an axial load where the brace does not have the required stiffness to resist the load.



(a) (b)

Figure 2.9. (a) Initially crooked member as shown in Smith (1991)

(b) Load vs. deflection for *e* = 0 as shown in Smith (1991)

designs included are symmetrical dual-pitched triangular, scissors, mono-pitched triangular, and 2x4/2x6 parallel chord metal plate connected wood trusses.

To determine a recommended brace spacing, a design dead load that represented the dead weight of the trusses was assumed to be 5 psf. The load was increased at a rate of 1 psf per 5 feet of span above a span of 25 feet for flat or parallel chord trusses. The load was increased at a rate of 1 psf per 7 feet of span above a span of 35 feet for triangular trusses. According to DSB-89, Commentary Section 5.6, the increase of the dead load weight over the increasing span of the truss includes an approximation of the weight of several construction workers on the truss. DSB-89 did not include live or wind loads in the analysis used to determine the bracing schedules.

The specification includes several assumptions in the analysis for required bracing. When considering L/d, a limit of 75 is permitted. The increase in the limit was due to the 50% increase allowed by the National Design Specification for Wood Construction (AF&PA, 1997) for temporary construction. The purpose of the original limit of 50 addresses creep buckling in a column, but due to the short duration of construction time, creep was determined to not be a factor and therefore the 50% increase was used (TPI, 1989).

Design criteria used for initial deflection of the top chord takes into account the natural imperfections of the material. According to DSB-89, an allowable initial deflection of the chords is L/200 or 2 inches, whichever is less. However, an initial deflection in the webs was not discussed.

DSB-89 requires a connection to consist of a minimum of 2-16d Common nails. Figure 8 in DSB-89 gives the allowable load per connection based on the lumber species and the number of nails used.

The brace force, which acts at a right angle to the top chord of the truss to help restrain the chord from buckling in the lateral direction, is assumed to be 2% of the maximum axial force. This assumption was based on the work of William Zuk. Zuk (1956) evaluated eight typical cases to determine a general relationship of the applied force or moment and the lateral bracing force. In his analysis, all columns were assumed to have an imperfection. The analysis was limited to elastic materials and small deflections. It was determined that lateral force is a direct function of the initial deflection. Zuk also showed that the value of the bracing force could be assumed to be 2% of the maximum applied load for axially compressed steel columns.

The brace force is considered to be cumulative at each row of lateral braces (TPI, 1989). This force must not exceed the strength of the connection at each truss. The accumulated bracing force must be transferred to a diagonal by means of a connection. The force in the diagonal must then be transmitted to the roof structure by additional connections between the diagonal brace and the structure.

The temporary bracing strategy presented by DSB-89 involves the principles of triangles in the various planes. Therefore, when designing temporary bracing for any structure, diagonals must be used to help stabilize the lateral bracing along with distributing the accumulated loads as shown in Figures 2.10 a and b.

DSB-89 provides design tables for quick reference when designing temporary bracing. These tables are limited to the shapes previously mentioned and the lateral brace configuration illustrated by each table. The design is based on the loads previously mentioned without live loads included. Therefore, permanent bracing design for webs or chords (without sheathing) can not be determined from the DSB-89 tables.

2.4.2 HIB-91 Pocketbook

Commentary and recommendations presented in this pocket size booklet are based on the information provided by DSB-89. The main differences between DSB-89 and HIB-91 are the target audience and the truss spacing limits.

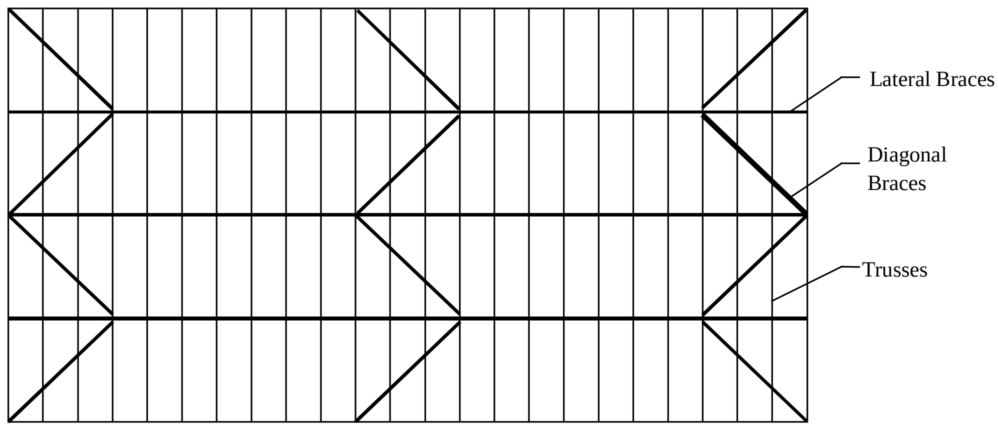


Figure 2.10a. Trusses with lateral and diagonal bracing installed as shown in DSB-89.

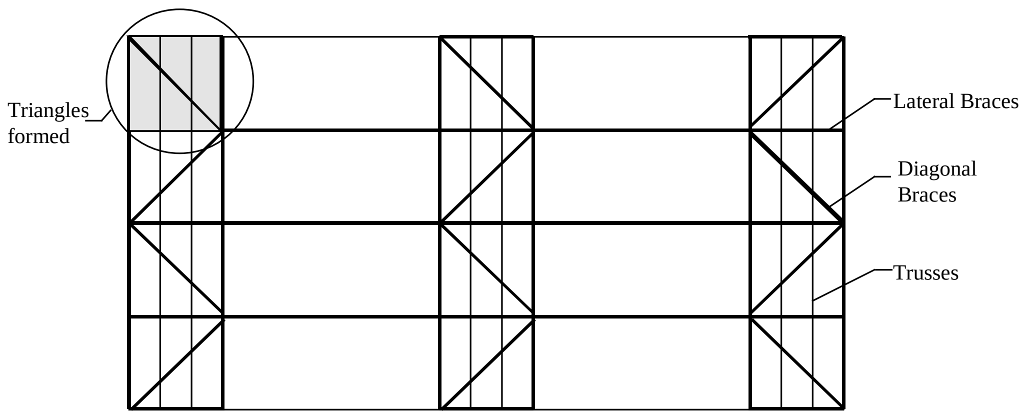


Figure 2.10b. Two triangles are created by a diagonal, two chords, and two lateral braces.

HIB-91 pocketbook was developed for truss installers, contractors, and building designers. The commentary and recommendations only apply to trusses spaced no greater than 2-feet on-center with a span 60-feet or less, and 54-feet or less for mono slope trusses. For spans over the stated limits, it is recommended that a registered professional engineer design the temporary bracing.

2.4.3 HIB-91 Summary Sheet

HIB-91 Summary Sheet is developed for building designers and installers. The HIB-91 Summary Sheet contains primarily graphic information from HIB-91 Pocketbook. The purpose of Summary Sheet matches the scope of the Pocketbook --up to 60 feet in span (54 feet for monoslope trusses) and two feet or less on-center spacing. This document is typically shipped with truss deliveries. Truss handling and bracing recommendations are given by tables and drawings of braced roofs ready for the application of sheathing.

2.4.4 HIB-98 Post-Frame Summary Sheet

HIB-98 Summary Sheet is written for post-frame construction. A step-by-step procedure is presented for truss installation. The recommendations provided by HIB-98 are only relevant if the structure is a post-frame building with metal-plate-connected wood trusses. The recommendations are based on several assumptions about the structure. One important assumption stated is that the “end-walls have columns which extend to the top chord of the gable end truss with adequate contact between the top chord and column for a structural connection” (TPI, 1998). A second important assumption stated is that the “side-wall columns extend above the mid-height of the truss heel at the connection of the column and the truss” (TPI, 1998).

Temporary bracing schedules provided in HIB-98 were developed assuming a load including two workers and their equipment. The document was produced for the post-frame industry because no other documentation specific to widely spaced trusses was available. A committee from the National Frame Builders Association (NFBA) was appointed to develop the document and truss industry people were then called on for review (Smith, 1999). HIB-98 was produced as a matter of safety and as a source of useful information for the contractor and anyone else involved at the job site, and the recommendations do not provide for resisting wind loads (TPI, 1998). Illustrations are used to clarify the written information. Updated practices are illustrated including column chaining but the specification is restricted to symmetrical triangular trusses with top chord pitches of 3:12 or greater, and a flat bottom chord. For any other truss configuration, it is recommended that a registered professional engineer be consulted.

2.4.5 Alpine/WTCA Video on Temporary Bracing

Alpine Engineered Products, Inc.(1996) in cooperation with WTCA produced a temporary bracing video that contains a segment on "buckling behavior" of a compression chord. A 60-foot parallel chord roof truss was placed in a testing laboratory, and inadequately braced by a series of temporary lateral braces only. The bottom chord was loaded with buckets containing weights that simulated the weight of truss installers. With one bucket lowered onto the bottom chord, no noticeable truss movement is visible in the video. Then, the second bucket was lowered onto the truss. The top chord slowly buckled into the classic S-shape, with the chord severely bending between points of lateral support. Finally, a third bucket was lowered on the truss and the truss violently collapsed. Reviewing this sequence can be very educational for erection personnel and others that design truss erection bracing, as "buckling behavior" may not be intuitive to everyone involved in wood truss erection.

2.5 Other Documents Providing Guidelines for Temporary and Permanent Bracing

Metal plate connected wood trusses are not the only building components that need to be braced laterally to achieve maximum strength. Steel trusses must also be braced laterally and therefore designers experience some of the same design challenges as for wood. The AISC Load and Resistance Factor Design (LRFD) Specification is one design method that considers lateral bracing and is discussed in Section 2.5.1. South Africa also has a standard for considering lateral bracing of multiple members. The South African Standard is discussed in Section 2.5.2.

2.5.1 LRFD Steel Approach

Dr. J.C. Smith, North Carolina State University, has written a textbook that follows the steel LRFD approach for bracing requirements (Smith, 1996). In considering bracing stiffness and strength requirements, the S-shaped buckling mode is desired. The S-shaped bucking mode as previously discussed is the most desirable buckling mode because brace forces act in opposing directions causing the net force of the system to approach zero. To achieve the asymmetrical bucking mode the proper amount of stiffness is required. The equations provided to determine the required strength are dependent on the S-shaped buckling mode (Smith, 1996).

In Smith's (1996) designs, all the braces are assumed to have the same stiffness. In the case of three braces where h = L/4, where L is the length of the column and h is the effective length, the displacement is maximum at the center brace and the other two braces displace a reduced amount of 0.707 times the maximum (Smith, 1996). For h = L/n where n is large, the strength requirements can be determined assuming the required stiffness is provided for the column to buckle asymmetrically (Smith, 1996). Equations 2.3 and 2.4 are used to estimate the required strength and stiffness of the brace (Smith 1996).

$$P_b = 0.008 * n * P_{ny} \tag{2.3}$$

$$S_b = \frac{8 * n * P_{ny}}{L} \tag{2.4}$$

where : P_b = the required bracing strength

S_b = required bracing stiffness

P_{ny} = axial force in the column

n = number of braces

L = length of column

Equations 2.3 and 2.4 are derived based on statics of the deformed structure.

The LRFD manual for steel is not directly applicable to wood. LRFD defines ϕP_n, the design compressive strength, with the assumption that the initial crookedness is a C-shape with a limit of L/1000 (Smith, 1996). The maximum out-of-plumbness is L/500. For wood these limits are not practical.

2.5.2 South African Standard Code of Practice…

South Africa has a provision in the South African Standard Code of Practice the Structural Use of Timber, Part 2: Allowable Stress Design (South African Bureau of Standards, 1994) for designing bracing for compression members. According to the code, the force on each lateral restraint, for a single strut braced against buckling can be determined using Equation 2.5.

$$P_L = \frac{0.10 * P_A}{(N+1)} \tag{2.5}$$

where: P_L = force on each lateral restraint

P_A = average axial force in the strut due to dead load only

N = number of lateral restraints over full compression

The code states that for truss members, the number of lateral restraints, N, is the number of restraints acting on the full span of the truss (South African Bureau of Standards, 1994).

For the case where lateral braces are used for multiple struts or trusses, Equation 2.6 can be used to estimate the cumulative force on each lateral brace, C_{PLN}:

$$C_{PLN} = P_L * n^{0.7} \tag{2.6}$$

where : P_L = force on each lateral restraint

n = number of struts being restrained

$n^{0.7}$ is based on the initial curvature of the struts. If all the struts had the same initial curvature, then the cumulative effect would be directly proportional to the number of struts. If the initial curvature of the members were random, then the cumulative effect on the laterally induced forces would be directly proportional to the square root of n. Since a combination of these two scenarios is possible, $n^{0.7}$ is an approximation based on the number of struts being restrained (South African Bureau of Standards, 1994).

2.5.3 Commentary for Permanent Bracing of Metal Plate Connected Wood Trusses

The Wood Truss Council of America has produced a document to provide guidelines for building designers who are responsible for permanent bracing design of metal plate connected wood trusses. Commentary for Permanent Bracing of Metal Plate Connected Wood Trusses (WTCA, 1999) contains an outline of the overall truss design responsibilities as previously discussed in Section 1. The commentary did not provide specific design requirements but it did outline the various locations in truss installations that typically require a permanent bracing design.

For the case where a truss has a long span or a high pitch and a piggyback truss must be used for shipping purposes, the building designer must design a bracing plan for the supporting trusses. The building designer must indicate the required spacing between diagonal braces needed to stabilize lateral braces. However, the truss designer must specify:

- The required spacing between each lateral
- The thickness of the bracing
- And minimum connection requirements between the braces and both pieces of the truss (WTCA, 1999).

The commentary provided several alternatives of how bracing the flat compression chord of the supporting truss (Figure 2.7) could be designed and states the following options:

> "... securely anchoring the lateral bracing to solid end walls designed to resist the lateral loading, connecting the lateral bracing into the roof diaphragm, adding diagonal bracing at intervals along the length of the building, adding structurally rated sheathing, or some other equivalent means" (WTCA, 1999).

There are no design guidelines however to help the building designer determine the necessary capacity of the diagonals or other support options used.

The commentary addressed many truss configurations and provided bracing options for different situations. It was clearly stated that the building designer has responsibility for the design of permanent bracing and although some permanent lateral bracing information may be shown on truss drawings, additional bracing design and details are needed to erect a reliable roof. An example was provided to illustrate the bracing needs the building designer needs to be concerned about (WTCA, 1999).

2.6 Previous Studies

2.6.1 Background

Miles Waltz studied the design requirements for bracing compression web members with one lateral brace. The lateral support provided to the webs by the bracing was intended to reduce the effective length of web members to prevent column buckling, or to increase safe load capacity of a truss web.

Waltz (1998) discussed two different types of lateral bracing and the needs for each. The first type of lateral bracing includes bracing to help trusses remain vertical under conditions such as wind, earthquake, or construction events. This type of lateral bracing helps provide stability to the entire structure and keeps trusses in their intended vertical plane. Diaphragm sheathing or a lateral and diagonals bracing system can be used for this type of support (Waltz, 1998). The second type of lateral bracing Waltz (1998) discussed is designed to reduce the effective length for flexural buckling of individual compression members. Under compression loads, the center of a compression member tends to translate laterally. This second type of lateral bracing was the concentration of Waltz's (1998) study.

In his discussion of lateral bracing, Waltz (1998) also noted the lack of information available for designing permanent truss bracing. Information is available for temporary bracing, as previously discussed, to help prevent accidents stemming from gravity and lateral loads during construction. Documents such as ANSI/TPI 1-1995 National Design Standard for Metal Plate Connected Wood Truss Construction (TPI, 1995) discussed the importance of such bracing and outlined design responsibilities for permanent bracing, but specific design information is not provided (Waltz, 1998).

Waltz (1998) concentrated on the case of a single brace at the center of the web and the effect of the brace on reducing the effective buckling length of the compression web. In doing this, his research objective was to determine if one of four existing analysis models could estimate required brace strength and stiffness. The four existing analysis models considered include Plaut's method (Plaut, 1993b; Plaut, 1993c), Winter's Method (Winter, 1960), the 2% Rule (Throop, 1947), and Tsien's method (Tsien, 1942).

2.6.1.1 Plaut's Method

Plaut's method for determining the required brace strength and stiffness for a single discrete brace located at mid-height of a column includes the following assumptions:

- linear elastic columns
- linear elastic braces
- brace placement at the shear center of the column
- homogeneous, isotropic column properties

Plaut (1993) and Plaut and Yang (1993) used differential equations of equilibrium to analyze stability of columns where the initial shape was assumed to be quadratic and sinusoidal. Due to the complexity of the resulting equations, Plaut (1993) introduced refined equations that could be used in design. Plaut's (1993) equations are based on the column buckling with reverse curvature. The additional moment caused by the reverse curvature is thought to increase the brace force. Plaut (1993) accounts for the additional moment with a 1.5 multiplier on the initial deflection of the column at mid-height.

2.6.1.2 Winter's method

George Winter (1960) used a rigid link model to estimate the strength and stiffness requirements for a lateral brace. Up to this time, most researchers had concentrated primarily on bracing strength alone. Winter (1960) recognized the need to include brace stiffness in the analysis of a bracing system.

Based on research done at Cornell University, Winter (1960) reported that a minimal amount of lateral bracing greatly increases the load capacity of columns and beams. Using his rigid link model illustrated in Figure 2.11, Winter (1960) developed equations to approximate the strength and stiffness requirements to fully brace an imperfect column. The column was assumed to buckle asymmetrically and the initial shape was assumed to promote the buckling mode. By summing moments about the support, Winter's (1960) Equations 2.7 and 2.8 can be derived.

$$K_{req} = \frac{4(P_e)}{L}\left(1+\frac{\Delta_0}{\Delta}\right) = K_{id}\left(1+\frac{\Delta_0}{\Delta}\right) \tag{2.7}$$

where: K_{req} is the stiffness required to produce full bracing,

K_{id} is the stiffness of an ideal column,

P_e is the Euler buckling load, and

Δ is the initial deflection or imperfection.

$$F_{br\text{-}req} = K_{req}\,\Delta = K_{id}\,(\Delta + \Delta_0) \tag{2.8}$$

However, Winter's (1960) stated that in order to account for the eccentricities and other imperfections in the column, initial lateral deflection at mid-height in Equations 2.7 and 2.8 can be approximately doubled when steel is the structural material. And when

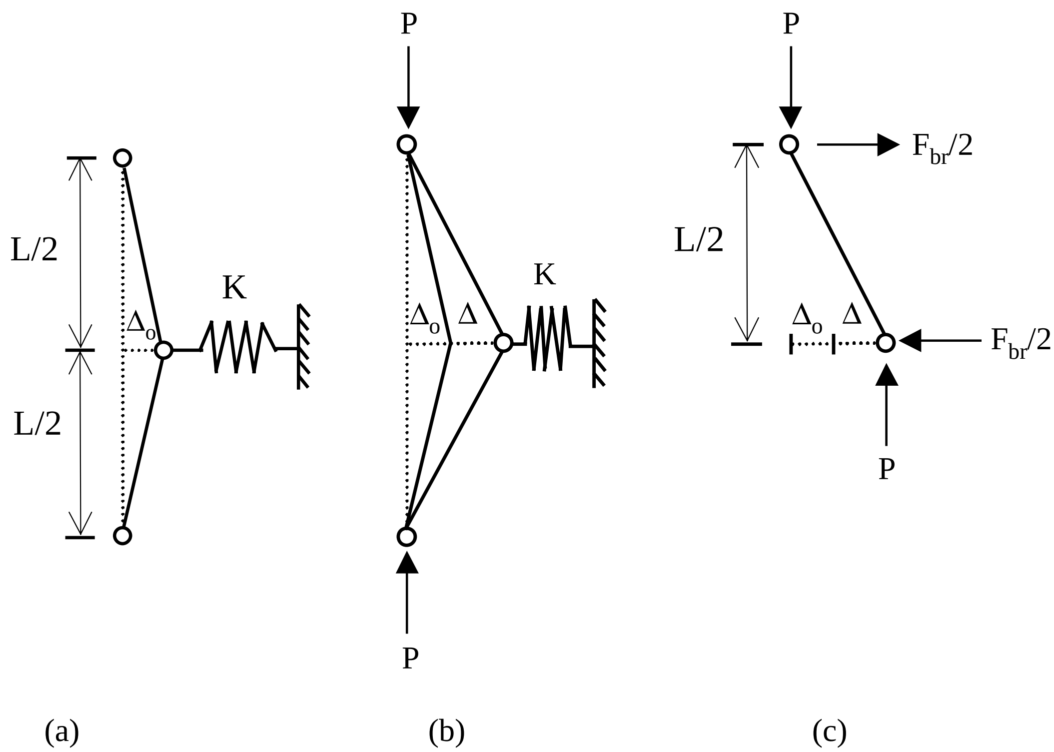


Figure 2.11. Winter's Rigid Link Model for Imperfect, Braced Columns as depicted by Waltz (1998), Yura (1996), and Winter (1960).

(a)A column with an initial deflection, Δ_0, with no axial load applied

(b)A column with an applied axial load and an additional deflection, Δ, at mid-height

(c)Force diagram of the column under applied axial load as depicted by Yura (1996), and Waltz (1998)

no other requirements are stated, a conservative estimate can be obtained by setting the initial lateral deflection equal to the additional lateral deflection ($\Delta_e = \Delta$) experienced at mid-height upon application of axial load. P_e can be assumed to follow code requirements and multiplied by the factor of safety specified within the code requirements (Winter, 1960).

Winter's (1960) findings have proved to be very useful in understanding bracing behavior (Yura, 1996). Yura (1996) expanded Winter's (1960) work to provide insight into cases where there is less than full bracing and the braces are not equally spaced. Yura (1996) and Winter (1960) concluded that braces with a stiffness equal to the ideal stiffness are not adequate for imperfect columns. The ideal stiffness is the bracing stiffness required for a fully brace a column, with no imperfections, where the applied load is equal to the Euler buckling load of the column. To fully brace a column, it is assumed that the lateral support is immovable (Winter, 1960). The ideal stiffness is only adequate for perfect columns.

2.6.1.3 Tsien's method

Using the energy method, Tsien (1942) investigated the problem of determining the strength and stiffness requirements for a laterally supported column. Tsien (1942) assumed the imperfect column to be linear elastic and the brace was assumed to be nonlinear elastic. A pair of equations relating the column load, the force in the brace and the initial and final deflections was developed to solve for the brace force and the deflection. One equation described the brace stiffness and the second equation described the lateral deflection.

2.6.1.4 2% Rule

The 2% Rule is a strength model based on a percentage of the axial load in a column needed to stabilize the column. Designers primarily use strength models during design due to the simplicity of the calculations. In the derivation of the 2% Rule, the column was assumed to be pinned at each end and at the center brace location. Throop (1947) explained where the 2% Rule originated and Nair (1992) and Waltz (1998) illustrated the use of a force balance in the development of the 2% Rule. The column is assumed to be one-inch out of plumb for an assumed story height of 100 inches (Throop, 1947). A compression chord braced at the center of its span will have a force of 1/100 above and below the brace as depicted in Figure 2.12. A force balance for the free body diagram at the brace is the basis for the 2% Rule (Nair, 1992).

2.6.2 Procedure

Waltz (1998) used finite element analysis to estimate the stiffness of support provided by a lateral and diagonal bracing system for a number of braced truss webs in a row. The finite element structural analog (FEM) Waltz used is illustrated in Figure 2.13. The lengths of the web members studied were 4, 6, 8, and 10 feet. The angle theta (θ) was the brace angle between the diagonal brace and lateral brace and should be approximately 45-degrees (TPI, 1991). Since the lateral and diagonal braces are assumed to intersect at the front and back of the same web member, the angle will not be exactly 45-degrees for the different length members (Waltz, 1998). (For the angle to be 45-degrees, the truss spacing must be equally divisible by the square root of two times the web length.)

Waltz (1998) followed TPI (1991) temporary bracing recommendations for brace to web connections. Therefore, two-16d Common nails were used for all wood-to-wood connections. Springs were used to represent the load-deflection response of the nailed connections. Equation 2.9 was developed by Mack (1966) to estimate the load-slip response expected from a nailed connection using 2-16d Common nails.

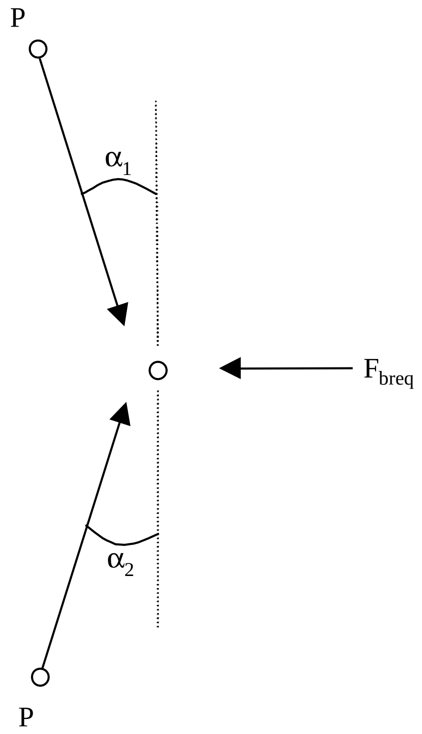
$$F_{nail} = 52d^{1.75}k_s(3.20\Omega + 0.68)\left(1 - e^{-75\Omega}\right)^{0.7} \tag{2.9}$$

where: F_{nail} = load applied to a 2-16d nailed joint (pounds)

Ω = slip between the wood members of a 2-16d nailed joint (inches)

d = nail diameter (inches)

k_s = species constant from Mack (1966)



where:

P = column load (pounds)

F_{br} = brace force (pounds)

α_1 = angle between brace and vertical plane

α_2 = angle between brace and vertical plane

<u>Force Balance</u>

Assuming pins at brace ends and at the point of brace attachment:

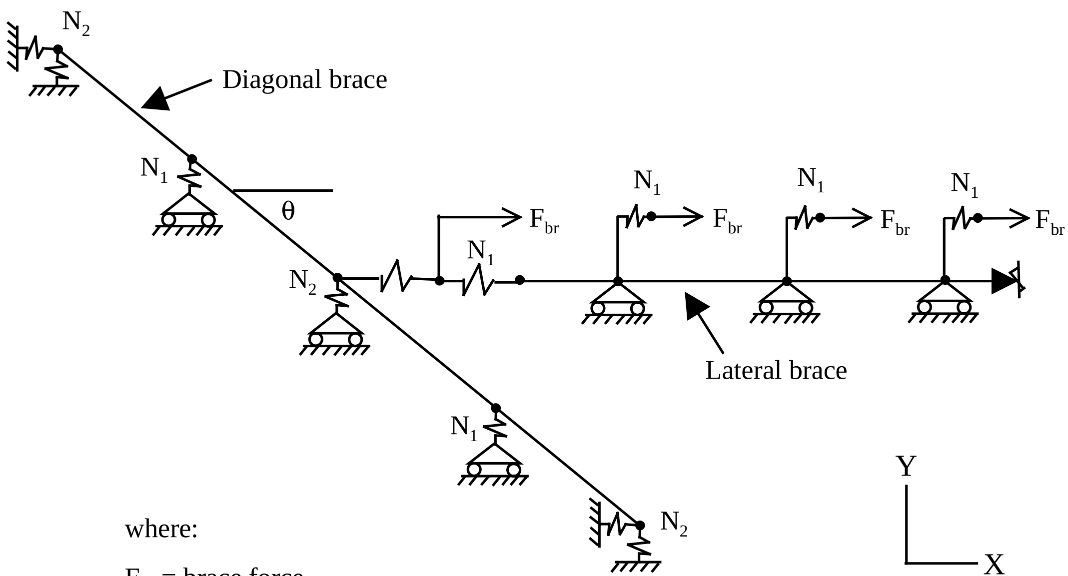
$F_{br} = P \sin(\alpha_1) + P \sin(\alpha_2)$

When α_1 and α_2 are small and equal, sin α approximately equals tan α. From Throop (1947), tan α was assumed to be 1/100, therefore:

$F_{br} \approx (1/100 + 1/100)\, P$

$F_{br} \approx 0.02P$, or 2% or P

Figure 2.12. A free body diagram and a force balance depicting the origin of the 2% Rule as presented by Waltz (1998), Throop (1947) and Nair (1992).



where:

F_{br} = brace force

N_1 = one-dimensional nailed joint

N_2 = two-dimensional nailed joint

θ = brace angle (radians)

Figure 2.13. Finite Element Structural Analog for a Diagonal/Lateral Brace Assembly from Waltz (1998)

Waltz (1998) used this relationship for modeling nail slip for all analyses. Waltz's FEM contained two types of nailed connections, N_1 and N_2 connections, as illustrated in Figure 2.13. N_1 connections represented a uniaxial load-slip behavior such as the case of a diagonal brace and a web. The connection between the diagonal brace and the web only resists vertical loads in the analog of Figure 2.13.

N_2 connections only occur at the middle and ends of the brace and consist of both X and Y components. The N_2 connections occur at the middle and ends because there is one connection between the diagonal and the web, and a second connection between the web and the continuous lateral brace (CLB). Two springs were used to model the connections. "The stiffness of the component spring within these connections was calibrated so that the resultant force experiences the load-slip behavior" of Equation 2.9 in the resultant direction (Waltz, 1998). Figure 2.14 illustrates the relationship of Equation 2.9. For this equation to be valid, a maximum allowable slip between wood members using two-16d Common nails is 0.1 inches, and the 0.1 inch slip value was defined as failure in the Waltz study as recommended by Mack (1966).

Waltz (1998) assumed the following for creating the structural analog depicted in Figure 2.13:

- All trusses connected by the lateral brace were the same size and configuration; all uniformly loaded (same compressive force in each web)
- Each diagonal brace was oriented at approximately 45-degrees from the webs long axis
- Truss spacing was 610 mm (24 inches) on center
- All lateral and diagonal braces were 2 x 4 Douglas-fir Larch lumber with modulus of elasticity of 8,270 MPa (1,200,000 psi)
- Two 16d Common nails with a diameter of 4.1mm (0.161 inches) were in all wood-to-wood connections
- One diagonal brace for each piece of lateral brace lumber (no lateral brace splices)

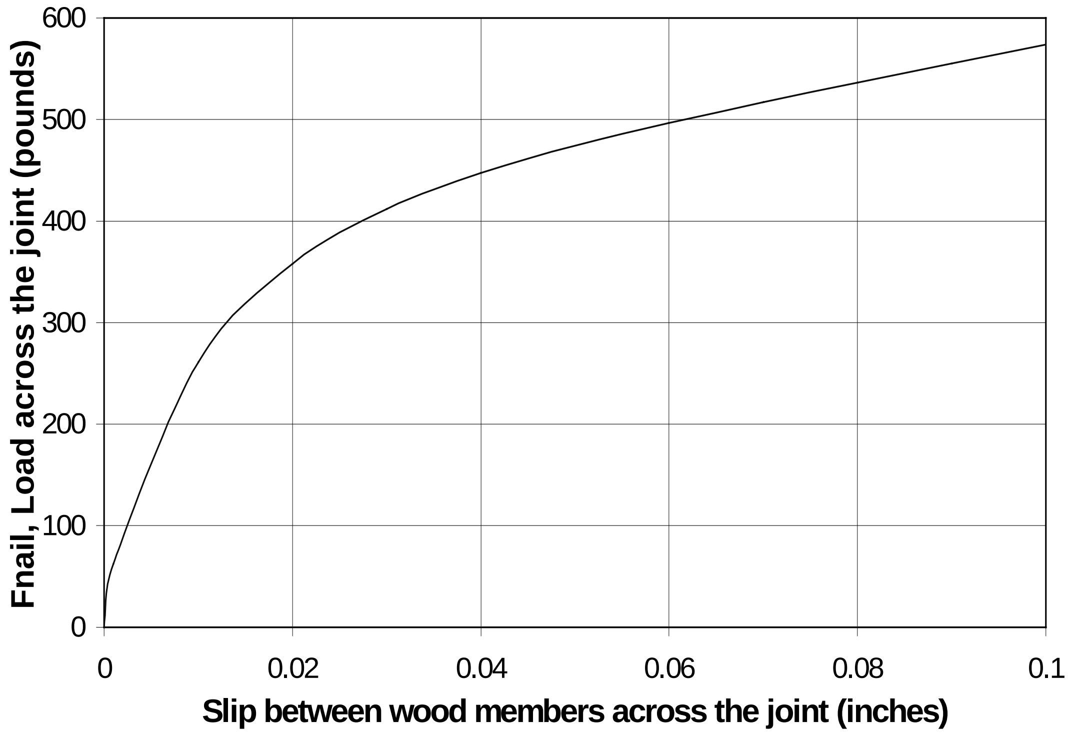


Figure 2.14. Load-slip response for a 2-16d Common nail connection between two-2x4 Spruce-Pine-Fir wood members.

- The ends of each diagonal brace were nailed to a wood member support (pin reaction that included nail slip)
- All compression webs transfer a lateral load of equal magnitude and direction to the lateral brace

The finite element structural analogs were developed to estimate the stiffness of the brace support provided to the varying length members (Waltz, 1998).

Brace curves were developed from the data obtained from the finite element models. The process involved analyzing the bracing system consisting of one lateral brace attached to n-webs and one diagonal brace that resisted the movement of the lateral brace. The force in each brace was increased (simulating more load in the webs) and the lateral deflection response was determined for the web(s) at the point of lateral brace attachment. When multiple webs were considered, the magnitude of the force due to the CLB was increased to determine the largest horizontal deflection experienced by a web member (Waltz, 1998). In reality, the webs did not all deflect the same amount. Waltz's (1998) FEM allowed slip in the joints and compression/stretch of the lateral brace. He concluded the compression/stretch in the lateral brace was negligible and therefore he assumed the lateral movement of the n-webs as part of a braced system was approximately equal. After determination of the brace load for one truss and the corresponding lateral deflections, an additional truss was considered. The incremental process continued until a total of 10 trusses had been considered. A non-linear plot illustrating the incremental brace force versus the lateral deflection at the braced web(s) for varying numbers of trusses was developed. These plots are the brace curves used in Waltz (1998) research.

2.6.3 Testing

To perform the braced web experiments, a supply of lumber was requested from three sawmills. Two grades of lumber were tested, Select Structural and Standard. A total of 800 pieces were tested varying in lengths of 4, 6, 8, 10 feet. Four hundred (400) samples were Select Structural and 400 samples were Standard grade. The moisture content for the testing specimens was requested to be 19% or less.

The Waltz (1998) test apparatus, shown in Figure 2.15, consisted of two steel pipes on the long sides and heavy steel beam sections on the short ends. A hydraulic cylinder was used to produce the axial load on the columns. For each test column, the ends were shimmed into a U-shaped boot to help prevent bending about its strong axis. Hinges were placed at each column end at designated web length. A lateral brace was simulated at the mid-height of the column using a mechanical brace controlled by a computer. The computer allowed the brace stiffness to be variable because the stiffness can effect the column performance and the brace load that develops.

Before testing the specimens, initial column measurements were taken. The measurements included cross sectional dimensions, moisture content, modulus of elasticity, weight, initial column deflection at mid-height and the initial shape of the column.

The second step of the testing process was to determine the axial test load for each column. Waltz (1998) assumed the 2x4 Douglas-fir Larch columns were braced sufficiently and the effective length of the column was one-half of the total length. The maximum axial test loads to be applied were intended to be as close to the critical column strength as possible and did not include safety and load duration factors (Waltz, 1998).

The brace stiffness required for testing was then selected using the brace curves previously discussed. For each sample, brace force curves were compared. If the brace support curves did not intersect with the theoretical brace analysis curve then the theoretical brace requirements were not met (Waltz, 1998). The most flexible brace support curve that intersected the theoretical brace curve for Plaut’s method was chosen for testing purposes.

2.6.4 Results

The initial measurements taken before testing on moisture content, member dimensions, weak-axis moment of inertia, and dry weight per unit length by inspection showed little

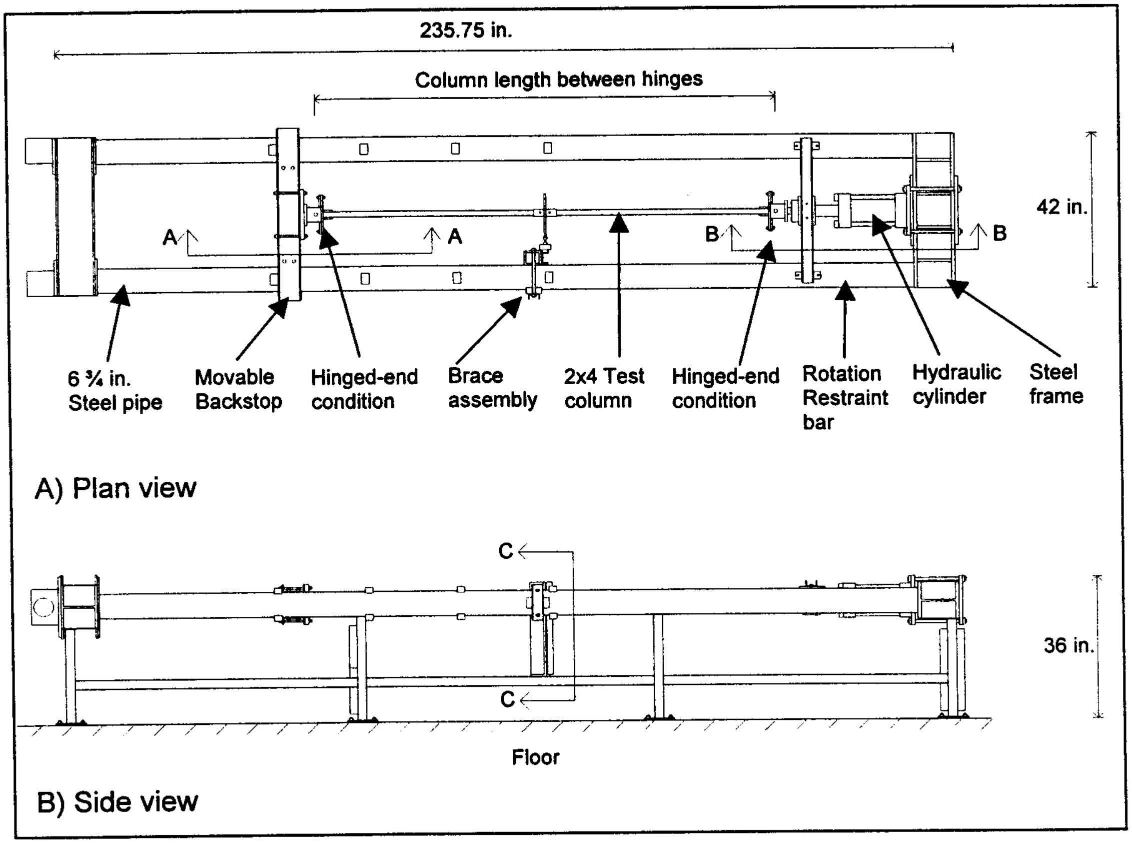


Figure 2.15. Test apparatus from Waltz (1998). The apparatus was used to test 800 lumber samples. The test apparatus was designed for Waltz's research.

differences between test groups (Waltz, 1998). A majority of the members had an initial profile of a "C-shaped" column. The modulus of elasticity, MOE, however, varied based on length and grade. A flatwise bending test was used to measure the longitudinal MOE. Within each grade, the MOE was less for the four-foot lengths than for the other three lengths. The MOE was considered to add variability to the results and were therefore considered in the test results.

Eight of the 774 columns tested failed when the column buckled asymmetrically. Fifteen of the twenty-one failures occurred because the brace force exceeded the capacity of the brace defined by 0.1-inch (2.5 mm) slip in the connection. Brace instability occurred when the stiffness selected for the test was inadequate to brace the column (Waltz, 1998).

2.6.5 Performance Variables

Waltz (1998) calculated the relative deviation, D_{theory}, between the predicted forces by the FEM and various brace models discussed in Section 2.6.1 and the experimental brace force for each test column. The relative deviation was defined in Equation 2.10:

$$D_{theory} = \frac{(F_{br})_{actual} - (F_{br})_{predicted}}{(F_{br})_{predicted}} \tag{2.10}$$

The relative deviation was considered a "performance variable" to compare the prediction performance of the different theories (Waltz, 1998).

His performance variable, D_{theory} ranged from negative one to positive infinity. If D_{theory} was less than zero, the brace analysis theory was considered to be a conservative overestimate of the support requirements. D_{theory} greater than zero signified the estimate was not conservative. D_{theory} was calculated for each of the test columns and each of the four prediction methods (Waltz, 1998).

For Waltz's research, D_{theory}, was based on the predicted and measured brace force at maximum deflection. The predicted brace force for each method was plotted along with the brace support curve for the test column. Looking at the actual deflection that occurred during testing enabled Waltz to determine D_{theory} for each test column. Both strength and stiffness are considered due to the brace support curves, except for the 2% Rule. When the predicted brace force exceeded the actual brace force, the theory was characterized as overestimating both the strength and stiffness requirements of the column. When the predicted brace force was less than the actual brace force, the theory was considered to underestimate the requirements (Waltz, 1998).

Non-parametric methods were used to compare the performance variables, which included D_{Plaut}, D_{Winter}, D_{Tsien}, and $D_{2\% Rule}$, among the species and lengths. Waltz (1998) determined there was not a significant grade effect on the mean predictions of Tsien's equation and the 2% rule but Plaut's and Winter's method may be slightly influenced by grade especially for the shorter columns.

Pooling the data from both grades, Waltz (1998) tested for brace length effects. No significant length effect was found for the mean performance of the 2% Rule, but length had a significant effect on the mean D_{theory} for the other three methods. The lumber could effectively be divided into two groups based on the lengths of the members: 4/6 feet and 8/10 feet.

The initial column profile was investigated in terms of its effect on the performance variable, D_{theory}. The comparisons indicated all four of the bracing theories to be less conservative for "C-shaped" columns than for "S-shaped" columns. It was therefore concluded that the initial "C-shaped" profile represents the worst case scenario for lateral bracing design (Waltz, 1998).

Waltz (1998) performed paired statistical tests within each of the two pooled length groups. It was determined that there was a significant difference between the three analysis methods.

Plaut's method proved to be the most conservative, for most cases. Plaut's method was consistently conservative and more accurate than the 2% Rule based on the analysis of the performance variable, D_{theory}.

The 2% Rule was the most conservative but it also provided the most variable estimate of the required brace force. The 2% Rule does not take into account the stiffness requirements and may not be the best for brace design (Waltz, 1998).

2.6.6 Conclusion

Waltz (1998) concluded that either Plaut's or Winter's method could be used. Plaut's method is more conservative and has the lowest prediction variability. Winter's method provided the best prediction of the actual brace needs although it was more variable. With proper adjustments, either method could be used to estimate the required bracing needs.

3. Finite Element Modeling and Analysis

3.1 General Assumptions

To accomplish the research objectives of this project, several issues must be considered. First, as previously discussed, webs can buckle in different modes (Plaut and Yang, Y.G., 1993; Plaut and Yang, Y.W., 1995; Waltz, 1998; Winter, 1960; Zuk, 1956). The critical case for permanent bracing, in terms of laterals and diagonals, occurs when the C-buckling mode is assumed (Waltz, 1998). Therefore, the C-buckling mode was the only buckling mode investigated in this research study. Diagonals must be designed to resist the maximum lateral load developed by the n-CLB's. Net lateral restraining force per roof truss due to n-CLB's (NL_{truss}), must be determined for different levels of compression force in the chord, varying numbers of CLB's, different chord sizes and different grades of lumber while the column is deflected in a C-shape buckling mode.

3.2 Design Considerations

3.2.1 n-CLB's

There are many truss applications where multiple CLB's are necessary to support chords that are not automatically braced with sheathing. For example, multiple CLB's are used to brace an unsheathed chord of a piggyback truss system. A piggyback truss system consists of two (or more) trusses connected together after shipping. The bottom truss is typically a trapezoid shape and is often referred to as the supporting truss. The top truss, supported by the supporting truss, is typically a triangular shape and is often referred to as a cap truss. The top chord of the supporting truss of a piggyback truss system can vary in length and must be braced to reduce the weak axis slenderness ratio. Figure 3.1 depicts a piggyback truss system with n-CLB's, and two diagonal braces bracing j-trusses. The trusses are assumed to buckle in a C-shape mode as depicted in Figure 3.1. The net restraining force to be carried by the diagonal braces is an unknown and must be determined to design the connection between the diagonal braces and the trusses.

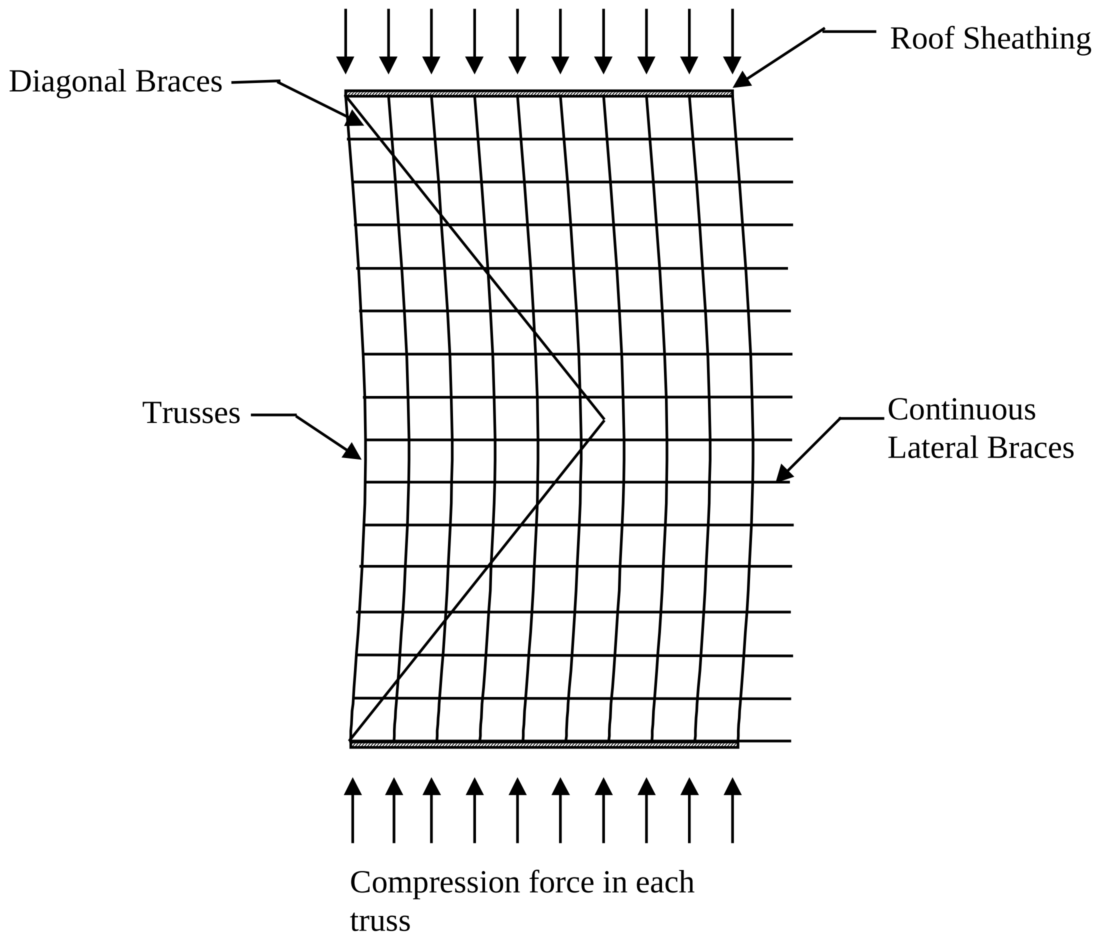


Figure 3.1. Example truss system with j-flat top trusses being braced by two diagonals, n-CLBs, and an axial compressive force in the top chords of the trusses.

3.2.2 One CLB

A column, braced in the center of its span, as illustrated in Figure 3.2, can be braced using the 2% Rule (TPI, 1989). When the single brace is applied, the column can buckle as shown in Figure 3.3. Currently, the 2% Rule is the most Common and accepted design practice used for designing permanent bracing for a compression web that utilizes one continuous lateral brace with diagonals spaced at some interval. When the 2% Rule is used, as discussed previously, the bracing force required to stabilize one CLB is assumed to be 2% of the axial force in the chord. While the 2% Rule produces reasonable results for the case of one CLB, the 2% Rule does not produce reasonable results for a compression chord, where multiple CLB's are used. Frequently, more than one CLB is needed on a chord for added strength. To prevent the displacements of points A and B in Figure 3.3, CLB's could be added to produce the two buckling modes depicted in Figures 3.4a and b.

3.2.3. Two CLB's

The buckling modes depicted in Figures 3.4a and b are based on the use of two CLB's to laterally support the column. The 2% Rule does not apply because it was based on a single brace located at the mid-span point of the column as described in Section 2.6.1.4.

Figure 3.4a depicts a column with two lateral braces with a multiple S-shape buckling mode. The net lateral restraining force is based on the direction of the force in the CLB's, depicted by vectors in Figure 3.4a. If the force in one CLB is in one direction and the force in the second CLB is in the opposite direction, then the net lateral restraining force would be significantly lower than if they are both in the same direction. Figure 3.4b depicts a column with two lateral braces with a C-shape buckling mode. The net lateral restraining force in this case would be critical for brace design since the forces, represented by vectors in Figure 3.4b, act in the same direction.

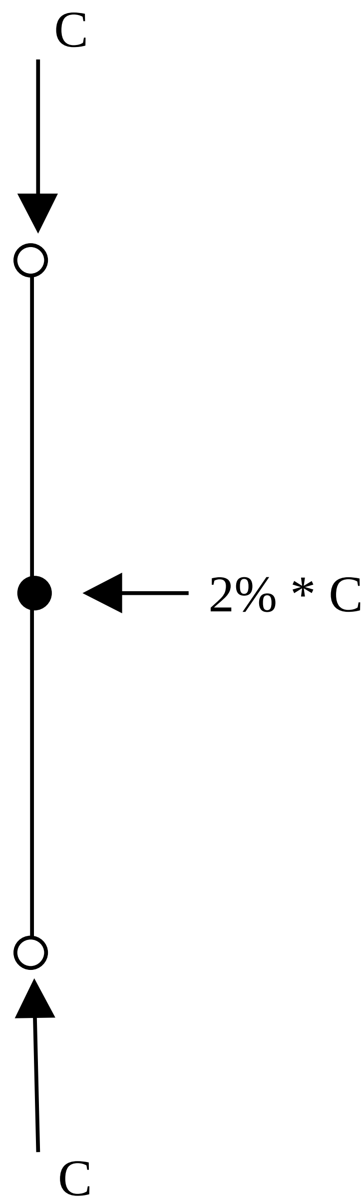


Figure 3.2. A column braced at center span requires 2% of the axial compressive force to stabilize the point of brace attachment from lateral movement (TPI, 1989).

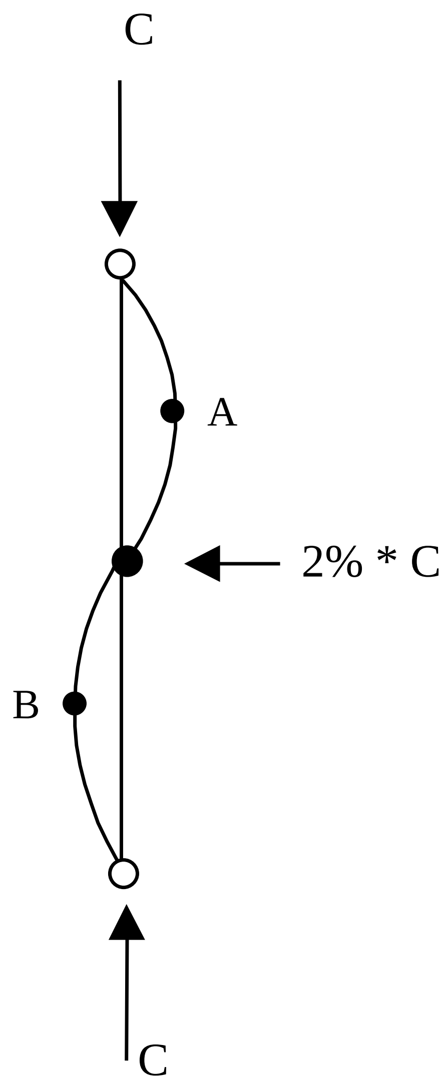


Figure 3.3. **The column buckles in an S-shape as depicted when a single brace is applied.**

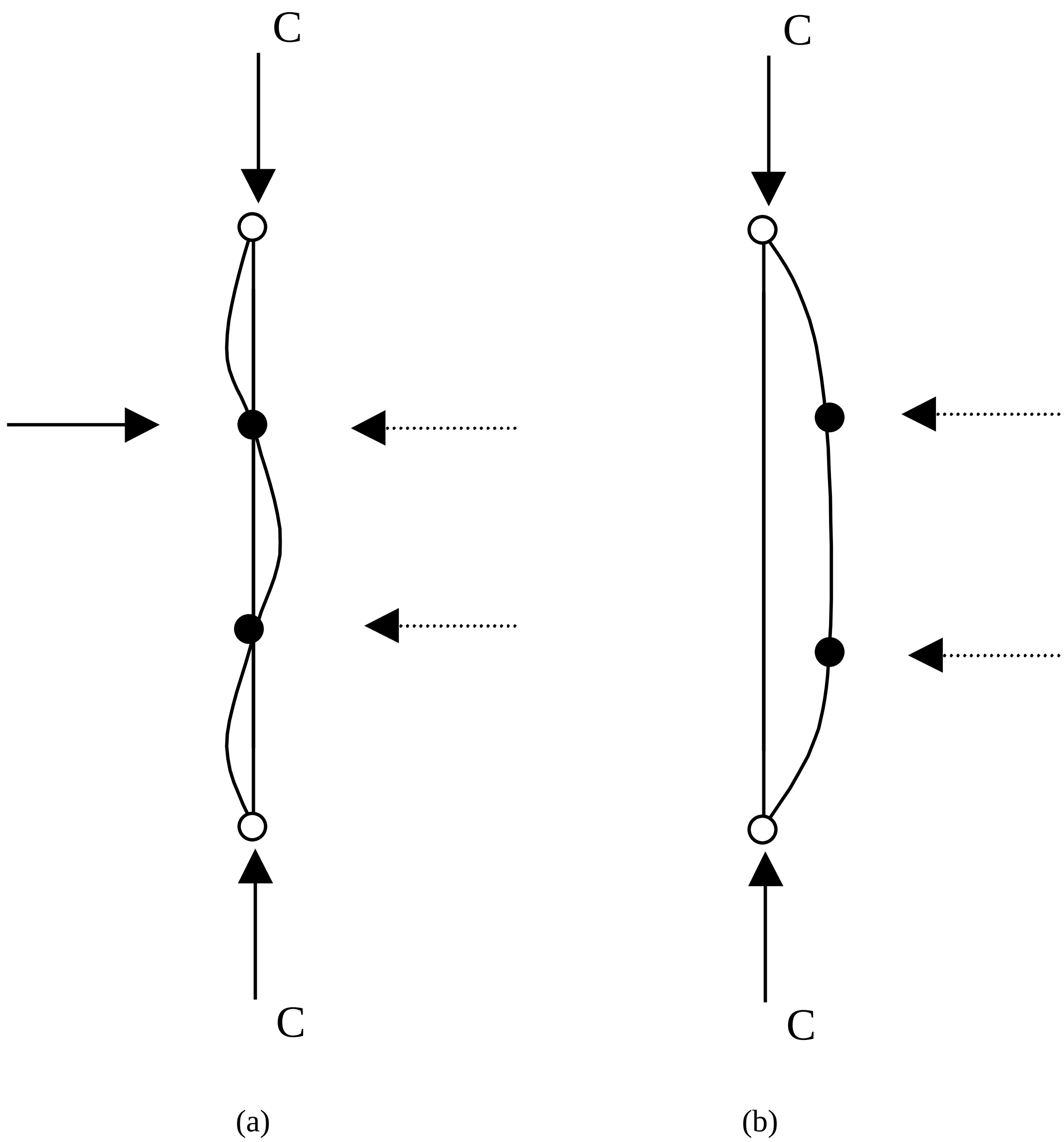


Figure 3.4. **(a) The column buckles in a multiple S-shape mode as depicted when two lateral braces are applied.**

(b) The column can buckle in a C-shape mode as depicted when two lateral braces are applied. The C-shape buckling mode is critical for brace design because the lateral forces due to the braces act in the same direction and are therefore additive.

An important issue resulting from the use of two CLB's is determining the net lateral restraining force for the two cases depicted in Figures 3.4a and b. Figure 3.4b represents the most critical case for brace design that can occur and will be the case considered for this research.

3.3 SAP2000 (CSI, 1995)

SAP2000 (CSI, 1995) is a structural analysis program that can be used for basic as well as complicated design problems. To verify that SAP2000 (CSI, 1995) was usable in this research, the buckling load of columns (with known theoretical solutions) of three different lengths was determined using SAP2000 and the theoretical formulae. The computer output was compared to the theoretical solution and then the results were studied to determine if the computer model was working as intended.

To accurately represent a column in a finite element analysis, it was necessary to divide the column into multiple elements. A convergence test was performed to determine the number of elements required to accurately represent the column under the applied compression loads.

To begin, a 12 foot column was represented by one element in SAP2000 (CSI, 1995) with one end support fixed and the other end free to translate and rotate. A compressive load was applied to the column and using the p-delta analysis tool of SAP2000 (CSI, 1995), the column was tested to determine if capacity of the column could withstand the load. The load was progressively increased until the column failed. A failure in SAP2000 (CSI, 1995) is indicated by a error message during the analysis of the structure. At the point of failure, the applied compressive load was recorded as the buckling load of the column. The results from the computer analysis were then compared to the results of the hand calculations determined from Euler's buckling equation, Equation 3.1.

$$Pcr = \frac{\pi^2 EI}{(kL)^2} \tag{3.1}$$

where: P_{cr} = critical buckling load (pounds)

E = modulus of elasticity (psi)

I = moment of inertia about the weak axis (in^4)

k = stiffness coefficient based on support conditions

L = effective length of the column (inches)

The buckling load determined from the computer analysis was then divided by the theoretical value determined by Euler's equation and the number was recorded in Table 3.1. The preceding steps were then repeated for the same column represented by an increasing number of elements.

The above procedure was repeated for fixed-pinned supports and pin-pin supports. Once convergence was determined for a twelve-foot column the process was repeated for a four-foot column and a thirty-foot column. Results of the calculations were summarized in Tables 3.1, 3.2, and 3.3. It was concluded from the convergence data that the three assumed column conditions represented using three elements was sufficiently accurate.

3.4 Waltz's Structural Analog in SAP2000 (CSI, 1995)

The first step to produce a data file for SAP2000 (CSI, 1995) to analyze Waltz's structural analog was understanding the connections. Two different connections were necessary to model the behavior of the nailed connections. One type of connection consisted of two springs and represented the nailed connections between the diagonal brace and the truss panel point and at the middle of the diagonal brace and web. The second type of connection consisted of one spring that was used to represent the connection between the diagonal brace and the web members. The single spring connection is based on the assumption that there is negligible weak-axis lateral support for the diagonal by the buckling web member (Waltz, 1998). The single spring acted in the vertical direction only.

To enter the analog into SAP2000 (CSI, 1995), a grid was developed on a one-inch scale. Nodes were placed at the geometry described by Waltz (1998). Members were assigned properties to represent Douglas Fir-Larch and a modulus of elasticity equal to 1,200,000

Table 3.1. Comparison of Euler buckling loads to buckling loads determine using SAP2000 (CSI, 1995) for a twelve foot column.

# of elements	**fixed-free**	**fixed-pinned**	**pin-pin**	**Actual / theoretical** fixed-free	fixed-pinned	pin-pin
Theoretical	*140*	*1147*	*562*			
1 element	141	1708	683	1.007	1.48	1.215
2 elements	140	1179	566	1.00	1.027	1.007
3 elements	140	1156	562	1.00	1.007	1.00
4 elements	140	1151	562	1.00	1.003	1.00

Table 3.2. Comparison of Euler buckling loads to buckling loads determine using SAP2000 (CSI, 1995) for a four foot column.

# of elements	**fixed-free**	**fixed-pinned**	**pin-pin**	**actual / theoretical**		
				fixed-free	**fixed-pinned**	**pin-pin**
Theoretical	*1265*	*10327*	*5060*			
1 element	1273	>15000	6152	1.006	>1.45	1.212
2 elements	1264	10569	5086	0.999	1.023	1.005
3 elements	1264	10362	5055	0.999	1.003	0.999
4 elements	1264	10316	5049	0.999	0.999	0.998

Table 3.3. Comparison of Euler buckling loads to buckling loads determine using SAP2000 (CSI, 1995) for a thirty foot column.

# of elements	**fixed-free**	**fixed-pinned**	**pin-pin**	**actual / theoretical**		
				fixed-free	**fixed-pinned**	**pin-pin**
Theoretical	*22.5*	*184*	*90*			
1 element	22.6	273	109	1.004	1.48	1.211
2 elements	22.5	189	90	1.00	1.027	1.00
3 elements	22.4	185	90	0.996	1.005	1.00

psi was assigned to each member. The lumber was oriented to assure that the 1.5-inch dimension was the depth and the 3.5-inch dimension was the width.

Two-dimensional connections at the ends of the diagonal and the one-dimensional connections between the diagonal and the compression webs were represented by support springs. The support springs were assigned a stiffness based on Equation 2.9 from Mack (1966).

Waltz (1998) had 23 failures during his research. Waltz concluded in his study that Mack's (1966) curve could be represented linearly due to the instability failures that occurred in the nonlinear portion of their brace support curves.

To represent Mack's curve linearly, the secant modulus was determined for the different forces. To find the secant modulus, a slip was determined and then the corresponding force was solved for using Equation 2.9. The force g(x), where x is slip, was determined by a line drawn from the origin to the point (x,g(x)). The slope of the line was the stiffness for the specified force and slip. When the force is increased, the stiffness decreases based on the changing secant modulus.

Connections between the diagonal brace and the compression chord at the middle of the brace and between the diagonal brace and the CLB were represented by internal springs (in SAP2000 (CSI, 1995), terminology). The stiffness of the internal springs was determined using the secant modulus as previously explained. Internal springs in SAP2000 (CSI, 1995) are represented by "nllink" elements. Two types of nllink elements can be specified, zero-length elements and elements that connect two joints. A zero-length element can consist of either a single joint with a spring connection to a reaction support, or two-joint elements sharing the same location in space. The coordinate system varies depending on the type of nllink element specified in the analog.

To develop Waltz's (1998) analog, only one type of nllink element was used. A joint-to-joint nllink element was used to represent the horizontal spring connection between the diagonal brace and the truss web. A second joint-to-joint nllink element was used to provide a load path for the force to get from the CLB through the diagonal brace and into the web. Each nllink element had six degrees of freedom and a spring stiffness (translational or rotational) can be specified for any of the six degrees of freedom. The degrees of freedom that receive no stiffness must be given restraints or other supports for stability purposes (CSI, 1996).

Waltz (1998) concluded that the axial deformation within a CLB member could be neglected. Therefore, for Waltz's (1998) analog, restraints were used to support the nllink elements. In SAP2000 (CSI, 1995), there is positive moment continuity across nodes but there is no moment continuity across springs. For this reason, restraints must be applied to help ensure stability about the model and the springs. The nodes on both sides of the nllink elements were restrained in the Y-direction, Z-direction, and all three rotations. In other words, the nllink elements or springs were only allowed to deflect in the X-direction or axially. Figure 3.5 depicts Waltz's (1998) structural analog conceptually as entered in SAP2000 (CSI, 1995).

To analyze a model in SAP2000 (CSI, 1995), the available degrees of freedom must be specified. To analyze Waltz's (1998) structural analog, the available degrees of freedom include: UX, UZ, RY. In other words, the structure can move in the X- and Z-directions and can rotate about the Y-axis.

3.5 System Analogs

3.5.1 Five Chords Braced by Three CLB's

The first system structural analog analyzed using SAP2000 (CSI, 1995) represented five eight-foot roof trusses spaced twenty-four inches on center, three continuous lateral braces (CLB's) spaced twenty-four inches on center and one diagonal, as depicted in Figure 3.5. The lumber used in the construction of the structural analog was assumed to be 2x4 STUD Spruce-Pine-Fir, with a modulus of elasticity of 1,200,000 psi for the CLB's and 2x4 No. 2 Southern Pine, with a modulus of elasticity of 1,600,000 psi for the

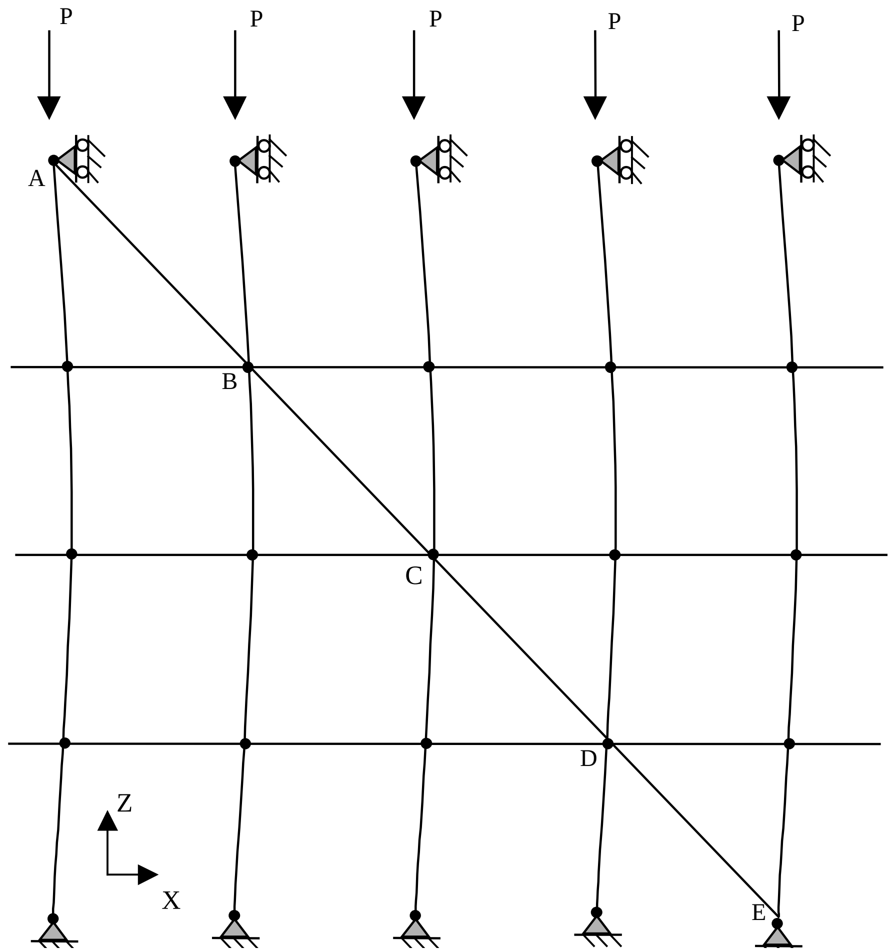


Figure 3.5. **The structural analog represents 5 trusses with an initial curvature, three continuous lateral braces (CLB’s), and 1 diagonal member. The initial curvature is in one direction and is exaggerated for visual purposes.**

truss chords. The truss chords were assumed to be a column with pin connections on one-end and roller connections on the other.

To model the inward movement of both chord ends, roller supports would need to be used on both ends of the truss chords to allow deflection on both sides. However, instability would occur during analysis of the structure if such support conditions were applied to the structural analog. The structural analog has quarter symmetry meaning the upper left quarter of the structure is symmetric with the lower right quarter of the structure and the same for the upper right quarter and the lower left quarters of the structure. The structure is said to be symmetric about the center point of the structural analog. However, if a roller support is applied to the truss at the center point of the structural analog, the applied loads cause the trusses to translate improperly and bending action occurs in the CLB's. Based on the problems associated with the above support conditions, the data file for SAP2000 (CSI, 1995) was created using the pin and roller support conditions originally described. All connections between chords and braces were assumed to be made with 2-16d Common nails and were represented with springs to model the slip in the connection.

ANSI/TPI 1-1995 (TPI, 1995) installation limits were assumed for all chord lengths studied. Equation 3.2 described the chord member as having a half sine wave configuration, with an assumed initial curvature of L/200.

$$\Delta_i = \frac{L}{200}\sin\left(\frac{pi * x}{L}\right) \tag{3.2}$$

where: Δ_i = assumed initial deflection of the truss chord,

L = length of the compression chord, and

x = the distance from the member end, inches

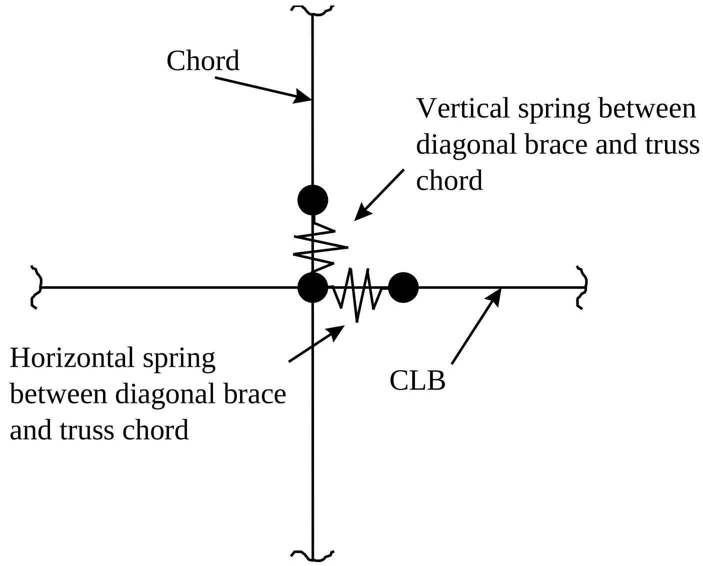
pi is in radians.

A deflected chord member, by nature, is a smooth curve as opposed to a series of straight lines. Therefore, the half sine configuration was assumed and used in all analyses.

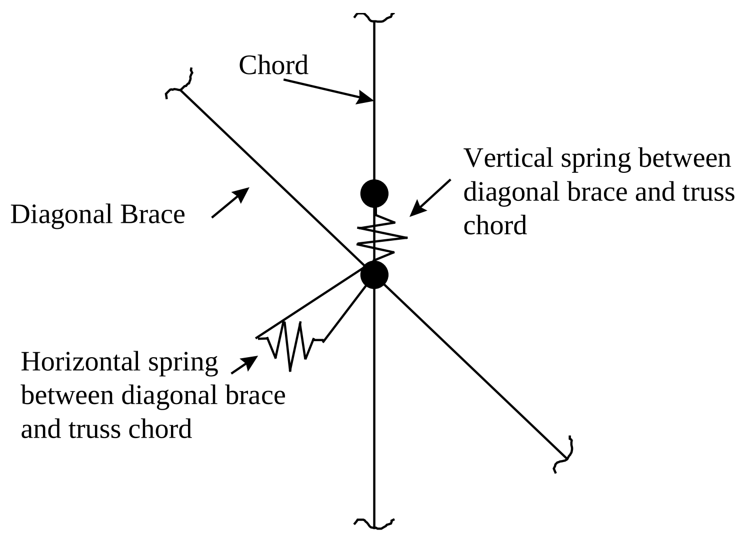
Connections A, B, C, D, and E, shown in Figure 3.5, were each modeled by a horizontal spring and a vertical spring. (Two springs were required for each nail connection.) The horizontal spring represented the lateral load-slip relationship slip at the diagonal and chord member connection. The vertical spring represented the connection slip in the vertical direction between the diagonal member and the chord member. The resultant spring force was determined for each of the connections between the diagonal brace and the truss chord members after the analysis was completed using vector addition.

A spring acting in the horizontal direction and a spring acting in the vertical direction represented the connections between the chords and the CLB. Joint C, as depicted in Figure 3.6, consisted of the two-spring connection between the diagonal member and the chord member and the two-spring connection between the CLB and the chord member. One horizontal spring or nailed connection allows the load to be transferred into the CLB and the other nailed connection transferred the load out of the CLB. Joints A and E, (Figure 3.5), represented the connection between the diagonal and the chord at the point where the chord is connected to the truss panel point and roof or ceiling diaphragm.

Once the data file for the structure was completed, loads were applied and the structure analyzed. Design load was determined based on the National Design Specification for Wood Construction (AF&PA, 1997) and an axial load ranging from 684 to 3,421 pounds was applied to each chord. The allowable design load (F_c') was determined to be 6,842 pounds. However, 50% of the allowable compressive load based on an l_e/d ratio of 16 is a typical load level in a wood truss chord. The load was increased from 10% to 50% of F_c'. Load levels above 50% were not studied because the iterative solution was manually conducted, and for higher load levels, manual solutions were not feasible due to the number of iterations required. In retrospect, ANSYS 5.4 (ANSYS, 1997) would have been a better choice of finite element analysis program to analyze the system at load levels approaching 100% of F_c'. Design load was based on the grade, species combination, and size of lumber and the duration of load, which in this case is assumed to be 1.15 for snow plus dead loading.



(a)



(b)

Figure 3.6. (a) The connection between the chord member and the CLB is represented by a horizontal and a vertical spring.

(b) The connection between the CLB and the chord member is also represented by a horizontal and a vertical spring.

The stiffness values for the 2-16d nailed connections were determined using Equation 2.9 from Mack (1966). As previously discussed in Section 3.4, the secant modulus method was used based on the load and deflection. Since Mack's (1966) paper did not provide a species factor for Spruce-Pine-Fir, a linear regression was performed to determine the equation suitable for that particular species. Equation 3.3 is the regression equation that was used to determine the species factor for use in Mack's (1966) load-slip equation.

$$k_s = 265 * SG + 3.49 \qquad (3.3)$$

where: k_s is the species factor for use in Mack's (1966) equation, and

SG is the specific gravity for the species, in this case Spruce-Pine-Fir.

Equation 3.4, derived from Mack's (1966) equation, was used in the analysis for the connection force in a Spruce-Pine-Fir connection modeled in SAP2000 (CSI, 1995).

$$F_{nail} = 618 * (3.20\Omega + 0.68)\left(1 - e^{-75\Omega}\right)^{0.7} \qquad (3.4)$$

where: F_{nail} = load applied to a 2-16d nailed joint (pounds), and

Ω = slip between the wood members of a 2-16d nailed joint (inches).

A linear spring stiffness was estimated for each joint and the structural analog of Figure 3.5 was analyzed. The calculated spring forces were then compared to the specific force and displacement used to input the linear spring (secant modulus) constants. The new stiffness value for each spring was entered into SAP2000 (CSI, 1995) and the structure was analyzed again. The procedure was repeated until the force in the springs matched the assumed force and displacement used to calculate the secant modulus spring stiffness within a tolerance of 1%.

The deflected shape, as depicted in Figure 3.7, resulted from the final stiffness of each spring, with 3,421 pounds of axial force applied to the chords. The moment diagram, Figure 3.8, illustrated the moment that developed due to the bracing connections and the initial curvature. The moment is zero at each end of the chords due to the moment-free

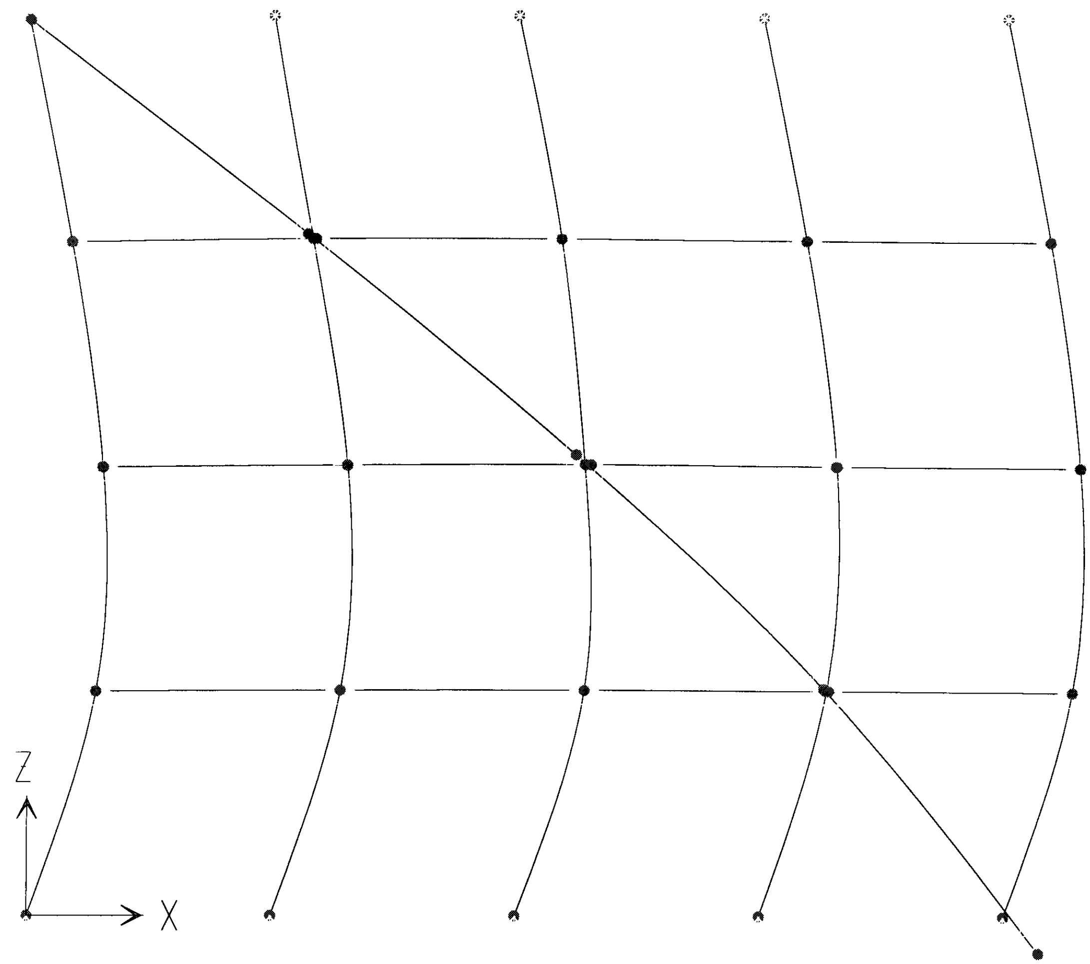


Figure 3.7. Five trusses with three continuous lateral braces and one diagonal brace primarily deflected in the C-mode except at the point of diagonal brace connections.

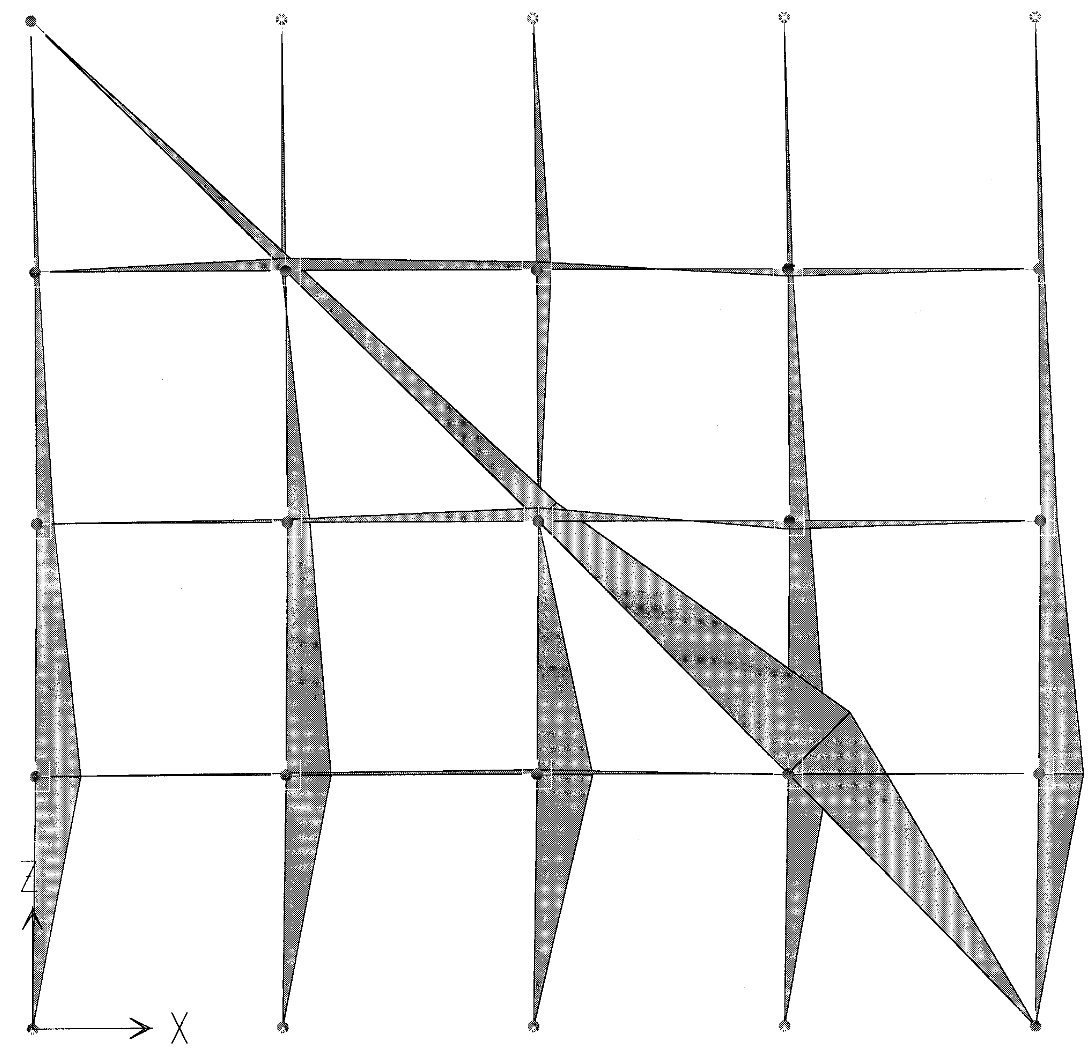


Figure 3.8. Moment is developed in the chords primarily due to the bracing connections and the initial curvature of the chord members.

pin supports. The moment is continuous across the nodes verifying the continuity of the wood members.

3.5.2 Six Chords Braced by Nine CLB's

The second system structural analog analyzed using SAP2000 (CSI, 1995) represented six twenty-foot roof trusses spaced twenty-four inches on center, nine continuous lateral braces (CLB's) spaced twenty-four inches on center, and two diagonals in a V-shape with an angle of 45-degees, as depicted in Figure 3.9. The lumber used in the construction of the structural analog was assumed to be 2x4 STUD Spruce-Pine-Fir, with a modulus of elasticity of 1,200,000 psi for the CLB's and 2x4 No. 2 Southern Pine, with a modulus of elasticity of 1,600,000 psi for the truss chords. The truss chords were assumed to be columns with roller connections, free to translate in the vertical or Z-direction, on both ends. Roller connections free to translate in the horizontal or X-direction were used on the chords where the middle CLB crossed the chords to stabilize the structure, but still allowed the chords to deflect. The roller connections could be applied to the chords at the center CLB because of the symmetry of the structure about the middle CLB. All connections between chords and braces were assumed to be made with 2-16d Common nails and were represented with springs to model the slip in the connection. The calculated spring constants were based on the assumption that both members of the joint were Spruce-Pine-Fir since data were not available for joints made with different species.

ANSI/TPI 1-1995 (TPI, 1995) installation limits were assumed for all chord lengths studied. Therefore, to model the chord member with initial curvature, the nodes were assigned for the data file for SAP2000 (CSI, 1995) using Equation 3.2 to produce a half sine wave configuration, with an assumed initial curvature of L/200.

All connections between the truss chords and the diagonals were modeled by a horizontal spring and a vertical spring. The horizontal spring represented the lateral load-slip relationship slip at the diagonal and chord member connection. The vertical spring represented the connection slip in the vertical direction between the diagonal member and

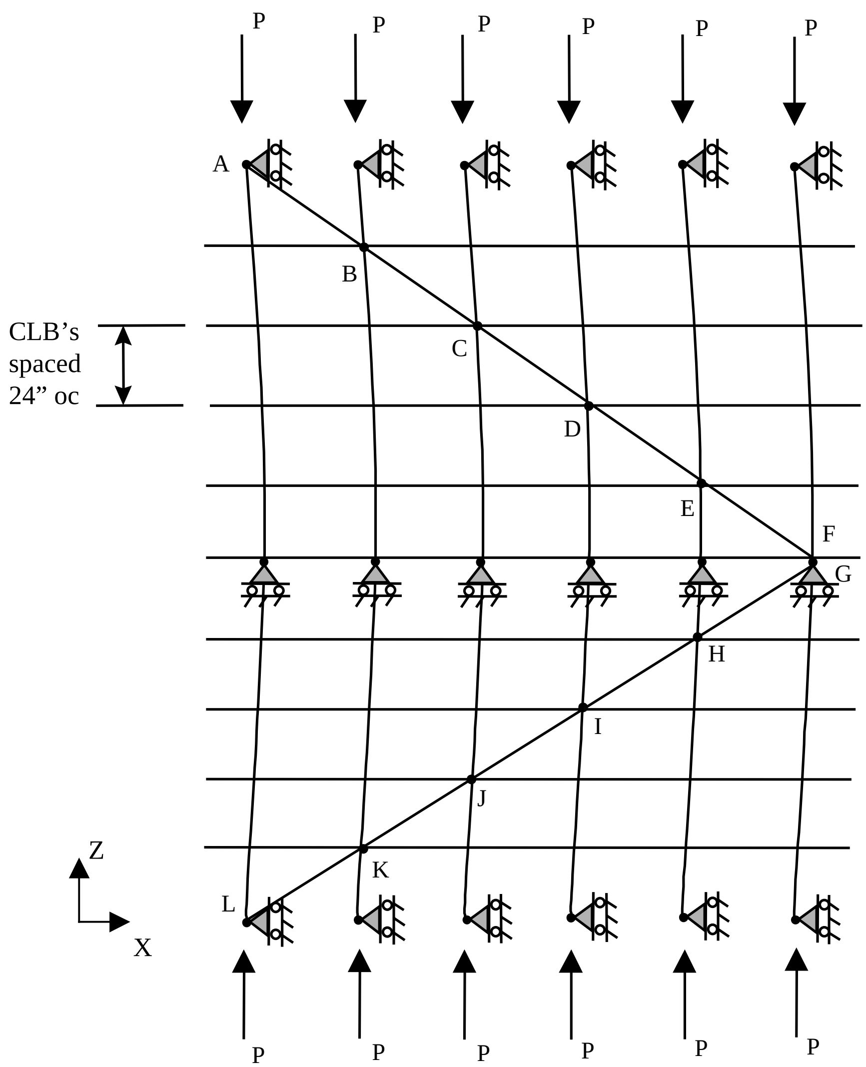


Figure 3.9. **The structural analog represents 6 trusses with an initial curvature, 9 continuous lateral braces (CLB's), and 2 diagonal bracing members in a V-shape. The initial curvature is in one direction and exaggerated for visual purposes.**

the chord member. The resultant spring force was determined for each of these connections, after the analysis was completed using vector addition.

A spring acting in the horizontal direction and a spring acting in the vertical direction represented the connections between the chords and the CLB. Joint F and G, as depicted in Figure 3.9, consisted of the two-spring connection between the diagonal member and the chord member and the two-spring connection between the CLB and the chord member. One horizontal spring or nailed connection allows the load to be transferred into the CLB and the other nailed connection transferred the load out of the CLB. Joints A and L, (Figure 3.9), represented the connection between the diagonal and the chord at the point where the chord is connected to the truss panel point and roof or ceiling diaphragm.

Once the data file for the structure was completed, loads were applied and the structure analyzed. Design load was determined based on the National Design Specification for Wood Construction (AF&PA, 1997) and an axial load ranging from 684 to 3,421 pounds was applied to each chord. The allowable design load (F_c') was determined to be 6,842 pounds based on an l_e/d ratio of 16. The load was increased from 10% to 50% of F_c'. As for the previous case, load levels above 50% were not studied because the iterative solution was manually conducted and for higher load levels manual solutions were not feasible due to the number of iterations required. Design load was based on the grade, species combination, size of lumber, and the duration of load, which in this case is assumed to be 1.15 for snow plus dead loading.

The stiffness values for the 2-16d nailed connections were determined using Equation 3.4 from Mack (1966). As previously discussed in Section 3.4, the secant modulus method was used based on the load and deflection.

A linear spring stiffness was estimated for each joint and the structural analog of Figure 3.9 was analyzed. The calculated spring forces were then compared to the specific force and displacement used to input the linear spring (secant modulus) constants. The new stiffness value for each spring was entered into SAP2000 (CSI, 1995) and the structure was analyzed again. The procedure was repeated until the force in the springs matched the assumed force and displacement used to calculate the secant modulus spring stiffness within a tolerance of 1%.

The deflected shape, as depicted in Figure 3.10, resulted from the final stiffness of each spring, with 3,421 pounds of axial force applied to the chords. The moment diagram, Figure 3.11, illustrated the moment that developed due to the bracing connections and the initial curvature. The moment is zero at each end of the chords due to the moment-free pin supports. The moment is continuous across the nodes verifying the continuity of the wood members.

3.5.3 Eleven Chords Braced by Nine CLB's

The third system structural analog analyzed using SAP2000 (CSI, 1995) represented eleven twenty-foot roof truss chords spaced twenty-four inches on center, nine continuous lateral braces (CLB's) spaced twenty-four inches on center and two diagonals in a V-shape with an angle of 45-degrees, as depicted in Figure 3.12. The lumber used in the construction of the structural analog was assumed to be 2x4 STUD Spruce-Pine-Fir, with a modulus of elasticity of 1,200,000 psi for the CLB's and 2x4 No. 2 Southern Pine, with a modulus of elasticity of 1,600,000 psi for the truss chords. The truss chords were assumed to be columns with roller connections, free to translate in the vertical or Z-direction, on both ends. Roller connections free to translate in the horizontal or X-direction were used on the chords where the middle CLB crossed the chords to stabilize the structure, but still allowed the chords to deflect. The roller connections could be applied to the chords at the center CLB because of symmetry of the structure about the middle CLB. All connections between chords and braces were assumed to be made with 2-16d Common nails with both members of the joint being Spruce-Pine-Fir for the purpose of validating the slip behavior of the joint.

ANSI/TPI 1-1995 (TPI, 1995) installation limits were assumed for all chord lengths studied. Therefore, to properly model the chord member with initial curvature, the nodes

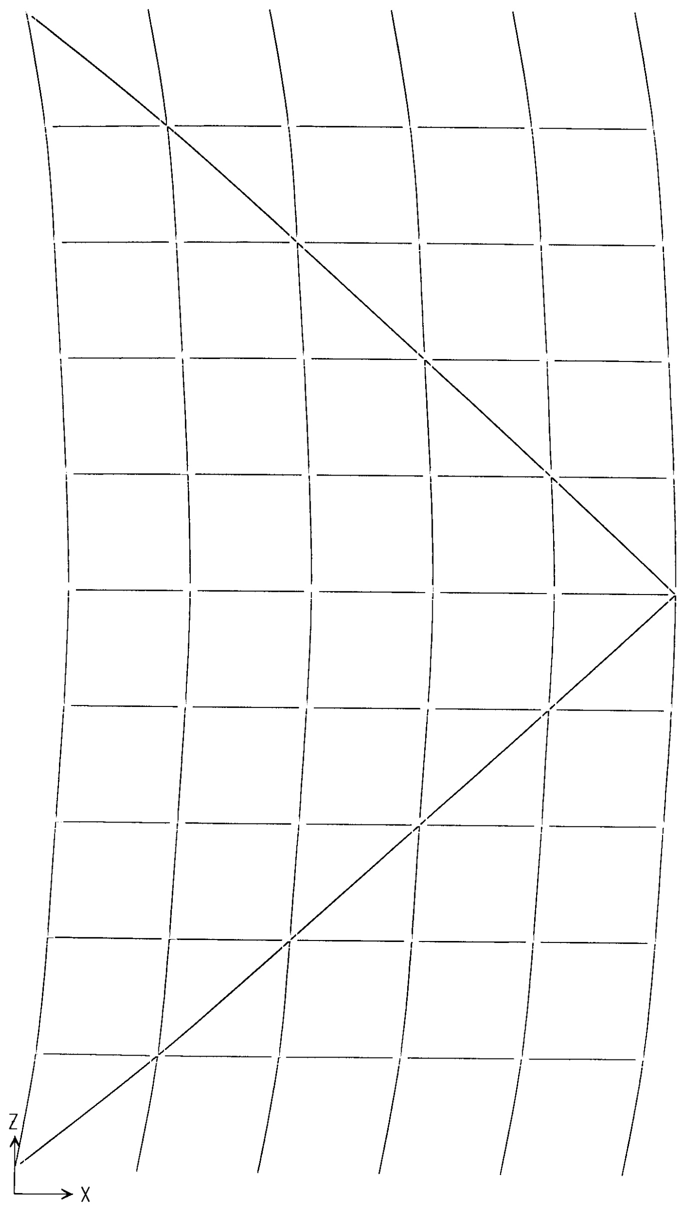


Figure 3.10. Six trusses with nine continuous lateral braces and two diagonal braces primarily deflected in the C-mode except at the point of diagonal brace connections.

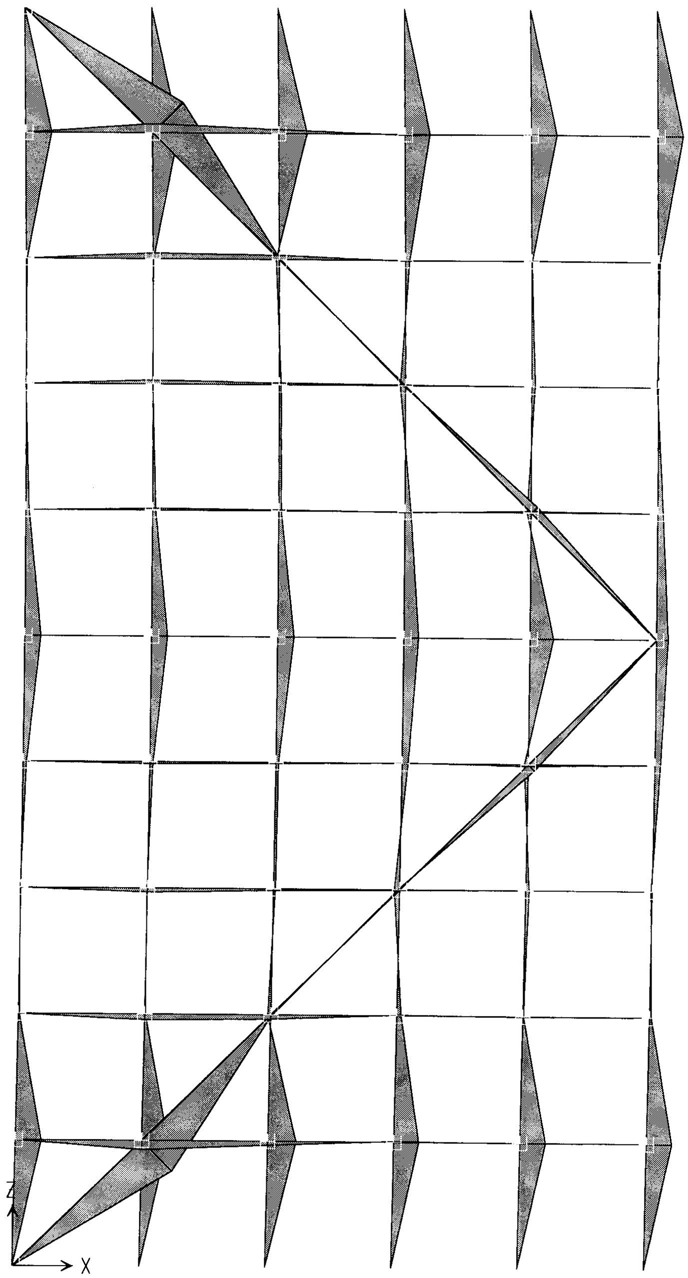


Figure 3.11. Moment is developed in the chords primarily due to the bracing connections and the initial curvature of the chord members.

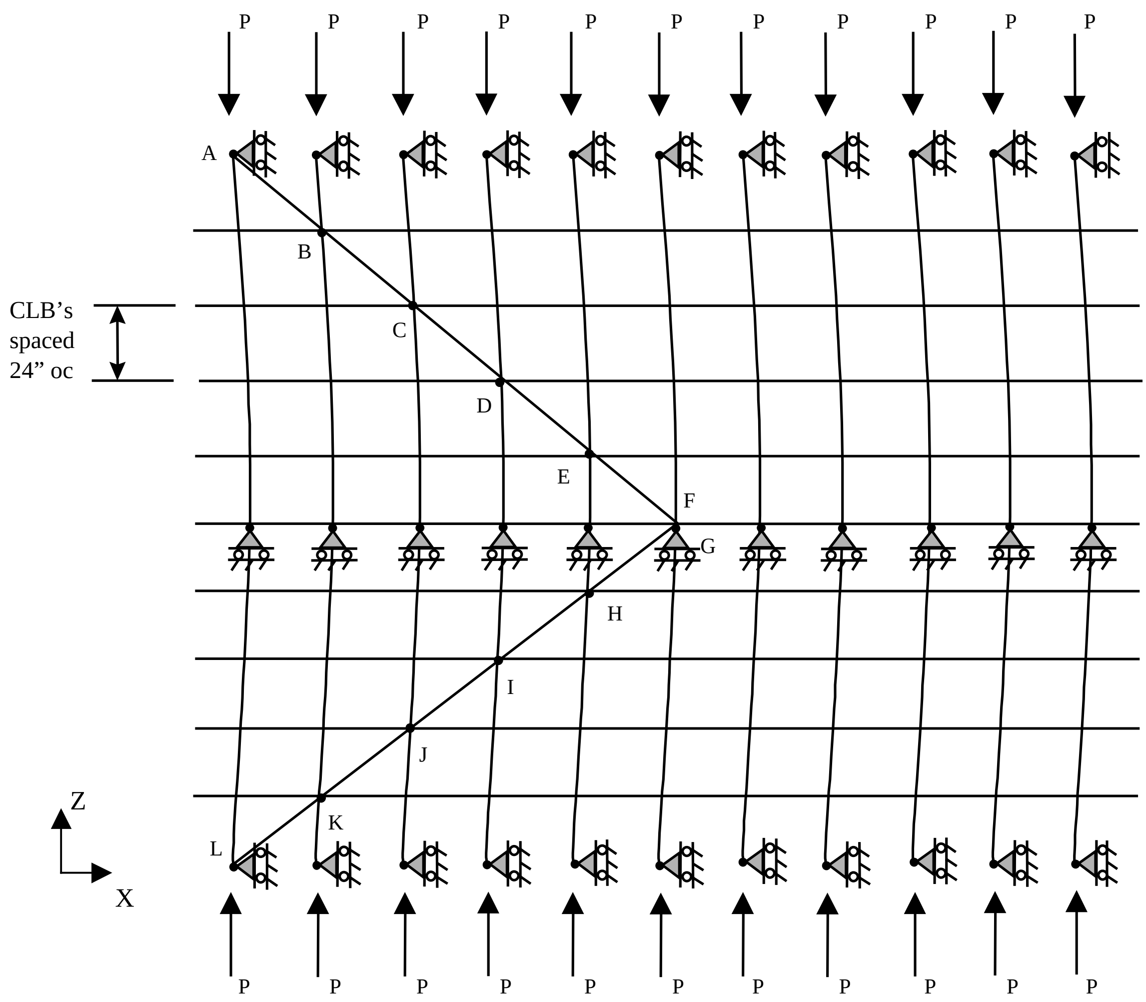


Figure 3.12. The structural analog represents 11 trusses with an initial curvature, 9 continuous lateral braces (CLB's), and 2 diagonal bracing members in a V-shape. The initial curvature is in one direction and exaggerated for visual purposes.

were assigned for the data file for SAP2000 (CSI, 1995) using Equation 3.2 to produce a half sine wave configuration, with an assumed initial curvature of L/200.

All connections between the truss chords and the diagonals were modeled by a horizontal spring and a vertical spring. The horizontal spring represented the lateral load-slip relationship slip at the diagonal and chord member connection. The vertical spring represented the connection slip in the vertical direction between the diagonal member and the chord member. The resultant spring force was determined for each of these connections, after the analysis was completed using vector addition.

A spring acting in the horizontal direction and a spring acting in the vertical direction represented the connections between the chords and the CLB. Joint F and G, as depicted in Figure 3.12, consisted of the two-spring connection between the diagonal member and the chord member and the two-spring connection between the CLB and the chord member. One horizontal spring or nailed connection allows the load to be transferred out of the CLB into the chord and the other nailed connection transferred the load out of the chord into the diagonal brace. Joints A and L, (Figure 3.12), represented the connection between the diagonal and the chord at the point where the chord is connected to the truss panel point and roof or ceiling diaphragm.

Once the data file for the structure was complete, loads were applied and the structure analyzed. Design load was determined based on the National Design Specification for Wood Construction (AF&PA, 1997) and an axial load ranging from 684 to 3,421 pounds was applied to each chord. The allowable design load (F_c') was determined to be 6,842 pounds. The load levels were applied as described in Section 3.5.2. Load levels above 50% were not studied as discussed in Section 3.5.1. Design load was based on the grade, species combination, size of lumber, and the duration of load, which in this case is assumed to be 1.15 for snow plus dead loading.

The stiffness values for the 2-16d nailed connections were determined using Equation 3.4 from Mack (1966). As previously discussed in Section 3.4, the secant modulus method was used based on the load and deflection.

A linear spring stiffness was estimated for each joint and the structural analog of Figure 3.12 was analyzed. The calculated spring forces were then compared to the specific force and displacement used to input the linear spring (secant modulus) constants. The new stiffness value for each spring was entered into SAP2000 (CSI, 1995) and the structure was analyzed again. The procedure was repeated until the force in the springs matched the assumed force and displacement used to calculate the secant modulus spring stiffness within a tolerance of 1%.

The deflected shape, as depicted in Figure 3.13, resulted from the final stiffness of each spring, with 3,421 pounds of axial force applied to the chords. The moment diagram, Figure 3.14, illustrated the moment that developed due to the bracing connections and the initial curvature. The moment is zero at each end of the chords due to the moment-free pin supports. The moment is continuous across the nodes verifying the continuity of the wood members.

3.6 Single Member Analogs

To simplify the structural analogs from multiple truss chords to a single member analog, the connection slip between the diagonal and chord member was not modeled. The j-truss system analogs were not practical for testing chord lengths and possible number of trusses to be braced (j) as a group. A simple analog was needed that would apply to all practical truss construction.

On average, the net lateral force in a CLB is 0.0 assuming the installed webs are bowed left and right and the bow follows some symmetric probability distribution. However, almost always there will be some imbalance in the net lateral force in the CLB due to random variations in the bow of the n-webs involved.

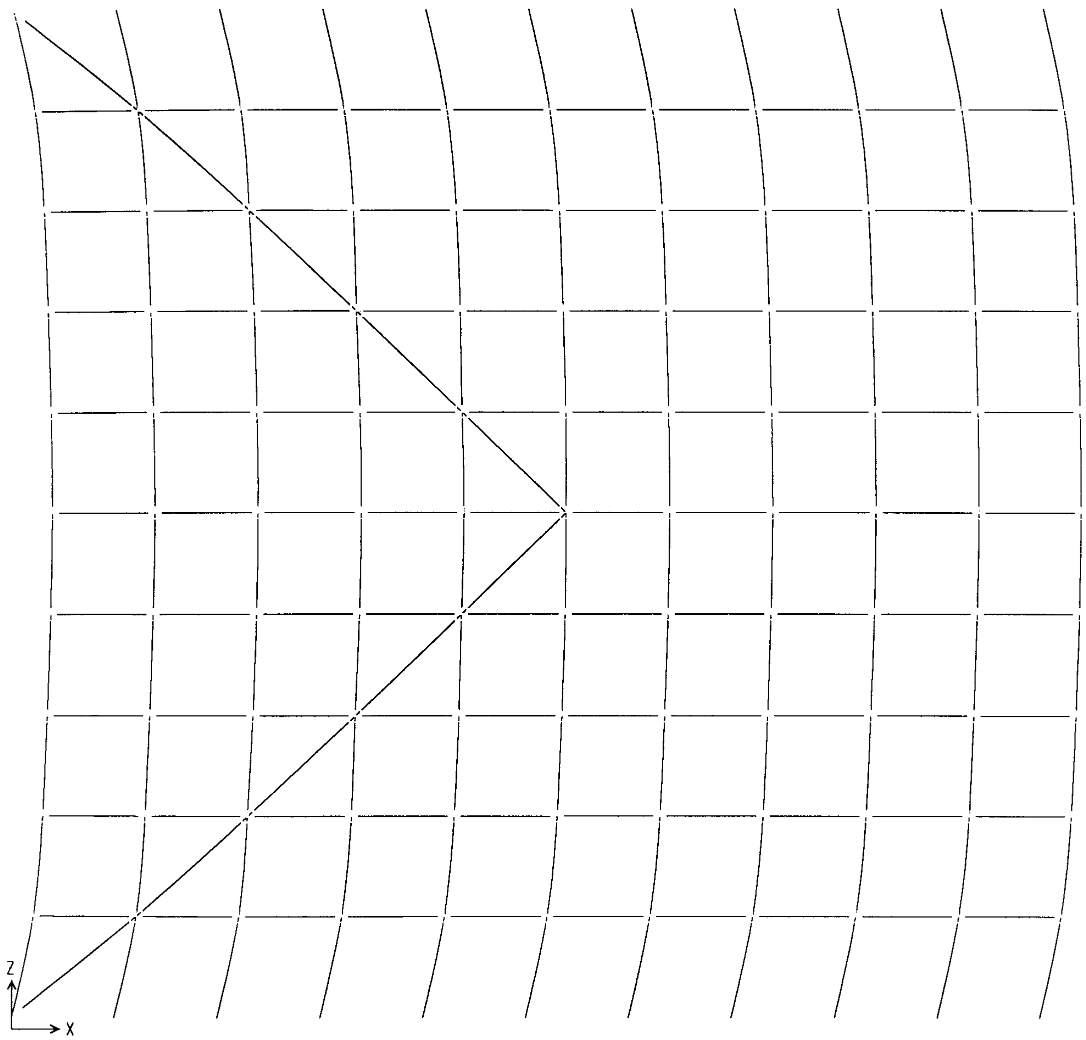


Figure 3.13. Eleven trusses with nine continuous lateral braces and two diagonal braces primarily deflected in the C-mode except at the point of diagonal brace connections.

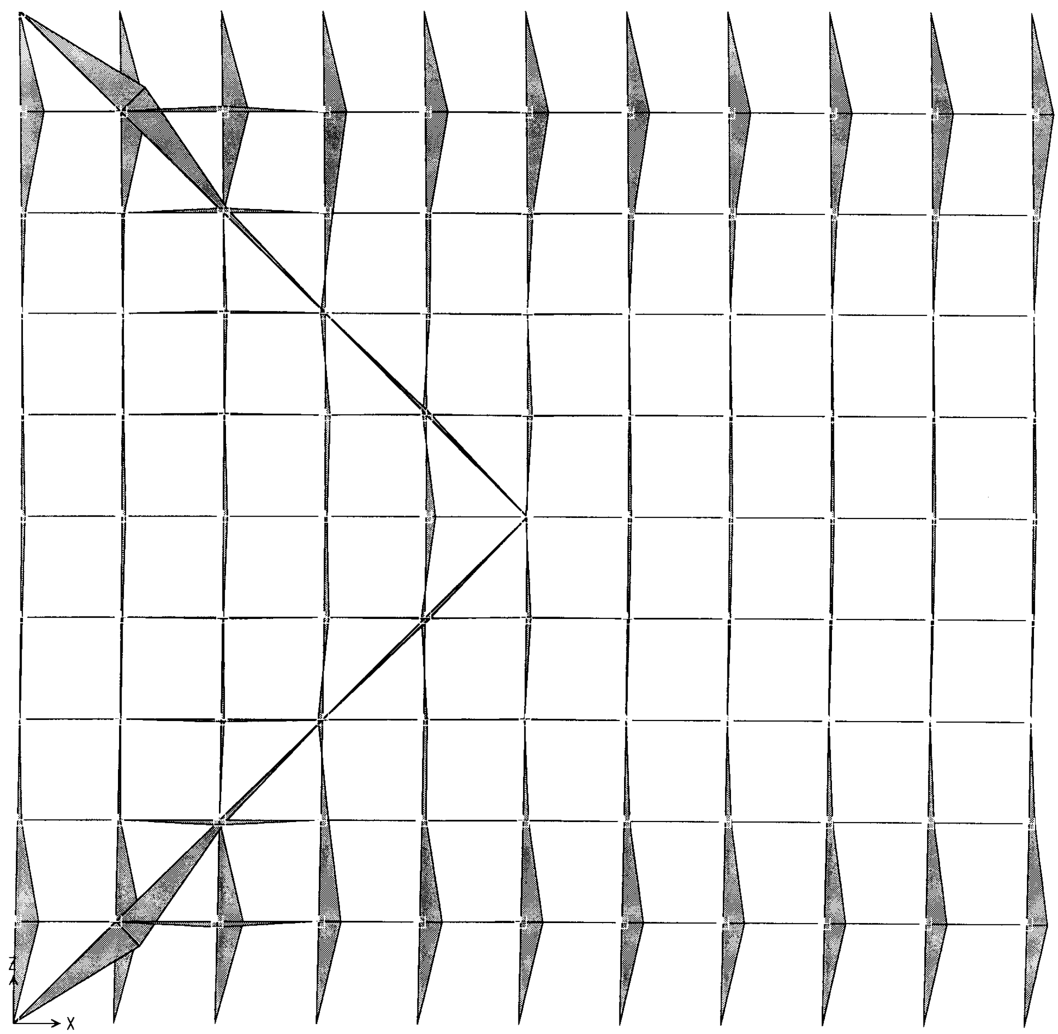


Figure 3.14. Moment is developed in the chords primarily due to the bracing connections and the initial curvature of the chord members.

3.6.1 One Web braced by One CLB

The structural analog was represented in SAP2000 (CSI, 1995) as depicted in Figure 3.15, where the length of the web varied from three feet to twelve feet. Chord members were assumed to be columns with pinned support connections on one-end and roller support connections on the other end. All of the lumber was assumed to be 2x4 STUD Spruce-Pine-Fir with a modulus of elasticity of 1,200,000 psi. The allowable load, P, applied to the web was determined based on the guidelines presented in the NDS (AF&PA, 1997). A sample calculation for the allowable load for one web braced by one CLB can be reviewed in Appendix A. The effective stiffness of the nailed connection represented by a single spring was determined using the secant method as discussed in Section 3.4.

ANSI/TPI 1-1995 (TPI, 1995) installation limits were assumed for all chord lengths studied. Therefore, to properly model the web member with initial curvature, the nodes were assigned for the data file for SAP2000 (CSI, 1995) using Equation 3.2 to provide a half sine wave configuration, with an assumed initial curvature of L/200.

3.6.2 One Web Braced by Two CLB's

For the case of one web braced by two CLB's, the structural analog included the same assumptions as the structural analogs representing one web braced by one CLB, but two CLBs were used to brace the truss web. The structural analogs representing one web braced by two CLB's, as depicted in Figure 3.16, consisted of two nailed connections represented by single springs. The material properties for the lumber were assumed to be the same as those described in Section 3.6.1. The effective stiffness of the springs were determined as previously discussed. The allowable loads applied to the truss webs were determined based on the design equations presented in the NDS (AF&PA, 1997). The applied axial loads were varied from ten percent of the allowable load to the allowable load in increments of ten percent. The length of the webs varied from five feet to twelve feet.

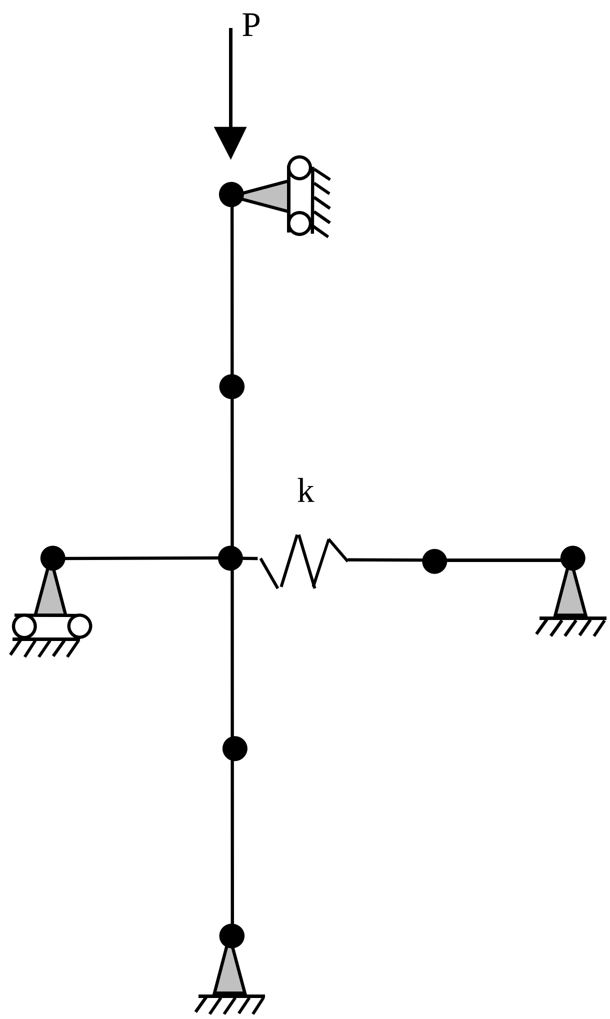


Figure 3.15. Structural analog representing one web braced by one CLB. The nailed connection is represented by a spring and an applied load, P, is a compression force determined using design equations outlined in the NDS 97 (AF&PA, 997).

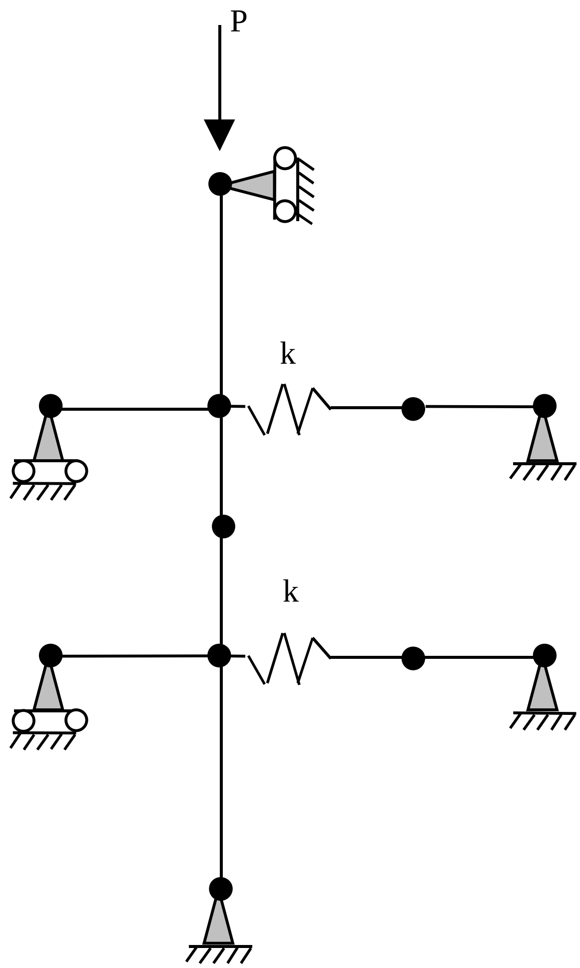


Figure 3.16. Structural analog representing one web braced by two CLBs. The nailed connections are represented by springs and an applied load, P, is a compression force determined using design equations provided in the NDS (AF&PA, 997).

3.6.3 Effects of Lumber Size

To determine if lumber size has an effect on the required bracing force, a test was run using 2x6 lumber. All lumber properties used in the construction of the structural analog was assumed to be 2x6 STUD Spruce-Pine-Fir, with a modulus of elasticity of 1,200,000 psi. Truss webs were assumed to be a column with pin connections on one-end and roller connections on the other. All connections between webs and braces were assumed to be made with 2-16d Common nails and were represented with springs to model the slip in the connection.

The allowable load level for the column was recalculated using the correct area (5.5 inches x 1.5 inches) and the requirements outlined in the NDS (AF&PA, 1997). Changes were also made within SAP2000 (CSI, 1995) to adjust for the larger dimensions.

3.6.4 Effects of Lumber Specific Gravity and Modulus of Elasticity, E

To determine if lumber species (specific gravity and modulus of elasticity, E) has an effect on the required bracing force, an analysis was run using 2x4 No. 2 Douglas Fir-Larch for the web and CLB's, which has a 17% higher E value than Spruce-Pine-Fir. The specific gravity for Douglas Fir-Larch is 0.5 versus 0.42 for Spruce-Pine-Fir. Douglas-Fir-Larch was chosen as the species to compare to Spruce-Pine-Fir because the nail slip data was available for a Douglas Fir-Larch joint and because of the high specific gravity value. The truss webs were assumed to be a column with pin connections on one-end and roller connections on the other. All connections between webs and braces were assumed to be made with 2-16d Common nails and were represented with springs to model the slip in the connection.

The allowable load level for the column was recalculated using the appropriate modulus of elasticity (1,400,000 psi) and the requirements outlined in the NDS (AF&PA, 1997). Changes were also made within SAP2000 (CSI, 1995) to adjust for the different modulus of elasticity. The web and the brace were both assumed to be No. 2 Douglas Fir-Larch.

Truss web lengths of four feet and twelve feet were tested at load levels of 10% and 100% of the maximum allowable axial compressive load calculated. SAP2000 (CSI, 1995) analyses were performed for both one web braced by one CLB and one web braced by two CLB's.

3.6.5 Truss Chord Braced by n-CLB's

The structural analogs to test truss chords braced by n-CLB's were designed to test the objectives previously described. In order to determine the net cumulative bracing force required to be braced with diagonals, a structural analog had to be created for various lengths of lumber. The first assumption for the structural analogs was the shortest truss panel length was assumed to be four feet requiring one CLB at the center and one on each end.

The second assumption for the structural analogs pertains to the bending and compression forces in the problem. The center panel (or two panels, if symmetrical) is subjected to the maximum compression. Assuming panel lengths are equal, the center panel (or two panels, if symmetrical) will have the maximum stress interaction per the NDS (AF&PA, 1997) shown as Equation 3.5.

$$\left(\frac{f_c}{F_c'}\right)^2 + \left(\frac{f_b}{F_b'(1-F_{ce})}\right) \leq 1 \qquad (3.5)$$

From a permanent bracing designer standpoint, one needs to determine the maximum axial forces in the panels. When the supporting truss chord is assumed to be continuous, in the structural analysis, bending moments will exist in all panels. The amount of bending moment will vary from one design to the next. A conservative assumption with respect to permanent bracing design is that the bending moment is zero in all panels and that the stress interaction is at the maximum equal to 1.0. Equation 3.5 therefore reduces to Equation 3.6.

$$f_c = F_c' \qquad (3.6)$$

Equation 3.6 applies to the center panel (or two panels if symmetrical). It is conservative because assuming the bending moment is zero allows for the maximum axial compression to be present in the assumed chord. The design compression load in the center panel (or two panels if symmetrical) is therefore illustrated by Equation 3.7.

$$C = A * F_c' \tag{3.7}$$

where: A is the chord area (in^2) and

F_c' is the allowable compression design value parallel to grain, psi

Axial load in the outer panels will be lower than the axial load in the center panels. A conservative assumption for permanent bracing design is to assume all panels have the same axial load and that load is equal to the center panel maximum value as determined using Equation 3.7.

The allowable compression parallel-to-grain design value, Fc', was calculated using NDS (AF&PA, 1997) procedures. Chords can buckle about both axes depending on the l_e/d of each axis. When CLBs are installed at 24 inches on center, the weak axis l_e/d was determined using Equation 3.8.

$$\frac{le}{d} = \frac{Ke * la}{d} = \frac{1.0 * 24''}{1.5} = 16 \tag{3.8}$$

If the strong axis l_e/d is greater than 16, the truss designer uses the larger l_e/d. A situation such as this occurs when determining l_e/d for a 2x4 member that is ten feet in length. If the strong axis l_e/d is less than 16, 16 is used. A situation such as this occurs when determining l_e/d for a 2x12 member that is ten feet in length. For permanent bracing design, it is therefore conservative to assume l_e/d equal 16.

A truss designer must determine the larger value of l_e/d between the weak axis and the strong axis. Upon comparison of values of l_e/d a truss designer will use weak axis l_e/d while the lumber size is large and then at some point the strong axis value for l_e/d is larger and the designer will then switch to using the l_e/d that is larger. The truss designer's approach versus the permanent truss bracing designer's approach can be seen more clearly in Figure 3.17. Using l_e/d equal 16 versus the larger l_e/d will always predict the maximum possible load in the top chord.

The final assumptions used in creating the structural analogs included the lumber type, chord lengths, and the duration of load factor. The duration of load was determined based on snow load plus dead load. The lumber was assumed to be No. 2 Southern Pine for the truss chords and STUD Spruce-Pine-Fir for the CLBs. The size of the truss chord was varied from 2x4 to 2x12. The length of the truss chord was varied from four feet to forty feet by increments of four feet but also included six feet.

A total of ten structural analogs were developed based on the varying lengths of lumber. As by standard industry practice, the CLBs were assumed to be spaced at 24 inches on center and therefore a spring was used to represent the connections. Table 3.4 and Figure 3.18 illustrate the top chord lengths studied based on the size of the lumber. Figure 3.19 depicts the structural models as they were analyzed in SAP2000 (CSI, 1995). The structural analogs were designed using the same procedure as for the cases of one web with one and two CLB's (Section 3.6.1 and Section 3.6.2). The allowable loads were determined based on the size of the members using the aforementioned l_e/d value and the NDS (AF&PA, 1997) design equations.

The assumed initial deflected shape of the chords was determined using Equation 3.2 and the assumptions presented in Section 3.6.1. If the length of the chord exceeded 400-inches, Equation 3.9 was used to stay within the guidelines provided in ANSI/TPI 1-1995 (TPI, 1995).

$$\Delta_i = 2 * \sin\left(\frac{pi * x}{L}\right) \tag{3.9}$$

ANSI/TPI 1-1995 (TPI, 1995) states that the maximum initial deflection allowed in a truss chord is the lesser of L/200 or 2 inches. In cases where compression chord length, L, is greater than 400 inches, the 2-inch maximum allowance was observed.

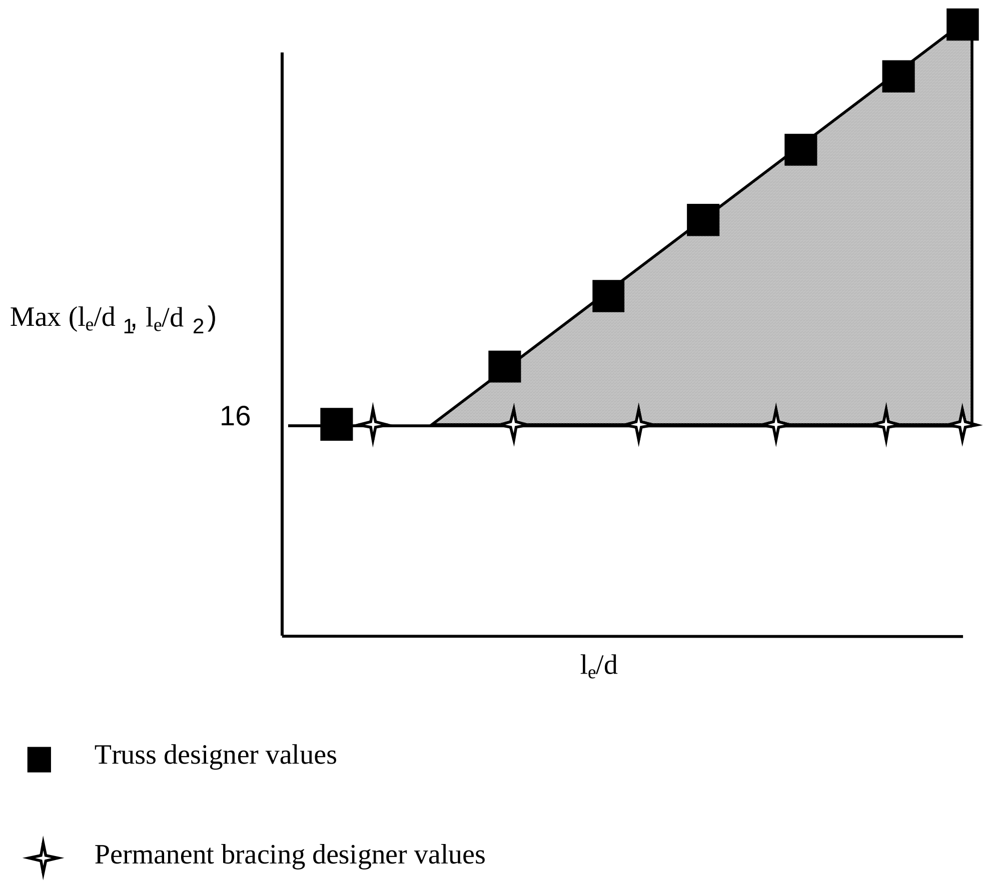


Figure 3.17. To determine the appropriate l_e/d ratio for use in calculating the allowable axial compressive load in a member, a truss designer and a permanent bracing designer use different values.

Table 3.4. Truss chord length based on lumber size and the test increments used to create the multiple structural analogs in SAP2000 (CSI, 1995).

Nominal Lumber Size	Allowable supporting truss chord length range	Test increments
2x4	4 feet ⟶ 24 feet including 6 feet	4 feet
2x6	4 feet ⟶ 36 feet including 6 feet	4 feet
2x8	4 feet ⟶ 36 feet including 6 feet	4 feet
2x10	4 feet ⟶ 40 feet including 6 feet	4 feet
2x12	4 feet ⟶ 40 feet including 6 feet	4 feet

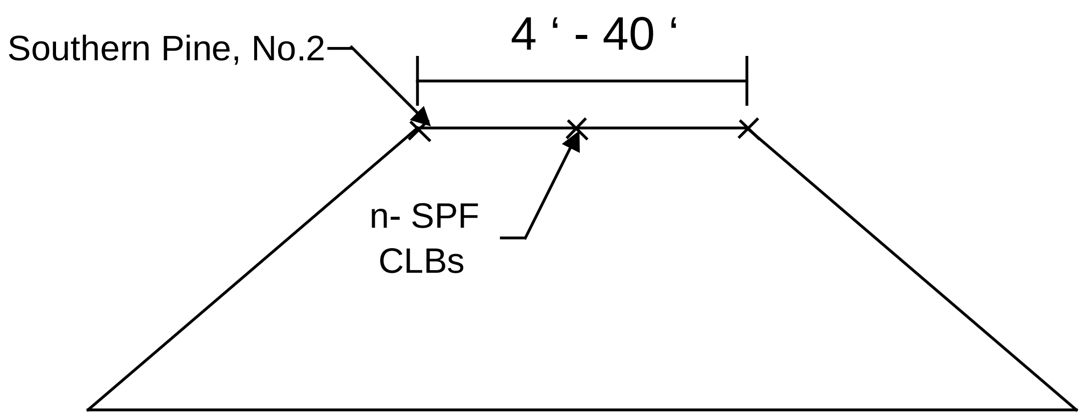


Figure 3.18. The truss chord length studied was based on the size of the Southern Pine, No. 2 lumber. Only one CLB-chord connection point is illustrated but a truss with multiple CLB's would be used on trusses of significant length.

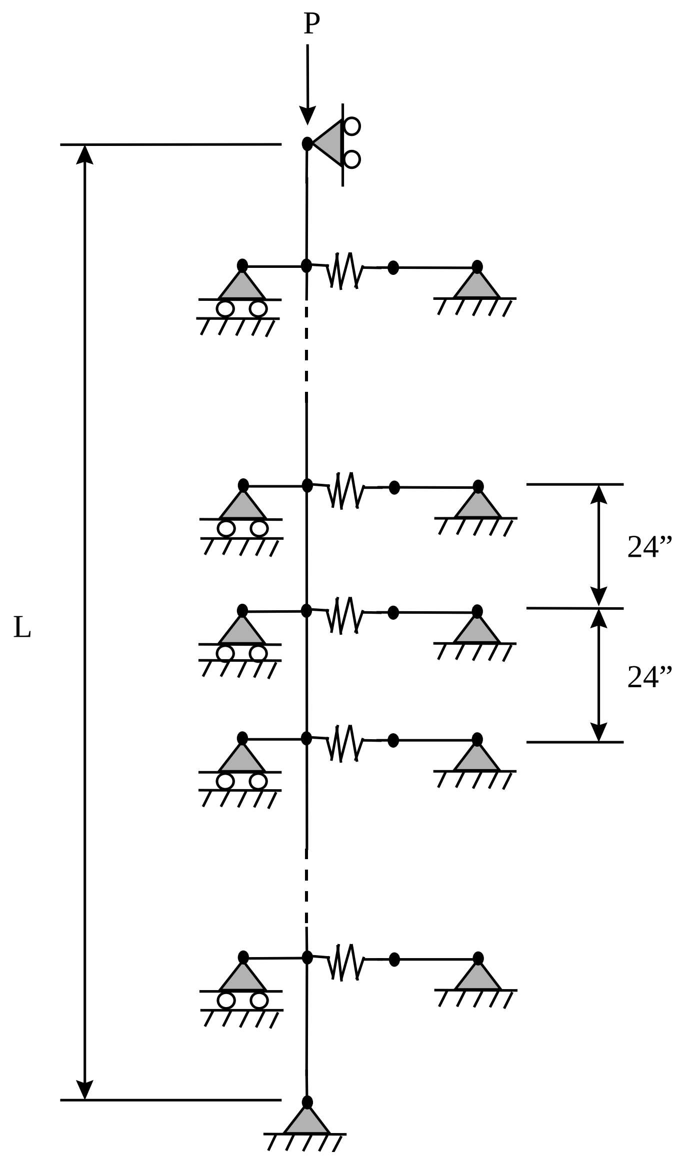


Figure 3.19. Structural analogs as depicted in SAP2000 (CSI, 1995) for n-CLBs spaced 24-inches on center, with an applied axial load, P, and the truss chord is length L.

4. Results

4.1 Forces Required to Brace System Analogs

4.1.1 Forces Required to Brace Eight Chords with Three CLB's and One Diagonal Brace

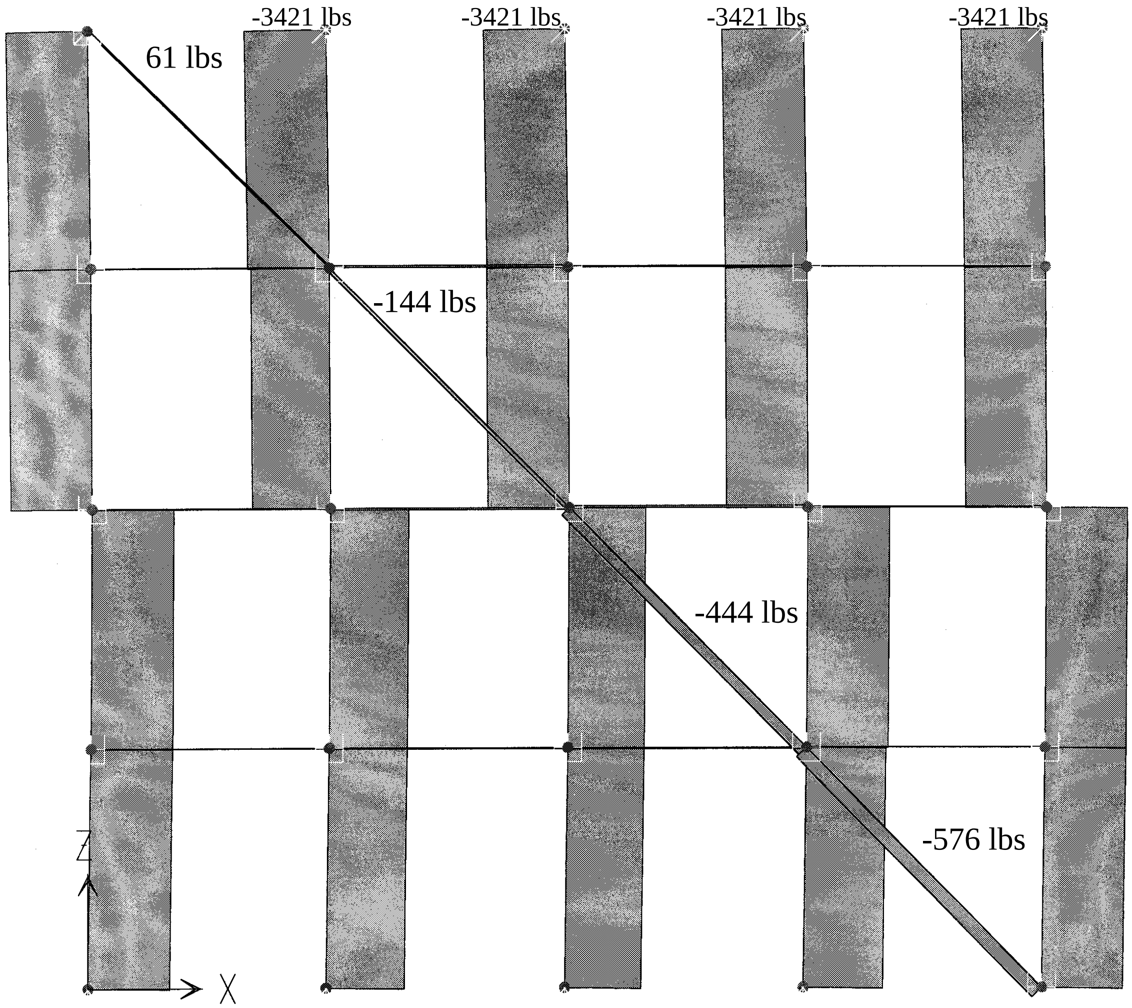
Lateral forces produced by the analysis of the system structural analog representing five eight-foot truss chords braced by three CLB's and one diagonal are summarized in Table 4.1. The lateral forces accumulate at Joint E as depicted in Figure 4.1. A positive number indicates a tension force and a negative number indicates compression. Figure 4.1 shows the axial forces in the diagonal for five-eight foot trusses spaced twenty-four inches on center with three CLB's and one diagonal with an applied compressive load in the truss chords of 3,421 pounds. The lateral forces accumulated at Joint E (Figure 3.5) because of the support conditions described in Section 3.5.1. A second reason the forces accumulated at Joint E (Figure 3.5) is based on the load path necessary to transfer the force from the truss chords to the bracing system, then finally into the roof or ceiling diaphragms at truss panel points. As the truss chords deflect, more load is transferred into the spring connections and ultimately into the diagonal member. Since the trusses are deflected to the right, the load "builds up" in the diagonal as force is added from the chords all deflecting in a C-shape to the right. The additional load accumulates in the connection where the force is transferred into the roof or ceiling diaphragms of the structure. As expected the lateral force increased as the load level was increased from 10% to 50% of the allowable compressive load.

The resultant force between the diagonal and the chord connections was calculated and the resultant forces were summarized in Table 4.2. The resultant forces were calculated using the spring forces from both the horizontal and the vertical springs produced in the SAP2000 (CSI, 1995) analysis of five eight-foot truss chords, spaced twenty-four inches on center, braced by three CLB's and one diagonal. The resultant forces in Table 4.2 illustrates that typically one joint (Joint E) had a higher connection load than the rest of the diagonal brace to chord connections. In most cases, the number of nails required for

Table 4.1 Net lateral forces (lbs) produced by n- Southern Pine truss chords braced by multiple Spruce-Pine-Fir (SPF) CLB's and one or two SPF diagonal(s).

Length of chords (ft)	No. of trusses	No. of CLB's	No. of Diagonal Braces	Applied Axial Compressive load from 10% to 50% of allowable load (lbs)*				
				684	1368	2053	2737	3421
8	5	3	1	91	182	272	363	453
20	6	9	2	124	247	367	486	602
20	11	9	2	221	434	637	824	983

* Based on l_e/d equal 16 and 2x4 No. 2 Southern Pine truss chords



Note: The two CLB's normally installed at the roof planes are not shown as they are laterally stabilized by the roof diaphragm.

Figure 4.1. Lateral forces accumulate down the length of the diagonal when the chords are braced by one diagonal spanning the length of the trusses. Axial forces in the diagonal are shown here for an applied chord load of 3,421 pounds in SAP2000 (CSI, 1995) on five eight-foot long chords.

Table 4.2 Resultant joint forces (lbs) calculated for the diagonal brace(s) to truss chord connections. The resultant forces were calculated using the results produced in the SAP2000 (CSI, 1995) analysis of j-truss chords braced by multiple CLB's and one or two diagonals.

Joint	5-8 ft. chords, 3 CLB, 1 diagonal					6-20 ft. chords, 9 CLB's, 2 diagonals					11-20 ft. chords, 9 CLB's, 2 diagonals				
	10% to 50% of the allowable load level (lbs)*					10% to 50% of the allowable load level (lbs)*					10% to 50% of the allowable load level (lbs)*				
	684	1368	2053	2737	3421	684	1368	2053	2737	3421	684	1368	2053	2737	3421
A	53	61	43	1.2	61	87	172	256	338	418	154	302	443	572	681
B	42	83	123	164	205	2	3	6	12	23	6	22	50	100	183
C	59	119	180	241	300	20	42	66	89	115	39	83	129	182	241
D	29	56	82	107	132	24	48	73	98	124	46	93	144	196	255
E	183	319	428	512	576	31	60	88	116	143	52	103	148	194	243
F						10	21	33	46	58	21	45	72	98	124
G						10	21	33	46	58	21	45	72	98	124
H						31	60	88	116	143	53	103	148	194	243
I						24	48	73	98	124	46	93	144	196	255
J						20	42	66	89	115	40	83	129	182	241
K						2	3	6	12	23	6	22	50	100	183
L						87	172	256	343	418	154	302	443	572	681

* Allowable load level was based on 2x4 No. 2 Southern Pine and an l_e/d of 16.

the diagonal brace to chord connections at Joint E, using NDS 97 (AF&PA, 1997) requirements, was larger than the number of 16d Common nails that will fit without splitting the end of a 2x4 diagonal brace. A design procedure for the connections between the diagonal brace and the truss chords cannot be offered at this time because of the number of nails required to resist 576 pounds per the NDS 97 (AF&PA, 1997) requirements is theoretically four 16d Common nails. From a practical standpoint, there is only room for at most three 16d Common nails.

4.1.2 Forces Required to Brace Six Chords with Nine CLB's and Two Diagonals

The lateral forces produced by the analysis of the system structural analog representing six-twenty foot roof truss chords braced by nine CLB's and two diagonals in a V-shape are summarized in Table 4.1. As expected the net lateral force increased as the load level was increased from 10% to 50% of the allowable compressive load. Lateral forces were higher for the twenty-foot chords than for the eight-foot long chords due to the longer length of the trusses. Longer trusses deflect more because the initial curvature is larger and more braces are required to resist the deflection produced by the applied compressive load in the truss chords thus leading to an increase in bracing forces.

The resultant force between the diagonal and the chord connections was calculated and the resultant forces were summarized in the center section of Table 4.2. The resultant forces were calculated using the spring forces from both the horizontal and the vertical springs produced in the SAP2000 (CSI, 1995) analysis of six-twenty foot truss chords braced by nine CLB's spaced twenty-four inches on center and two diagonals in a V-shape. The resultant forces in Table 4.2 illustrated that typically two joints (Joint A and L from Figure 3.9) had a higher joint load than the rest of the diagonal brace to chord connections. A design for the connections between the diagonal braces and the truss chords can be executed because the number of nails required to resist 418 pounds per NDS 97 (AF&PA, 1997) requirements is three 16d Common nails.

4.1.3 Forces Required to Brace Eleven Chords with Nine CLB's and Two Diagonals

Lateral forces produced by the analysis of the system structural analog representing eleven-twenty foot roof truss chords braced by nine CLB's and two diagonals in a V-shape are summarized in Table 4.1. As expected the lateral force increased as the load level was increased from 10% to 50% of the allowable compressive load. Net lateral forces were higher for the eleven twenty-foot roof trusses than for six twenty-foot roof trusses because of the additional load induced in the CLB's due to the additional truss chords. The diagonal bracing crossed six truss chords as illustrated in Figure 3.12. The five additional trusses are tied in by the CLB's.

The resultant joint forces in the diagonal to chord connections were calculated and the resultant joint forces were summarized in Table 4.2. The resultant joint forces were calculated using the spring forces from both the horizontal and the vertical springs produced in the SAP2000 (CSI, 1995) analysis of eleven twenty-foot truss chords braced by nine CLB's spaced twenty-four inches on center and two diagonals in a V-shape. Referring to Table 4.2, two joints (Joint A and L from Figure 3.12) typically had a higher connection load than the rest of the diagonal brace to chord connections. At 30% of the allowable compressive load or more, the number of nails required for the diagonal brace to chord connections at Joints A and L, using NDS 97 (AF&PA, 1997) specifications, was larger than 2-16d Common nails typically used in truss construction.

As previously discussed in Section 2.6.2, Mack (1966) defined failure of a connection consisting of 2-16d Common nails by a joint slip of 0.1 inches. When both members are Spruce-Pine-Fir, the joint force at 0.1 inches slip is 618 pounds. Based on the 0.1 inch failure criterion, at loads larger than 618 pounds, the nailed connection has failed. Table 4.2 shows that at 3,421 pounds applied axial chord load, the nail connections at Joints A and L have failed per Mack's (1966) rule. Based on a joint load of 681 pounds, for the case of a 3,421 pound chord load, five 16d Common nails are theoretically required per the NDS 97 (AF&PA, 1997) specification.

A design procedure for the connections between the diagonal braces and the truss chords cannot be offered at this time, because from a practical standpoint, there is only room for at most three 16d Common nails.

4.2 Forces Required to Brace Single Member Analogs

4.2.1 Forces Required to Brace a Web with One CLB

The lateral forces produced by the analysis of the structural analog representing a truss web are presented in Table 4.3. For the purpose of discussion and comparison to the 2% Rule, the net lateral restraining force was divided by the axial load in the compression web and will be referred to as R. R is defined by Equation 4.1 and the results of the analysis are summarized in Table 4.4.

$$\frac{\text{Net lateral restraining force (lbs)}}{\text{Axial load level in web/chord (lbs)}} \qquad (4.1)$$

As previously discussed, in Section 2.7.1.4, the 2% Rule is based on a web pinned at both ends and at the center. The tangent of the angle based on the initial curvature is 1/100 as shown in Figure 2.12.

The R values in Table 4.4 were not affected by web lengths and load levels studied (that ranged from 10% to 100% of the allowable compression for the assumed lumber grade). The difference in the two values, 2% Rule versus 2.3% found in Table 4.4, is due to the fact that a flatwise 2x4 is very flexible, and thus not dramatically affected by member continuity. The computer analog constructed for this thesis does not have a pin connection at the mid-span (center) of the web as is assumed for the derivation of the 2% Rule.

The deflected shape as depicted from SAP2000 (CSI, 1995) is illustrated in Figure 4.2a for the case of a 12-foot web with 788 pounds applied to the web. The maximum deflection of the web was 0.0191 inches. The moment diagram, depicted in Figure 4.2b, illustrates a non-zero moment at the CLB and web connection. Therefore, the moment diagram verifies that the web is being modeled as one continuous member supported by a CLB with a nail connection (represented by a spring).

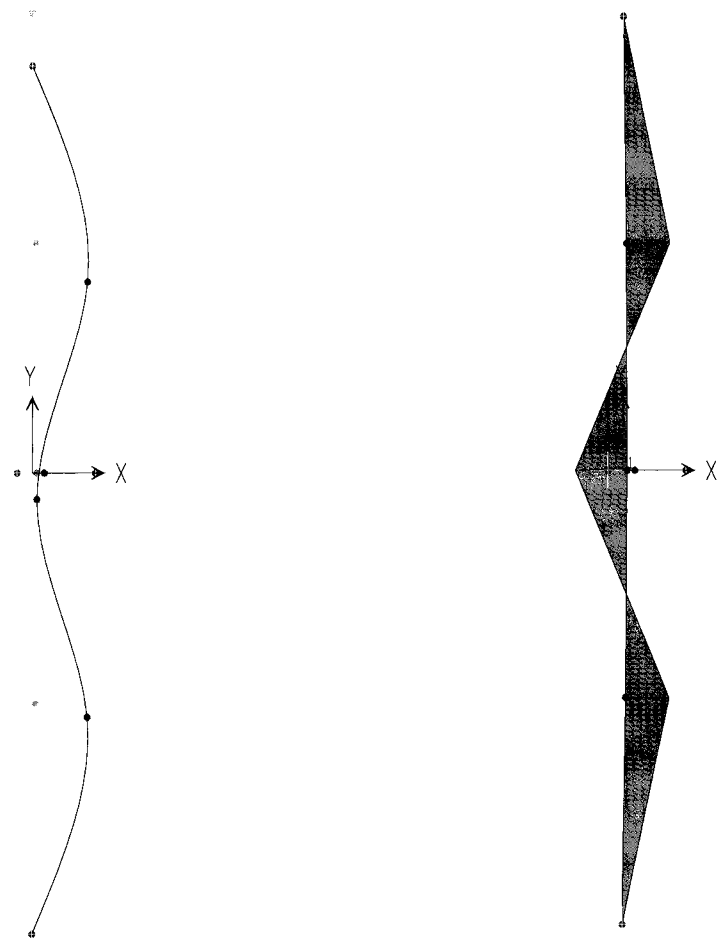
Table 4.3. Lateral force produced by a 2x4 STUD Spruce-Pine-Fir web when braced by a CLB having a specific gravity of 0.42. Connection is assumed to be 2-16d Common nails, and the CLB was assumed to be restrained from lateral movement.

Web Length (feet)	Axial Load Level in Web(lbs.)[1] Lateral force produced in the web-CLB connection(lbs.)									
3	420 10	840 19	1260 29	1680 39	2100 48	2520 58	2940 67	3360 77	3781 86	4201 96
4	379 9	759 17	1138 26	1518 35	1897 44	2276 52	2656 61	3035 70	3415 78	3794 87
5	322 7	644 15	966 22	1288 30	1610 37	1932 44	2254 52	2575 59	2897 66	3219 74
6	260 6	520 12	781 18	1041 24	1301 30	1561 36	1821 42	2082 48	2342 54	2602 60
7	207 5	414 10	621 14	828 19	1035 24	1243 29	1450 34	1657 38	1864 43	2071 48
8	166 4	332 8	498 12	663 15	829 19	995 23	1161 27	1327 31	1493 34	1658 38
9	135 3	269 6	404 9	539 12	673 16	808 19	943 22	1077 25	1212 28	1347 31
10	111 3	222 5	333 8	444 10	555 13	666 15	777 18	888 20	999 23	1110 26
11	93 2	186 4	279 6	372 9	465 11	557 13	650 15	743 17	836 19	929 22
12	79 2	158 4	236 5	315 7	394 9	473 11	551 13	630 15	709 16	788 18

[1]The rightmost column is 100% of the allowable and the leftmost load column is 10% of the allowable assuming C_D equals 1.15.

Table 4.4. Net lateral restraining force (lbs) for a web with one CLB divided by the axial load (lbs) for comparison to the 2% Rule.

Web Length (ft)	Lateral force produced in the web-CLB connection(lbs.) / Axial Load Level in Web(lbs.)									
3	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
4	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
5	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
6	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
7	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
8	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
9	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
10	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
11	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
12	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023



(a.) (b.)

Figure 4.2. **(a.) The deflected shape of a web braced with one CLB as represented in SAP2000 (CSI, 1995). The web is twelve feet long with an applied axial load of 788 pounds.**

(b.) The moment diagram for a web braced with one CLB as represented in SAP2000 (CSI, 1995). The moment at the connection is non-zero illustrating continuity in the web member.

4.2.2 Forces Required to Brace a Web with Two CLB's

This case, consisting of one web and two CLBs, produced net lateral forces of particular interest. In the past, one option for design purposes was to assume the bracing force was equal to 2% of the applied load, times the number of connections per web, which yields 4% of the axial load as the required bracing force per web. For the purpose of discussion and comparison to the 2% Rule, the net lateral restraining force was divided by the axial load in the web and will be referred to as R defined in Equation 4.1. R, for the case of one web and two CLB's, is summarized in Table 4.6. The 2.8% R-value is significantly less than the 4% calculated by the assumption that the brace force increases in proportion to the number of CLB's. Based on the net lateral restraining forces, in Table 4.5, for the case of one web with two CLBs, the required net lateral restraining force needs to be 2.8% of the applied load as illustrated in Table 4.6. Based on R values reported in Table 4.6, R is not affected by length of the web (when using two significant figures).

The deflected shape is illustrated in Figure 4.3a for the case of a twelve-foot web with 1,055 pounds applied to the web. The maximum deflection of the web was 0.006 inches and it occurred at the center of web. The moment diagram, depicted in Figure 4.3b, illustrates a non-zero moment at the connections. The maximum moment was 59 in-lb. The maximum shear in the web was 4 pounds.

4.3 Effects of Lumber Size

The next structural analog was designed to test the effects of lumber size on the net lateral restraining force for the cases of one web and one CLB and one web and two CLB's. The structural analog analysis for the case of one web and one CLB consisted of a 2x6 STUD Spruce-Pine-Fir web, ranging in length from three-feet to twelve-feet with one bracing location at the center of the web. The bracing location (a 2-16d Common nail connection) was represented in the same way as for the 2x4 web by a single spring in SAP2000 (CSI, 1995). The structural analogs were analyzed using SAP2000 (CSI, 1995) with loads varying from 10% to 100% of the allowable compressive load for the web, F_c', calculated using procedures outlined in the NDS 97 (AF&PA, 1997).

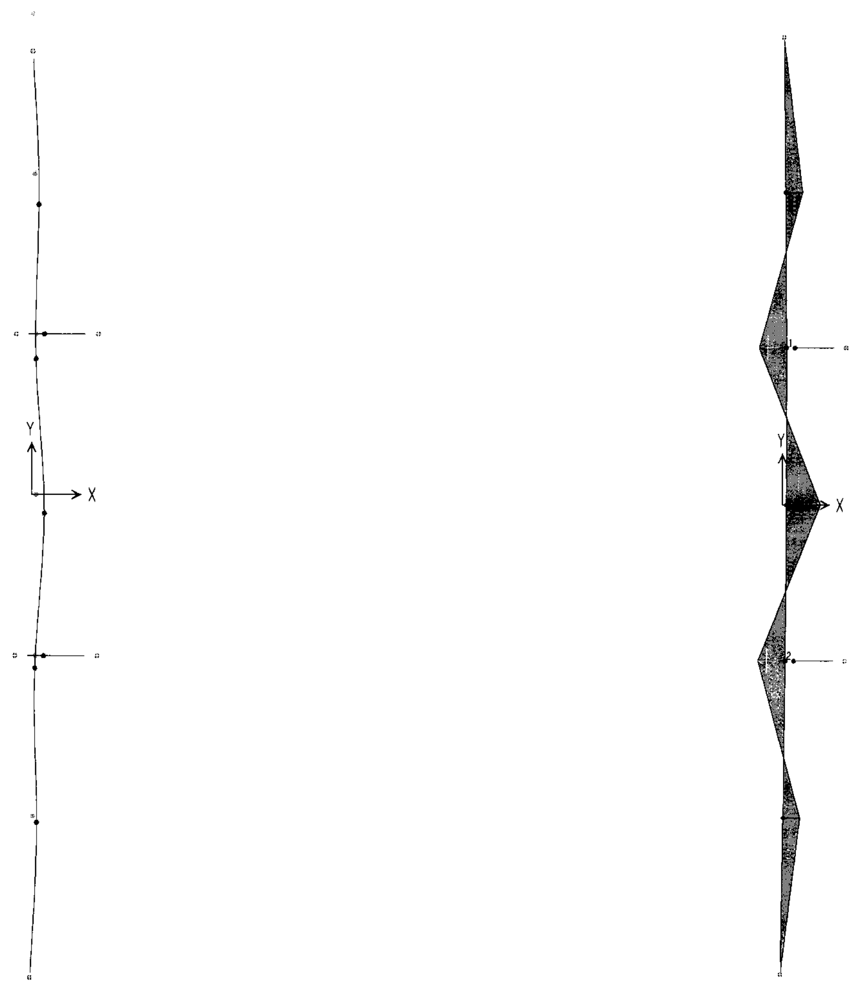
Table 4.5. Lateral force produced by a 2x4 STUD Spruce-Pine-Fir web when braced by two 2x4 CLB's having a specific gravity of 0.42. Connections are assumed to be 2-16d Common nails, and the CLB's are assumed to be restrained from lateral movement.

Web Length (feet)	Axial Load Level in Web(lbs.)[1] Lateral force produced in the web-CLB connection(lbs.)									
5	364	729	1093	1457	1822	2186	2551	2915	3279	3644
	5	10	15	20	25	30	35	40	45	51
6	313	626	939	1252	1565	1878	2191	2504	2817	3130
	4	9	13	17	22	26	30	35	39	43
7	260	520	781	1041	1301	1561	1821	2082	2342	2602
	4	7	11	14	18	22	25	29	32	36
8	214	428	642	856	1070	1284	1498	1712	1926	2140
	3	6	9	12	15	18	21	24	27	30
9	176	353	529	706	882	1059	1235	1412	1588	1765
	2	5	7	10	12	15	17	20	22	25
10	147	294	441	588	735	882	1029	1176	1323	1470
	2	4	6	8	10	12	14	16	18	20
11	124	248	371	495	619	743	866	990	1114	1238
	2	3	5	7	9	10	12	14	15	17
12	105	211	3146	422	527	632	738	843	948	1054
	1	3	4	6	7	9	10	12	13	15

[1]The rightmost column is 100% of the allowable and the leftmost load column is 10% of the allowable assuming C_D equals 1.15.

Table 4.6. Net lateral restraining force (lbs) divided by the axial load (lbs) for comparison to the 2% Rule.

Web Length (ft)	Lateral force produced in both web-CLB connections(lbs.) / Axial Load Level in Web(lbs.)									
5	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
6	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
7	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
8	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
9	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
10	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
11	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
12	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028



(a.) (b.)

Figure 4.3. **(a.) The deflected shape of a web braced with two CLBs as represented in SAP2000 (CSI, 1995). The web is twelve feet long with an applied axial load of 1055 pounds.**

(b.) The moment diagram for a web braced with two CLBs as represented in SAP2000 (CSI, 1995). The moment at the connections is non-zero illustrating continuity in the web member.

The structural analog for the case of one web and two CLB's consisted of a 2x6 STUD Spruce-Pine-Fir web, ranging in length from five-feet to twelve-feet with two bracing locations at the third points of the web. Again, the bracing locations (2-16d Common nail connections) were represented by single springs in SAP2000 (CSI, 1995). The structural analogs were analyzed using SAP2000 (CSI, 1995) with loads varying from 10% to 100% of the allowable compressive load for the web, F_c', calculated using procedures outlined in the NDS 97 (AF&PA, 1997).

Upon completion of the analyses, the net lateral restraining forces were obtained for comparison to the 2x4 web study cases with one and two CLB's. The R-ratios, representing the net lateral restraining force divided by the axial load in the web, were the same as the R-values for the 2x4 STUD Spruce-Pine-Fir webs. When one CLB was installed, R was equal to 0.023 for all web lengths and load levels studied. When two CLB's were installed, R was equal to 0.028 for all web lengths and load levels studied.

4.4 Effects of Lumber Specific Gravity and Modulus of Elasticity, E

The next structural analog was designed to test the effects of lumber species on the net lateral restraining force for the cases of one web and one CLB and one web and two CLB's. The structural analog for the case of one web and one CLB consisted of a 2x4 No. 2 Douglas Fir-Larch (specific gravity equal to 0.5) web and CLB, with a web length three-feet and twelve-feet with one bracing location at the center of the web. Douglas-Fir-Larch was chosen as the species to compare to Spruce-Pine-Fir (specific gravity of 0.42) because the nail slip data was available for a Douglas Fir-Larch joint and because of the high specific gravity value. The E of 2x4 No. 2 Douglas Fir-Larch is 17% greater than the E of 2x4 STUD Spruce-Pine-Fir (specific gravity of 0.42). The bracing location (a 2-16d Common nail connection) was represented by a single spring in SAP2000 (CSI, 1995). The structural analogs were analyzed using SAP2000 (CSI, 1995) with loads equal to 10% and 100% of the allowable compressive load for the web, F_c', calculated using procedures outlined in the NDS 97 (AF&PA, 1997).

The structural analogs for the case of one web and two CLB's consisted of a 2x4 No. 2 Douglas Fir-Larch (specific gravity equal to 0.5) web and CLB, with a web length five-feet and twelve-feet with two bracing locations at the third points of the web. The bracing locations (2-16d Common nail connections) were represented by single springs in SAP2000 (CSI, 1995). The structural analogs were analyzed using SAP2000 (CSI, 1995) with loads equal to 10% and 100% of the allowable compressive load for the web, F_c', calculated using procedures outlined in the NDS 97 (AF&PA, 1997).

Upon completion of the analyses, the net lateral restraining forces for the case of one Douglas Fir-Larch web and one Douglas Fir-Larch CLB connected by a 2-16d nail connection were recorded as shown in Table 4.7. The R-values (Table 4.8) for one Douglas Fir-Larch web and one Douglas Fir-Larch CLB (equal to 0.023) were the same as the R-values for the case of one Spruce-Pine-Fir web and one Spruce-Pine-Fir CLB case. It can be concluded that the bracing ratio, R, for one web braced by one CLB is not affected by the specific gravity of the lumber.

The net lateral restraining forces were recorded in Table 4.9 for one Douglas Fir-Larch web braced by two Douglas Fir-Larch CLB's. The R-values (Table 4.10) for Douglas Fir-Larch (equal to 0.028) were the same as the R-values for the case of one web and two CLB's for Spruce-Pine-Fir for the same lumber lengths and load levels. It can be concluded that the bracing ratio, R, for one web braced by two CLB's is not affected by the specific gravity of the lumber.

4.5 Force Required to Brace a Chord with n-CLB's

The same analysis and procedures as were used for the case of a braced web were used to analyze chords with n-CLB's, except the chords were assumed to be No. 2 Southern Pine lumber. In calculations of the nail slip of the 2-16d Common nail connections, it was assumed that both the chord and the CLB were Spruce-Pine-Fir because nail slip data was not available for a joint having mixed species. The net lateral restraining forces were calculated using structural analogs representing a range of chord sizes (varying from 2x4 to 2x12) and number of bracing locations (varying chord length).

Table 4.7. Sample of Lateral forces produced by a No. 2 Douglas Fir-Larch web when braced by a CLB having a specific gravity of 0.5. Connection is assumed to be 2-16d Common nails, and the CLB was assumed to be restrained from lateral movement.

Web Length (feet)	Axial Load Level in Web(lbs.)[1] Lateral force produced in the web-CLB connections(lbs.)									
3	483 10.98									4827 107.9
4										
5										
6										
7										
8										
9										
10										
11										
12	79 1.83									793 18.3

[1]The rightmost column is 100% of the allowable and the leftmost load column is 10% of the allowable assuming C_D equals 1.15.

Table 4.8. Net lateral restraining forces (lbs) from Table 4.7 divided by the axial load (lbs) for comparison to the 2% Rule.

Web Length (ft)	Lateral force produced in the web-CLB connections(lbs.) / Axial Load Level in Web(lbs.)									
3	0.023									0.022
4										
5										
6										
7										
8										
9										
10										
11										
12	0.023									0.023

Table 4.9. Sample of Lateral forces produced by a No. 2 Douglas Fir-Larch web when braced by two CLB's having a specific gravity of 0.5. Connections are assumed to be 2-16d Common nails, and the CLB's are assumed to be restrained from lateral movement.

Web Length (feet)	Axial Load Level in Web(lbs.)[1] Lateral force produced in the web-CLB connections(lbs.)									
5	403 5.6									4033 55.9
6										
7										
8										
9										
10										
11										
12	106 1.47									1064 14.7

[1]The rightmost column is 100% of the allowable and the leftmost load column is 10% of the allowable assuming C_D equals 1.15.

Table 4.10. Net lateral restraining forces (lbs) from Table 4.9 divided by the axial load (lbs) for comparison to the 2% Rule for a No. 2 Douglas Fir-Larch web.

Web Length (ft)	Lateral force produced in both web-CLB connections(lbs.) Axial Load Level in Web(lbs.)									
5	0.028									0.028
6										
7										
8										
9										
10										
11										
12	0.028									0.028

For the purpose of discussion and comparison to the 2% Rule, the net lateral restraining force was divided by the axial load in the compression chord and will be referred to as R. R-values for 2x4, 2x6, 2x8, 2x10, and 2x12 truss chords are summarized in Tables 4.11 through 4.15. The 2x4 truss chord was tested for lengths ranging from four-feet to twelve-feet. The lateral restraining forces based on the allowable compressive load levels and length of the truss chord are presented in Appendix B. R-values, all equal to 0.023, for the four-foot 2x4 No. 2 Southern Pine *chord* were the same as R for the case of a Spruce-Pine-Fir *web* braced with one CLB. R was the same because the same number of bracing locations were present for both cases (one at the center) and it was determined in Tables 4.3 and 4.4 that web length did not affect the R-value.

The R-values (all equal to 0.028) for the six-foot Southern Pine chord (four bracing locations) were the same as the R-values for the case of a Spruce-Pine-Fir web braced with two CLB's. Again, the results were the same due to the bracing locations being the same (at the 1/3 points). The R-values for the eight-foot member (all equal to 0.028) were the same as for the six-foot member using two significant figures.

The R-values for chords between twelve-feet and 32-feet have a peak value of 0.031, as shown in Tables 4.12 through 4.15. R-values for all lumber sizes (2x4 to 2x12) for 36-, and 40 feet chords were less than R-values for the shorter lengths. R was 0.029 for the 36- foot Southern Pine chord with n-CLB's, spaced twenty-four inches on center, independent of lumber size. R was equal to 0.026 for the 40-foot Southern Pine truss chord with n-CLB's spaced twenty-four inches on center, independent of lumber size.

The values for R for chord lengths, L, greater than 400-inches, were different due to the maximum initial member deflection (2") discussed in Section 3.6.5. The angles, γ_1 and γ_2, produced by drawing a tangent at x equal zero, as depicted in Figure 4.4, were compared to identify why the cumulative bracing force is less for cases when the length of the member is greater than 400-inches. The angle γ_1 is smaller than γ_2 for the 40-foot (480-inches) case limited to an initial deflection of 2-inches (versus the 480-inches case

Table 4.11. Net lateral bracing force (lbs) divided by the axial load (lbs) for comparison to the 2% Rule for 2x4 Southern Pine truss chords.

Chord Length, ft	No. of braces (n+2)[1]	Lateral force produced in the n-web-CLB connections(lbs.) / Axial Load Level in Chord(lbs.)									
		10[2]	20	30	40	50	60	70	80	90	100
4	3	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
6	4	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
8	5	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
12	7	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
16	9	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
20	11	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
24	13	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031

[1] When n-CLB's are used, one additional brace is typically installed on each end of the chord.

[2] Percent of maximum allowable axial load in the truss chords.

Table 4.12. Net lateral bracing force (lbs) divided by the axial load (lbs) for comparison to the 2% Rule for 2x6 Southern Pine truss chords.

Chord Length, Feet	No. of braces (n+2)[1]	Lateral force produced in the n-web-CLB connections(lbs.) / Axial Load Level in Chord(lbs.)									
		10[2]	20	30	40	50	60	70	80	90	100
4	3	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023
6	4	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
8	5	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
12	7	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
16	9	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
20	11	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
24	13	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
28	15	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
32	17	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.033	0.031
36	19	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029

[1] When n-CLB's are used, one additional brace is typically installed on each end of the chord.

[2] Percent of maximum allowable axial load in the truss chords.

Table 4.13. Net lateral bracing force (lbs) divided by the axial load (lbs) for comparison to the 2% Rule for 2x8 Southern Pine truss chords.

Chord Length, Feet	No. of braces (n+2)[1]	Lateral force produced in the n-web-CLB connections(lbs.) Axial Load Level in Chord(lbs.)									
		10[2]	20	30	40	50	60	70	80	90	100
4	3	0.023	0.023	0.023	0.023	0.023	0.022	0.022	0.022	0.022	0.022
6	4	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
8	5	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
12	7	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
16	9	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
20	11	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
24	13	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
28	15	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
32	17	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
36	19	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029

[1] When n-CLB's are used, one additional brace is typically installed on each end of the chord.

[2] Percent of maximum allowable axial load in the truss chords.

Table 4.14. Net lateral bracing force (lbs) divided by the axial load (lbs) for comparison to the 2% Rule for 2x10 Southern Pine truss chords.

Chord Length, Feet	No. of braces (n+2)[1]	Lateral force produced in the n-web-CLB connections(lbs.) Axial Load Level in Chord(lbs.)									
		10[2]	20	30	40	50	60	70	80	90	100
4	3	0.023	0.023	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
6	4	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
8	5	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
12	7	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
16	9	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
20	11	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
24	13	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
28	15	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
32	17	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
36	19	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
40	21	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029

[1] When n-CLB's are used, one additional brace is typically installed on each end of the chord.

[2] Percent of maximum allowable axial load in the truss chords.

Table 4.15. Net lateral bracing force (lbs) divided by the axial load (lbs) for comparison to the 2% Rule for 2x12 Southern Pine truss chords.

Chord Length, Feet	No. of braces (n+2)[1]	Lateral force produced in the n-web-CLB connections(lbs.) / Axial Load Level in Chord(lbs.)									
		10[2]	20	30	40	50	60	70	80	90	100
4	3	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.021	0.021	0.020
6	4	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.027	0.027
8	5	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028	0.028
12	7	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
16	9	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
20	11	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
24	13	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
28	15	0.032	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
32	17	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031	0.031
36	19	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
40	21	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029

[1] When n-CLB's are used, one additional brace is typically installed on each end of the chord.

[2] Percent of maximum allowable axial load in the truss chords.

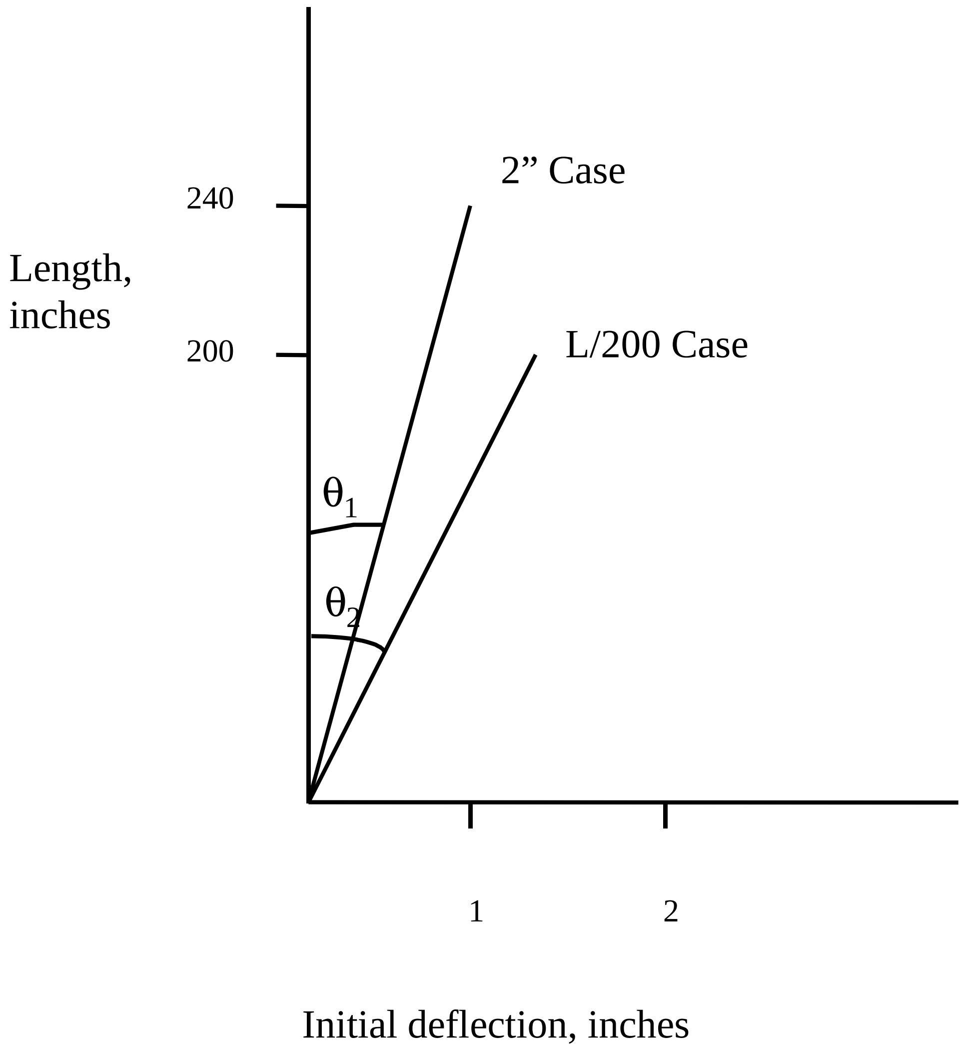


Figure 4.4. **The maximum allowable deflection for a truss chord member is limited to 2” when L > 400” (TPI, 1995). A tangent line at x = 0 shows that when L > 400” then angle γ is smaller for an initial member deflection of 2”.**

at L/200). The tangents shown in Figure 4.4 are represented by the derivative of Equations 3.5 and 3.10 as shown below. The derivatives of the Equations 3.5 and 3.10 produced Equations 4.2 and 4.3, respectively.

$$\frac{d}{dx}=\left[\frac{L}{200}\sin\left(\frac{\pi x}{L}\right)\right]=\frac{L}{200}\cos\left(\frac{\pi x}{L}\right)=\frac{\pi}{200}\cos\left(\frac{\pi x}{L}\right) \tag{4.2}$$

When x = 0 and L ≤ 400 inches, then the slope of the tangent is $\frac{\pi}{200}$.

$$\frac{d}{dx}=\left[2*\sin\left(\frac{\pi x}{L}\right)\right]=2*\cos\left(\frac{\pi x}{L}\right)=\frac{2\pi}{L}\cos\left(\frac{\pi x}{L}\right) \tag{4.3}$$

When x = 0 and L > 400 inches, then the slope of the tangent is $\frac{2\pi}{L}$. When L > 400, $\frac{2\pi}{L}$ is less than $\frac{\pi}{200}$.

As L increases in Equation 4.3, the angle of the tangent to the assumed initial deflected slope decreases, and therefore the smaller angle reduces the force in the braces. Theoretically, as L gets very large, for example 1000-feet, the member is almost straight. Therefore, the net lateral restraining force produced by the axial loads decreases when the column length is increased above 400-inches and the maximum initial deflection is limited to 2-inches.

In addition, the chord load level as a percent of F_c' did not affect R for any size or length. The analysis was based on a linear system with nonlinear springs and thus one would expect the system to behave in a non-linear manner. However, the springs are so stiff, that the calculated R is not significantly affected by the load level. Equation 3.4, using Mack's (1966) relationship representing 2-16d nails remains in the "linear part" of the load-deflection curve during the analysis of the structural models. The "nonlinear region" of the curve is not involved when the load in the chord is varied from 10% to 100% of the F_c' value.

The size of the truss chord had no significant effect on R. R changed slightly depending on whether the lumber was 2x4 or 2x12. To understand why the size of the braced column had an insignificant effect on R, the structural analog with one chord and one CLB can be viewed as a series of two springs. The 2-16d nailed connection between the Southern Pine chord and the Spruce-Pine-Fir CLB acts as one spring. The second spring represents the bending stiffness of the axially compressed Southern Pine chord itself. Under an applied load, the chord having an initial deflection will deflect a certain amount based on the size of the truss chord.

When the springs are in series, if one spring has a constant stiffness (the nail connection) and the other one becomes stiffer, then the one having constant stiffness will deflect more. The stiffness of two springs in series is given by Equation 4.4.

$$k_s = k_1 k_2 / (k_1 + k_2) \tag{4.4}$$

where, k_s is the stiffness of the system, and

k_1 and k_2 are stiffnesses of each component spring.

Considering two springs in series, R given by Equation 4.1 can be rewritten as Equation 4.5.

$$R = \frac{\dfrac{k_1 k_2}{(k_1 + k_2)}}{C} x \tag{4.5}$$

The effective bending stiffness values for the braced truss chord, k_1, can be calculated using Equation4.5. Effective bending stiffness for the truss chord, k_1, in Equation 4.5, was calculated by first calculating R-values for a truss chord with n-CLB's using the net lateral restraining forces and the applied axial loads from SAP2000 (CSI, 1995). The stiffness of the 2-16d Common nail connection, k_2, was determined by iterating the analysis in SAP2000 (CSI, 1995) until the force in the spring was equal to the assumed force and nail slip used to calculate the secant modulus spring stiffness, in Equation 3.1 (Mack, 1966). Once R-values and k_2 were known, assuming a spring system with two springs in series, k_1 was determined using Equation 4.5 for each lumber size and 100% of the load level, F_c'. The values and labels for the variables in Equation 4.5 are shown in Table 4.16.

The calculated effective bending stiffnesses of the truss chord, k_1, are much larger than the effective stiffness of the 2-16d Common nail connections. The bending stiffness, k_1, is about twenty times larger than k_2 for both a 2x4 and 2x12 truss chord. Therefore, the effective bending stiffness of the chord is "controlling" the behavior of the two springs in the series system. When chord size increases, k_1 decreases but k_2 decreases also as it is simulating a non-linear load-slip behavior of the nail connection. The larger allowable load for a 2x12 chord produces more load in the nail connection, and thus the secant modulus, representing nail slip, is lower. The net result of k_1 dominating and the lower k_2 due to the increased load in the spring (due to a 2x12 versus a 2x4) representing the non-linear nail connection is no significant change in the R ratio.

4.6 Proposed Design Procedure

The net lateral restraining force per truss, NL_{truss}, can be used to determine the required connection capacity between the diagonal braces and the truss compression chords. The required connection capacity is dependent on the diagonal brace pattern, either one diagonal or two diagonals forming a V-shape, and the spacing of the diagonal(s) along the length of the building. A step-by-step procedure to determine the required connection capacity based on the Case I or Case II diagonal brace pattern depicted in Figures 1.2 and 1.3 follows.

4.6.1 Case I – One diagonal brace

For Case I, one diagonal brace extends from one side of the compression chord section to be braced to the other side as depicted in Figure 1.2.

Step 1. Assume j-trusses will be braced by one diagonal as a starting point for the design of the diagonal.

Step 2. Determine NL_{truss} using the R-values found in this research and C, the design axial compression load in the chord) that can be obtained from the truss design drawing, or from the Truss Designer.

Table 4.16. Variables for a 2x4 and 2x12 chord with one CLB that produce essentially the same R factor when the braced chord is modeled as two springs in series.

Labels	2x4	2x12
C (lbs)	6,842	20,539
x (inches)	0.00359	0.02522
$R = \frac{\frac{k_1 k_2}{(k_1 + k_2)}}{C} x$	0.023	0.02
K_1 (lb/in)	931,160	388,823
K_2 (lb/in)	46,000	17,000
Force in springs (lbs)	156	419
k_1/k_2	20.2	22.9

$NL_{truss} = R * C$

Step 3. Determine the net lateral restraining force, NL, required for j-trusses.

$NL = j * NL_{truss}$

Step 4. Determine the brace force in the diagonal, $BF_{diagonal}$, based on theta (θ) and NL.

$BF_{diagonal} = NL / \cos \theta$

Note: The connection is typically between the diagonal brace and the truss chord as illustrated in Figure 4.5 when lumber is used for both CLB's and diagonal braces.

For two out of three cases studied, a rational calculation based procedure sure as the NDS-97 could not be used to design the connections between the diagonal and the truss chords. When a rational procedure sure as the NDS-97 fails to yield a design that can be constructed, the connections must be designed using professional judgement or be based on proven experience with similar truss configurations. The design solution to this problem may be to simply specify properly nailed sheathing in place of CLB's and diagonals. When sheathing is used, provisions must be made to allow for proper ventilation.

4.6.2 Case II – Two diagonal braces in a V-shape

For Case II, two diagonal braces forming a V-shape extend from the ends of the compression chord section to be braced to the middle of the compression chord as depicted in Figure 1.3.

Step 1. Assume j-trusses will be braced by two diagonal braces in a V-shape as a starting point for the design of the diagonals.

Step 2. Determine NL_{truss} using the R-values found in this research and C, the design axial compression load in the chord) that can be obtained from the truss design drawing, or from the Truss Designer.

$NL_{truss} = R * C$

Step 4. Determine the brace force in the diagonals, $BF_{diagonal}$, based on theta (θ) and NL.

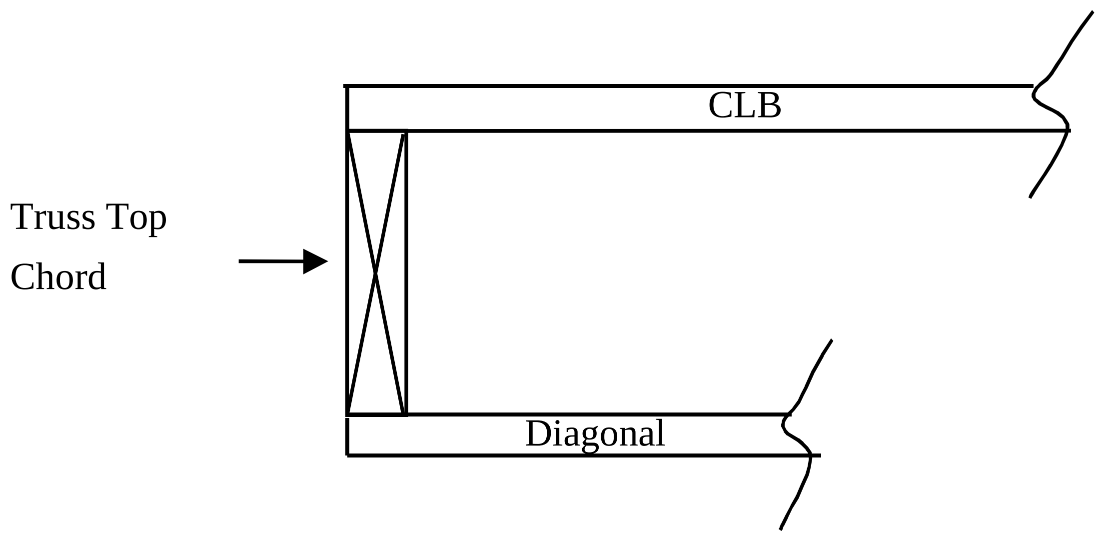


Figure 4.5. **When lumber is used for both the CLB's and the diagonals, the diagonals are connected to the top compression chord on the opposite of the CLB's.**

$$BF_{diagonal} = (NL / \cos\theta)/2$$

Step 3. Determine the net lateral restraining force, NL, required for j-trusses.

$$NL = j * NL_{truss}$$

Note: The connection is typically between the diagonal brace and the truss chord as illustrated in Figure 4.5 when lumber is used for both CLB's and diagonal braces.

The connections between the diagonal and the truss chords, should be designed using the NDS-97 when possible, however this approach may lead to more nails being required in the joint than can be installed. Professional judgement or a design based on proven experience with similar truss configurations may be required. The design solution to this problem may be to simply specify properly nailed sheathing in place of CLB's and diagonals. When sheathing is used, provisions must be made to allow for proper ventilation.

4.7 System Versus Single Member Analogs

The system analogs analyzed as discussed in Section 3.5 were limited in number compared to the single member analogs analyzed and discussed in Section 3.6. To compare the lateral bracing forces from the system analog and the single member analogs, the proposed design procedure was used to determine the net lateral restraining forces for the single member analogs. Using the design procedure and the R-value determined after the SAP2000 (CSI, 1995) analysis, the net lateral restraining force (NL) needed to stabilize j-truss chords could be determined. The single member analogs neglected the slip between the diagonal and the chords and was based on the assumption that the behavior of n-chords tied together by CLB's could be predicted by analyzing one chord and multiplying the bracing forces obtained by n. Therefore, in comparing the single member to the system analogs, required net lateral bracing forces were tabulated for the system analogs and compared to the net lateral bracing force determined by the proposed design procedure for the same number of trusses.

The chords, assumed to be located parallel to y-axis of a coordinate system, are laterally stabilized by the x-component of the joint force developed at each diagonal and chord connection. The required net lateral restraining force was calculated for the case of five eight-foot chords braced by three CLB's, six twenty-foot truss chords braced by nine CLB's, and eleven twenty-foot truss chords braced by nine CLB's. The net force was used in the calculation because some of the x-components of the joint forces are to the left and some are to the right.

4.7.1 Comparison of Required NL for Five Eight-foot Truss Chords

To calculate the required NL using the SAP2000 (CSI, 1995) analysis results for five 2x4, eight-foot truss chords braced by three CLB's and one diagonal, the x-components of the joint force between each diagonal and truss chord (tabulated in Appendix C) was summed taking into account the direction of the force. When the spring pushes to the left, the force was assumed to be positive and when the spring is pushing right, the force was assumed to be negative. When the truss chords were loaded with an axial load of 684 pounds, at Joint A (Figure 3.5) an x-component of –38 pounds exists but the force is not a lateral bracing force because the truss is laterally stabilized by the roof diaphragm at that point. The joint force of –38 pounds at Joint A stems from the compression of the chord due to the axial chord load. At Joints B, C, and D (Figure 3.5), the x-components were –29, -41, and –21 pounds, respectively. The x-components at Joints B, C, and D represent forces required to laterally stabilize the chords. At Joint E (Figure 3.5), a reaction point simulating the action of the diaphragm, the x-component of the joint force was equal to 129 pounds. This force is equal and opposite to the vector sum of the x-components at Joints A, B, C, and D.

To determine the net lateral restraining force for comparison to the single member analogs, the x-components at Joints B, C, and D were summed for each of the five assumed chord load levels and are given in Table 4.17. By inspecting Table 4.17, the bracing forces predicted by the single member analogs are a conservative estimate of the bracing forces predicted by the system analogs by approximately five to six percent.

Table 4.17 The lateral forces calculated using the design procedure for the single member analog compared to the system analogs for five-eight foot trusses braced by three CLB's and one diagonal brace

	Applied compressive force 10-50% of allowable (lbs)				
	684	1368	2053	2737	3421
Single member net lateral force (lbs)	96	192	287	383	479
System net lateral force (lbs)	91	182	272	363	453
Single Member NL / System NL	1.05	1.05	1.06	1.06	1.06

4.7.2 Comparison of Required NL for Six Twenty-foot Truss Chords

To calculate the required NL using the SAP2000 (CSI, 1995) analysis results for six 2x4, twenty-foot truss chords braced by nine CLB's and two diagonals, the x-components of the joint force between each diagonal and truss chord (tabulated in Appendix C) was summed taking into account the direction of the force as discussed in Section 4.7.1. When the truss chords were loaded with an axial load of 684 pounds, at Joints A and L(Figure 3.9) an x-component of 62 pounds exists but the force is not a lateral bracing force because the truss is laterally stabilized by the roof diaphragm at that point. The joint force of 62 pounds at Joints A and L stems from the compression of the chord due to the axial chord load. At Joints B through K (Figure 3.9), the x-components were -2, -14, –17, -22, -7, -7, -22, -17, -14, and -2 pounds, respectively. The x-components at Joints B through K represent forces required to laterally stabilize the chords. Referring to Figure 3.9, the x-component of the joint force at Joints B through K stabilizes the chord. Through equilibrium, the sum of the x-components of the joint force of Joints B through K was simply equal to two times the x-component of the joint force at Joint A or Joint J (due to symmetry either joint may be used).

To determine the net lateral restraining force for comparison to the single member analogs, the x-components at Joints B through K were summed for each assumed chord load level and are given in Table 4.18. By inspecting Table 4.18, the bracing forces predicted by the single member analogs are a conservative estimate of the bracing forces predicted by the system analogs starting at two percent and increasing as the load level was increased.

4.7.3 Comparison of Required NL for Eleven Twenty-foot Truss Chords

To calculate the required NL using the SAP2000 (CSI, 1995) analysis results for eleven 2x4, twenty-foot truss chords braced by nine CLB's and two diagonals, the x-components of the joint force between each diagonal and truss chord (tabulated in Appendix C) was summed taking into account the direction of the force as discussed in Section 4.7.1. When the truss chords were loaded with an axial load of 684 pounds, at Joints A and L (Figure 3.12) an x-component of 110 pounds exists but the force is not a lateral bracing

Table 4.18 The lateral forces calculated using the design procedure for the single member analog compared to the system analogs for six-twenty foot trusses braced by nine CLB's and two diagonal braces

	Applied compressive force 10-50% of allowable (lbs)				
	684	1368	2053	2737	3421
Single member net lateral force (lbs)	127	254	382	509	636
System net lateral force (lbs)	124	247	367	486	602
Single Member NL / System NL	1.02	1.03	1.04	1.05	1.06

force for the same reasons discussed in Section 4.7.2. At Joints B through K (Figure 3.12), the x-components were 2, -28, –33, -37, -15, -15, -38, -32, -28, and 2 pounds, respectively. The x-components at Joints B through K represent forces required to laterally stabilize the chords. Referring to Figure 3.12, the x-component of the joint force at Joints B through K stabilizes the chord. Through equilibrium, the sum of the x-components of the joint force of Joints B through K was simply equal to two times the x-component of the joint force at Joint A or Joint J (due to symmetry either joint may be used).

To determine the net lateral restraining force for comparison to the single member analogs, the x-components at Joints B through K were summed and are given in Table 4.19. By inspecting Table 4.19, the bracing forces predicted by the single member analogs are a conservative estimate of the bracing forces predicted by the system analogs starting at five percent and increasing as the load level was increased.

Table 4.19 The lateral forces calculated using the design procedure for the single member analog compared to the system analogs for eleven-twenty foot trusses braced by nine CLB's and two diagonal braces

	Applied compressive force 10-50% of allowable (lbs)				
	684	1368	2053	2737	3421
Single member net lateral force (lbs)	233	466	700	933	1167
System net lateral force (lbs)	221	434	637	824	983
Single Member NL / System NL	1.05	1.07	1.1	1.13	1.19

5.0 Conclusions

5.1 System and Single Member Analogs

Analyses on systems of roof truss chords braced by n-CLB's and one or two diagonal brace(s) was implemented in SAP2000 (CSI, 1995). Systems of five eight-foot truss chords braced by three CLB's and one diagonal, six twenty-foot truss chords braced by nine CLB's and two diagonals, and eleven twenty-foot truss chords braced by nine CLB's and two diagonals were analyzed. For each of the three cases analyzed, the chord lumber was assumed to be 2x4 No. 2 Southern Pine (S. Pine) braced by 2x4 STUD Spruce-Pine-Fir (SPF). Chord load levels of 10% to 50% of the allowable load were studied.

For the case of five eight-foot trusses braced by three CLB's and one diagonal brace, the single member analog estimate of the required net lateral bracing forces was approximately five to six percent greater than the estimate of the required net lateral bracing forces predicted by the system analog analysis. For the case of six twenty-foot trusses braced by nine CLB's and two diagonal braces and chord load levels of 10% to 50% of the allowable load, the single member analog estimate of the required NL was two percent or more greater than the estimate of the required NL predicted by the system analog analysis. For the case of eleven twenty-foot trusses braced by nine CLB's and two diagonal braces and chord load levels of 10% to 50% of the allowable load, the single member analog estimate of the system required NL was five percent or more greater than the bracing force from the system analog analysis.

For the three cases studied, with chord loads from 10 to 50% of the allowable F_c', the predicted net lateral bracing force by the single member analysis was greater than the bracing force predicted by the system analog analysis. Based on the three cases studied involving 2x4 chords braced as a unit (and believed to be representative of typical truss construction), the bracing force from the single member analog analysis was a conservative estimate for bracing design purposes. Based on other single member studies in this thesis that showed chord size and chord lumber did not affect bracing forces, it is concluded that the single member analysis analog will yield approximate bracing forces for chords greater than 2x4 and for typical constructions beyond the three cases studied in this research. It is believed that the presence of a diagonal brace(s) stiffens the braced set of j-chords and thereby reduces the net lateral force required to brace the j-chords compared to the required bracing force from the single member analysis. It is not practical to attempt to analyze all possible combinations of truss lumber and bracing scenarios (n-chords braced either by a V-diagonal or a single diagonal, and all possible spans and chord load levels).

5.2 One Web Braced with One CLB

A linear beam model a with non-linear spring connection at the brace point was used to represent one web braced by one CLB. By assuming 2x4 STUD Spruce-Pine-Fir (SPF) for roof truss webs up to twelve feet in length and braced with one SPF CLB utilizing a 2-16d Common nail connection, the net lateral restraining force from the SAP2000 (CSI, 1995) analysis was 0.023 or 2.3% of the web compression web.

When designing braces for j-webs in a row, the required net lateral restraining force, NL, for j-webs braced with one CLB can be calculated by:

$$NL = j * 2.3\% * \text{axial force in web}$$

where, j is the number of webs in a row having the same design axial load.
NL is input to the proposed design method in Section 4.6.

Since nail slip data was available for a Douglas Fir-Larch joint, the structural analog was analyzed assuming a No. 2 Douglas Fir-Larch web and Douglas Fir-Larch CLB. Douglas Fir-Larch has a specific gravity of 0.5 versus 0.42 of SPF. Douglas Fir-Larch also has a 17% higher modulus of elasticity, E, than SPF. This case examined the effect of higher specific gravity on the nail slip and resulting net lateral restraining forces. Based on the net lateral restraining forces obtained during the SAP2000 (CSI, 1995) analyses, for design purposes, it is reasonable to assume 2.3% is applicable to species having a specific gravity greater than 0.42.

The lumber size was also varied in order to test the impact of lumber size on the net lateral restraining forces produced during analysis. Based on the SAP2000 (CSI, 1995) analyses, for design purposes, it is reasonable to assume 2.3% is also applicable to a 2x6 web.

5.3 One web Braced with Two CLB's

A linear beam model with non-linear springs representing the behavior of the CLB connections was used to analyze the case of one web braced by two CLB's. By assuming STUD Spruce-Pine-Fir (SPF) for 2x4 roof truss webs up to fifteen feet in length and braced with two 2x4 SPF CLB's connected to the web with 2-16d Common nail connections, the net lateral restraining force from the SAP2000 (CSI, 1995) analysis was 0.028 or 2.8% of the web compression web.

When designing braces for j-webs in a row, the required net lateral restraining force, NL, for j-webs braced by two CLB's can be calculated:

$$NL = j * 2.8\% * \text{axial force in web}$$

where, j is the number of webs in a row having the same design axial load.
NL is input to the proposed design method in Section 4.6.

Since nail slip data was available for a Douglas Fir-Larch joint, the structural analog was analyzed assuming a No. 2 Douglas Fir-Larch web and Douglas Fir-Larch CLB's. Douglas Fir-Larch has a specific gravity of 0.5 versus 0.42 of SPF. Douglas Fir-Larch also has a 17% higher modulus of elasticity, E, than SPF. This case examined the effect of higher specific gravity on the nail slip and resulting net lateral restraining forces. Based on the net lateral restraining forces obtained during the SAP2000 (CSI, 1995) analyses, for design purposes, it is reasonable to assume 2.8% is applicable to species having a specific gravity greater than 0.42.

The lumber size was also varied in order to test the impact of lumber size on the net lateral restraining forces produced during analysis. Based on the SAP2000 (CSI, 1995) analyses, for design purposes, it is reasonable to assume 2.8% is also applicable to a 2x6 web.

5.4 Roof Truss Chord braced by n-CLB's

A linear beam model was used to represent one roof truss chord that required n-CLB's. The nail connections between the CLB's and the chord were modeled by a non-linear spring. The structural analog was created assuming No. 2 Southern Pine chords braced by 2x4 Spruce-Pine-Fir CLB's (specific gravity equal to 0.42). In calculating the slip of the 2-16d Common nail connections, it was assumed that both the chord and the CLB were SPF because nail slip data was not available for a joint having mixed species.

By assuming No. 2 Southern Pine (2x4 to 2x12) truss chords ranging from four feet to forty feet length and braced with n-Spruce-Pine-Fir CLB's at two feet on-center each installed with 2-16d Common nails, the net lateral restraining force from the SAP2000 (CSI, 1995) analysis was found to be a maximum of 3.1% of the compression force in the chord. Peak value of 3.1% occurred at chord lengths of sixteen feet to thirty-two feet. Chord lengths shorter than sixteen feet required a lower net lateral restraining force. Chords longer than thirty-two feet required a lower net lateral restraining force because TPI's installation tolerances as provided in DSB-89 (TPI, 1989) were assumed for the maximum initial deflections for the chords.

When designing permanent bracing for j-chords in a row, the required net lateral restraining force, NL, for j-chords braced by n-CLB's can be approximated by:

$$NL = j * R * \text{axial force in chord}$$

where j is the number of truss chords in a row having the same design axial load, and

R is the ratio between the net lateral bracing force (lbs) and the axial load level in the web/chord (lbs), for design purposes. An R-value of 3.1% is conservative with respect to the variable chord length since for chord lengths between four and forty-feet evaluated using the single member analog, it was the maximum R-value obtained. NL is then input to the proposed bracing design method given in Section 4.6.

For a specific design, Tables 4.11 through 4.15, can be used in place of the conservative R-value equal to 3.1% of the axial compression load in the truss chord.

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Appendix A

Sample calculations to determine F_c' for use in SAP2000 (CSI, 1995) analysis

The following analysis was used to determine the allowable axial compressive loads for the web/chord members. The analysis was based on the procedure outlined in the NDS 97 (AF&PA, 1997). The example given was calculated for a eight foot long, 2x4, STUD Spruce-Pine-Fir web.

F'_c (A) = allowable load

$F_c' = F_c * C_D * C_P * C_F$

$F_c = 725$ psi (Fc, page 29, NDS 97 supplement)

$E = 1.2 \times 10^6$ (E, page 29, NDS 97 supplement)

$C_D = 1.15$

$C_F = 1.05$

l_e/d = $$\frac{0.8 * L}{d} = \frac{\frac{0.8(8*12)}{2}}{1.5} = 25.6 < 50$$ o.k.

$F_c^* = F_c * C_D * C_F = 725 * 1.15 * 1.05 = 875$

$$F_{CE} = \frac{K_{CE} E'}{\left(\frac{l_e}{d}\right)^2} = \frac{0.3(1.2 * 10^6)}{(25.6)^2} = 549$$ (K_{CE}, page 22, NDS 97)

$F_{CE} / F_C^* = 549 / 875 = 0.627$

$$C_P = \frac{1 + \left(\frac{F_{CE}}{F_C^*}\right)}{2c} - \sqrt{\left(\frac{1 + \left(\frac{F_{CE}}{F_C^*}\right)}{2c}\right)^2 - \frac{\left(\frac{F_{CE}}{F_C^*}\right)}{c}}$$

(C_P, page 22, NDS 97)

c = 0.8 for sawn lumber (c, page 22, NDS 97)

$$C_P = \frac{1+(0.627)}{2*0.8} - \sqrt{\left(\frac{1+(0.627)}{2*0.8}\right)^2 - \frac{(0.627)}{0.8}}$$

C_P = 1.017 – 0.5003 = 0.5167

F_C’ = 725 * 1.15 * 0.5167 * 1.05 = 452 psi

F_C’ * A = 468 psi * 1.5 inches * 3.5 inches = 2375 lbs.

The maximum allowable axial compressive load for a eight foot long, 2x4, STUD Spruce-Pine-Fir web was 2,375 pounds.

Appendix B

Spring forces produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for Southern Pine Chords braced by n-Spruce-Pine-Fir webs for a single member analysis

Table B1. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x4 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by a 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	684		1368		2053		2737		3421		4105		4790		5474		6158		6842	
4	15.72	15.73	31.46	31.45	47.21	47.07	62.76	62.71	78.39	78.29	93.95	93.91	109.6	109.4	125.1	125	140.7	140.6	156.2	155.6
6	9.49	9.49	18.99	18.99	28.49	28.49	37.99	37.98	47.47	47.46	56.95	56.95	66.45	66.44	75.93	75.92	85.41	85.4	94.88	94.88
	9.49	9.49	18.99	18.99	28.49	28.49	37.99	37.98	47.47	47.46	56.95	56.95	66.45	66.44	75.93	75.92	85.41	85.4	94.88	94.88
8	5.69	5.7	11.39	11.39	17.1	17.1	22.79	22.79	28.49	28.49	34.23	34.25	39.96	39.92	45.62	45.77	51.49	51.34	57.04	57.08
	7.99	7.98	15.95	15.95	23.94	23.94	31.92	31.92	39.89	39.84	47.81	47.78	55.75	55.8	63.77	63.56	71.5	71.72	79.68	79.6
	5.69	5.7	11.39	11.39	17.1	17.1	22.79	22.79	28.49	28.49	34.23	34.25	39.96	39.92	45.62	45.77	51.49	51.34	57.04	57.08
12	2.74	2.74	5.47	5.47	8.21	8.22	10.96	10.96	13.69	13.69	16.42	16.43	19.17	19.16	21.9	21.9	24.63	24.64	27.38	27.37
	4.78	4.79	9.57	9.57	14.37	14.36	19.14	19.14	23.93	23.95	28.73	28.73	33.52	33.53	38.32	38.32	43.11	43.09	47.88	47.92
	5.48	5.47	10.94	10.94	16.42	16.43	21.9	21.9	27.38	27.35	32.82	32.83	38.31	38.3	43.77	43.77	49.23	49.25	54.72	54.66
	4.78	4.79	9.57	9.57	14.37	14.36	19.14	19.14	23.93	23.95	28.73	28.73	33.52	33.53	38.32	38.32	43.11	43.09	47.88	47.92
	2.74	2.74	5.47	5.47	8.21	8.22	10.96	10.96	13.69	13.69	16.42	16.43	19.17	19.16	21.9	21.9	24.63	24.64	27.38	27.37
16	1.57	1.57	3.14	3.14	4.71	4.71	6.27	6.27	7.84	7.84	9.41	9.41	10.98	10.99	12.56	12.56	14.13	14.13	15.69	15.69
	2.96	2.96	5.93	5.93	8.89	8.89	11.86	11.85	14.82	14.82	17.79	17.8	20.77	20.74	23.71	23.71	26.67	26.67	29.63	29.64
	3.85	3.85	7.69	7.69	11.55	11.55	15.4	15.41	19.26	19.26	23.09	23.07	26.92	26.95	30.8	30.8	34.65	34.65	38.49	38.5
	4.16	4.16	8.32	8.32	12.49	12.49	16.65	16.63	20.79	20.79	24.96	24.98	29.15	29.13	33.29	33.29	37.45	37.45	41.61	41.6
	3.85	3.85	7.69	7.69	11.55	11.55	15.4	15.41	19.26	19.26	23.09	23.07	26.92	26.95	30.8	30.8	34.65	34.65	38.49	38.5
	2.96	2.96	5.93	5.93	8.89	8.89	11.86	11.85	14.82	14.82	17.79	17.8	20.77	20.74	23.71	23.71	26.67	26.67	29.63	29.64
	1.57	1.57	3.14	3.14	4.71	4.71	6.27	6.27	7.84	7.84	9.41	9.41	10.98	10.99	12.56	12.56	14.13	14.13	15.69	15.69
20	1.05	1.05	2.11	2.11	3.16	3.16	4.22	4.22	5.27	5.27	6.32	6.32	7.38	7.38	8.43	8.43	9.49	9.48	10.54	10.54
	1.94	1.94	3.88	3.88	5.82	5.82	7.76	7.76	9.7	9.7	11.64	11.64	13.58	13.58	15.52	15.52	17.46	17.47	19.41	19.41
	2.76	2.76	5.53	5.53	8.3	8.3	11.06	11.06	13.82	13.82	16.59	16.59	19.35	19.35	22.12	22.12	24.88	24.86	27.62	27.62
	3.1	3.1	6.21	6.21	9.32	9.32	12.42	12.42	15.53	15.53	18.63	18.63	21.74	21.74	24.85	24.85	27.95	28	31.11	31.11
	3.42	3.42	6.85	6.85	10.27	10.27	13.7	13.7	17.12	17.12	20.54	20.54	23.97	23.97	27.4	27.4	30.82	30.75	34.17	34.17
	3.1	3.1	6.21	6.21	9.32	9.32	12.42	12.42	15.53	15.53	18.63	18.63	21.74	21.74	24.85	24.85	27.95	28	31.11	31.11
	2.76	2.76	5.53	5.53	8.3	8.3	11.06	11.06	13.82	13.82	16.59	16.59	19.35	19.35	22.12	22.12	24.88	24.86	27.62	27.62
	1.94	1.94	3.88	3.88	5.82	5.82	7.76	7.76	9.7	9.7	11.64	11.64	13.58	13.58	15.52	15.52	17.46	17.47	19.41	19.41
	1.05	1.05	2.11	2.11	3.16	3.16	4.22	4.22	5.27	5.27	6.32	6.32	7.38	7.38	8.43	8.43	9.49	9.48	10.54	10.54
24	0.74	0.74	1.48	1.48	2.22	2.22	2.96	2.96	3.7	3.7	4.44	4.44	5.19	5.19	5.93	5.93	6.67	6.67	7.41	7.41
	1.34	1.34	2.68	2.68	4.02	4.02	5.36	5.36	6.7	6.7	8.04	8.04	9.38	9.38	10.72	10.72	12.06	12.06	13.4	13.4
	2	2	3.99	3.99	5.99	5.99	7.99	7.99	9.98	9.98	11.98	11.98	13.98	13.98	15.97	15.97	17.97	17.97	19.97	19.97
	2.56	2.56	5.13	5.12	7.69	7.69	10.25	10.25	12.81	12.81	15.37	15.37	17.94	17.94	20.5	20.5	23.06	23.06	25.63	25.63

Table B1 continued. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x4 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by a 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	684		1368		2053		2737		3421		4105		4790		5474		6158		6842	
	2.57	2.57	5.13	5.14	7.71	7.71	10.28	10.28	12.85	12.85	15.42	15.42	17.99	17.99	20.56	20.56	23.13	23.13	25.7	25.7
	2.85	2.85	5.7	5.69	8.54	8.54	11.39	11.39	14.23	14.23	17.08	17.08	19.93	19.93	22.77	22.77	25.62	25.62	28.47	28.47
	2.57	2.57	5.13	5.14	7.71	7.71	10.28	10.28	12.85	12.85	15.42	15.42	17.99	17.99	20.56	20.56	23.13	23.13	25.7	25.7
	2.56	2.56	5.13	5.12	7.69	7.69	10.25	10.25	12.81	12.81	15.37	15.37	17.94	17.94	20.5	20.5	23.06	23.06	25.63	25.63
	2	2	3.99	3.99	5.99	5.99	7.99	7.99	9.98	9.98	11.98	11.98	13.98	13.98	15.97	15.97	17.97	17.97	19.97	19.97
	1.34	1.34	2.68	2.68	4.02	4.02	5.36	5.36	6.7	6.7	8.04	8.04	9.38	9.38	10.72	10.72	12.06	12.06	13.4	13.4
	0.74	0.74	1.48	1.48	2.22	2.22	2.96	2.96	3.7	3.7	4.44	4.44	5.19	5.19	5.93	5.93	6.67	6.67	7.41	7.41

Table B2. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x6 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	1059		2117		3176		4235		5294		6352		7411		8470		9529		10587	
4	24.18	24.22	48.25	48.34	72.24	72.38	96.2	96.33	120.1	120.3	143.7	144	167.5	167.7	191	191.4	214.5	214.9	239.7	238.3
6	14.69	14.69	29.36	29.36	44.05	44.03	58.74	58.7	73.38	73.35	88.01	87.99	102.7	102.7	117.3	117.3	132	131.9	146.6	146.5
	14.69	14.69	29.36	29.36	44.05	44.03	58.74	58.7	73.38	73.35	88.01	87.99	102.7	102.7	117.3	117.3	132	131.9	146.6	146.5
8	8.83	8.82	17.65	17.66	26.47	26.49	35.34	35.3	44.24	44.17	53.09	53.09	61.98	61.98	70.81	70.84	79.7	79.67	88.4	88.55
	12.32	12.35	24.64	24.64	36.98	36.96	49.25	49.31	61.46	61.56	73.73	73.74	85.95	86.02	98.26	98.23	110.5	110.5	123	122.8
	8.83	8.82	17.65	17.66	26.47	26.49	35.34	35.3	44.24	44.17	53.09	53.09	61.98	61.94	70.81	70.84	79.7	79.67	88.4	88.55
12	4.24	4.24	8.47	8.47	12.71	12.71	16.96	16.94	21.22	21.2	25.46	25.46	29.74	29.7	33.95	33.99	38.22	38.19	42.35	42.47
	7.41	7.41	14.82	14.82	22.23	22.23	29.63	29.64	37.01	37.04	44.42	44.41	51.77	51.82	59.27	59.16	66.65	66.68	74.17	74.05
	8.47	8.47	16.93	16.93	25.39	25.39	33.86	33.86	42.36	42.33	50.81	50.83	59.34	59.28	67.68	67.81	76.16	76.14	84.53	84.62
	7.41	7.41	14.82	14.82	22.23	22.23	29.63	29.64	37.01	37.04	44.42	44.42	51.77	51.82	59.27	59.16	66.65	66.68	74.17	74.05
	4.24	4.24	8.47	8.47	12.71	12.71	16.96	16.94	21.22	21.2	25.46	25.46	29.74	29.7	33.95	33.99	38.22	38.19	42.35	42.47
16	2.43	2.43	4.85	4.85	7.28	7.28	9.71	9.7	12.12	12.12	14.55	14.55	16.97	17	19.43	19.42	21.84	21.85	24.28	24.28
	4.59	4.59	9.17	9.17	13.76	13.76	18.35	18.37	22.97	22.98	27.57	27.57	32.16	32.11	36.7	36.71	41.3	41.28	45.86	45.86
	5.96	5.96	11.91	11.91	17.87	17.87	23.82	23.8	29.75	29.73	35.67	35.67	41.62	41.68	47.63	47.63	53.59	53.65	59.61	59.61
	6.44	6.44	12.88	12.88	19.32	19.32	25.76	25.78	32.23	32.24	38.69	38.69	45.13	45.08	51.52	51.52	57.96	57.86	64.29	64.29
	5.96	5.96	11.91	11.91	17.87	17.87	23.82	23.8	29.75	29.73	35.67	35.67	41.62	41.68	47.63	47.63	53.59	53.65	59.61	59.61
	4.59	4.59	9.17	9.17	13.76	13.76	18.35	18.37	22.97	22.98	27.57	27.57	32.16	32.11	36.7	36.71	41.3	41.28	45.86	45.86
	2.43	2.43	4.85	4.85	7.28	7.28	9.71	9.7	12.12	12.12	14.55	14.55	16.97	17	19.43	19.42	21.84	21.85	24.28	24.28
20	1.63	1.63	3.26	3.26	4.89	4.89	6.52	6.52	8.15	8.15	9.78	9.78	11.42	11.41	13.04	13.05	14.68	14.68	16.31	16.3
	3	3	6	6	9.01	9.01	12.01	12.01	15.01	15.01	18.01	18.01	21.01	21.04	24.04	24.03	27.04	27.05	30.05	30.06
	4.27	4.27	8.55	8.55	12.82	12.82	17.09	17.11	21.39	21.39	25.66	25.66	29.94	29.89	34.17	34.18	38.45	38.43	42.7	42.68
	4.82	4.82	9.63	9.63	14.44	14.44	19.26	19.24	24.06	24.06	28.86	28.86	33.68	33.72	38.54	38.53	43.35	43.37	48.19	48.21
	5.29	5.29	10.57	10.57	15.86	15.86	21.15	21.16	26.45	26.45	31.73	31.73	37.03	36.98	42.27	42.27	47.55	47.54	52.82	52.8
	4.82	4.82	9.63	9.63	14.44	14.44	19.26	19.24	24.06	24.06	28.86	28.86	33.68	33.72	38.54	38.53	43.35	43.37	48.19	48.21
	4.27	4.27	8.55	8.55	12.82	12.82	17.09	17.11	21.39	21.39	25.66	25.66	29.94	29.89	34.17	34.18	38.45	38.43	42.7	42.68
	3	3	6	6	9.01	9.01	12.01	12.01	15.01	15.01	18.01	18.01	21.01	21.04	24.04	24.03	27.04	27.05	30.05	30.06
	1.63	1.63	3.26	3.26	4.89	4.89	6.52	6.52	8.15	8.15	9.78	9.78	11.42	11.41	13.04	13.05	14.68	14.68	16.31	16.3
24	1.15	1.15	2.29	2.29	3.44	3.44	4.58	4.58	5.73	5.73	6.88	6.88	8.02	8.02	9.17	9.19	10.33	10.33	11.48	11.47
	2.07	2.07	4.14	4.14	6.22	6.22	8.29	8.29	10.36	10.36	12.43	12.43	14.5	14.5	16.58	16.57	18.64	18.64	20.71	20.72
	3.1	3.1	6.19	6.19	9.28	9.28	12.38	12.38	15.48	15.48	18.57	18.57	21.67	21.67	24.76	24.75	27.85	27.85	30.94	30.94
	3.96	3.96	7.91	7.91	11.87	11.87	15.83	15.83	19.79	19.79	23.74	23.74	27.7	27.69	31.65	31.67	35.63	35.63	39.58	39.56
	3.99	3.99	7.97	7.97	11.96	11.96	15.94	15.94	19.93	19.93	23.91	23.91	27.9	27.92	31.91	31.89	35.87	35.87	39.86	39.91
	4.4	4.4	8.79	8.79	13.19	13.19	17.58	17.58	21.98	21.98	26.37	26.37	30.77	30.74	35.13	35.16	39.55	39.55	43.94	43.87
	3.99	3.99	7.97	7.97	11.96	11.96	15.94	15.94	19.93	19.93	23.91	23.91	27.9	27.92	31.91	37.89	35.87	35.87	39.86	39.91
	3.96	3.96	7.91	7.91	11.87	11.87	15.83	15.83	19.79	19.79	23.74	23.74	27.7	27.69	31.65	31.67	35.63	35.63	39.58	39.56
	3.1	3.1	6.19	6.19	9.28	9.28	12.38	12.38	15.48	15.48	18.57	18.57	21.67	21.67	24.76	24.75	27.85	27.85	30.94	30.94
	2.07	2.07	4.14	4.14	6.22	6.22	8.29	8.29	10.36	10.36	12.43	12.43	14.5	14.5	16.58	16.57	16.64	16.64	20.71	20.72
	1.15	1.15	2.29	2.29	3.44	3.44	4.58	4.58	5.73	5.73	6.88	6.88	8.02	8.02	9.17	9.19	10.33	10.33	11.48	11.47
28	0.83	0.83	1.67	1.67	2.5	2.5	3.34	3.34	4.17	4.17	5.01	5.01	5.84	5.84	6.68	6.68	7.52	7.52	8.35	8.35
	1.51	1.51	3.02	3.02	4.53	4.53	6.03	6.03	7.54	7.54	9.04	9.04	10.56	10.56	12.07	12.07	13.56	13.56	15.08	15.08
	2.68	2.68	5.36	5.36	8.04	8.04	10.72	10.72	13.4	13.4	16.1	16.1	18.76	18.76	21.46	21.46	24.15	24.14	26.02	26.02

Table B2 continued. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x6 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	1059		2117		3176		4235		5294		6352		7411		8470		9529		10587	
	2.65	2.65	5.31	5.31	7.96	7.96	10.61	10.61	13.27	13.27	15.9	15.9	18.57	18.57	21.2	21.2	23.86	23.87	26.52	26.52
	3.09	3.09	6.18	6.18	9.28	9.28	12.37	12.37	15.46	15.46	18.53	18.53	21.65	21.65	24.79	24.79	27.83	27.82	30.91	30.91
	3.96	3.96	7.91	7.91	11.88	11.88	15.83	15.83	19.8	19.8	23.76	23.76	27.72	27.72	31.68	31.68	35.64	35.64	39.32	39.32
	3.55	3.55	7.09	7.09	10.62	10.62	14.18	14.18	17.7	17.7	21.24	21.24	24.78	24.78	28.33	28.33	31.87	31.88	35.42	35.42
	3.96	3.96	7.91	7.91	11.88	11.88	15.83	15.83	19.8	19.8	23.76	23.76	27.72	27.72	31.68	31.68	35.64	35.64	39.32	39.32
	3.09	3.09	6.18	6.18	9.28	9.28	12.37	12.37	15.46	15.46	18.53	18.53	21.65	21.65	24.74	24.74	27.83	27.82	30.91	30.91
	2.65	2.65	5.31	5.31	7.96	7.96	10.61	10.61	13.27	13.27	15.9	15.9	18.57	18.57	21.2	21.2	23.86	23.87	26.52	26.52
	2.68	2.68	5.36	5.36	8.04	8.04	10.72	10.72	13.4	13.4	16.1	16.1	18.76	18.76	21.46	21.46	24.15	24.14	26.02	26.02
	1.51	1.51	3.02	3.02	4.53	4.53	6.03	6.03	7.54	7.54	9.04	9.04	10.56	10.56	12.07	12.07	13.56	13.56	15.08	15.08
	0.83	0.83	1.67	1.67	2.5	2.5	3.34	3.34	4.17	4.17	5.01	5.01	5.84	5.84	6.68	6.68	7.52	7.52	8.35	8.35
32	0.65	0.65	1.32	1.32	1.97	1.97	2.63	2.63	3.29	3.29	3.95	3.95	4.61	4.61	5.27	5.27	5.92	5.92	6.58	6.58
	1.11	1.11	2.22	2.22	3.33	3.33	4.44	4.44	5.55	5.55	6.66	6.66	7.77	7.77	8.88	8.88	9.99	9.99	11.1	11.1
	1.97	1.97	3.95	3.95	5.92	5.92	7.9	7.9	9.88	9.88	11.85	11.85	13.83	13.83	15.8	15.8	17.78	17.76	19.73	19.73
	2.22	2.22	4.44	4.44	6.66	6.66	8.87	8.87	11.09	11.09	13.31	13.31	15.53	15.53	17.75	17.75	19.97	20	22.23	22.23
	3.07	3.07	6.14	6.14	9.22	9.22	12.29	12.29	15.37	15.37	18.44	18.44	21.51	21.51	24.59	24.59	27.66	27.61	30.67	30.67
	2.66	2.66	5.31	5.31	7.97	7.97	10.63	10.63	13.29	13.29	15.94	15.94	18.6	18.6	21.26	21.26	23.92	23.95	26.61	26.61
	3.09	3.09	6.17	6.17	9.26	9.26	12.35	12.35	15.43	15.43	18.52	18.52	21.61	21.61	24.69	24.69	27.78	27.79	30.88	30.88
	3.53	3.53	7.05	7.05	10.58	10.58	14.1	14.1	17.63	17.63	21.15	21.15	24.68	24.68	28.2	28.2	31.73	31.69	35.21	35.21
	3.09	3.09	6.17	6.17	9.26	9.26	12.35	12.35	15.43	15.43	18.52	18.52	21.61	21.61	24.69	24.69	27.78	27.79	30.88	30.88
	2.66	2.66	5.31	5.31	7.97	7.97	10.63	10.63	13.29	13.29	15.94	15.94	18.6	18.6	21.26	21.26	23.92	23.95	26.61	26.61
	3.07	3.07	6.14	6.14	9.22	9.22	12.29	12.29	15.37	15.37	18.44	18.44	21.51	21.51	24.59	24.59	27.66	27.61	30.67	30.67
	2.22	2.22	4.44	4.44	6.66	6.66	8.87	8.87	11.09	11.09	13.31	13.31	15.53	15.53	17.75	17.75	19.97	20	22.23	22.23
	1.97	1.97	3.95	3.95	5.92	5.92	7.9	7.9	9.88	9.88	11.85	11.85	13.83	13.83	15.8	15.8	17.78	17.76	19.73	19.73
	1.11	1.11	2.22	2.22	3.33	3.33	4.44	4.44	5.55	5.55	6.66	6.66	7.77	7.77	8.88	8.88	9.99	9.99	11.1	11.1
	0.65	0.65	1.32	1.32	1.97	1.97	2.63	2.63	3.29	3.29	3.95	3.95	4.61	4.61	5.27	5.27	5.92	5.92	6.58	6.58
36	0.44	0.44	0.881	0.881	1.32	1.32	1.76	1.76	2.2	2.2	2.64	2.64	3.09	3.09	3.53	3.53	3.97	3.97	4.41	4.41
	0.927	0.927	1.85	1.85	2.78	2.78	3.71	3.71	4.63	4.63	5.56	5.56	6.49	6.49	7.41	7.41	8.34	8.34	9.27	9.27
	1.32	1.32	2.65	2.65	3.97	3.97	5.3	5.3	6.62	6.62	7.94	7.94	9.27	9.27	10.59	10.59	11.91	11.91	13.24	13.24
	1.76	1.76	3.53	3.53	5.29	5.29	7.05	7.05	8.82	8.82	10.58	10.58	12.34	12.34	14.11	14.11	15.87	15.87	17.63	17.63
	2.03	2.03	4.06	4.06	6.09	6.09	8.12	8.12	10.16	10.16	12.18	12.18	14.22	14.22	16.25	16.25	18.28	18.28	20.31	20.31
	2.34	2.34	4.67	4.67	7.01	7.01	9.34	9.34	11.68	11.68	14.01	14.01	16.35	16.35	18.69	18.69	21.02	21.02	23.36	23.36
	2.47	2.47	4.95	4.95	7.42	7.42	9.89	9.89	12.37	12.37	14.84	14.84	17.31	17.31	19.79	19.79	22.26	22.26	24.73	24.73
	2.69	2.69	5.37	5.37	8.06	8.06	10.75	10.75	13.44	13.44	16.13	16.13	18.81	18.81	21.5	21.5	24.19	24.19	26.88	26.88
	2.65	2.65	5.3	5.3	7.95	7.95	10.6	10.6	13.25	13.25	15.9	15.9	18.55	18.55	21.2	21.2	23.85	23.85	26.5	26.5
	2.69	2.69	5.37	5.37	8.06	8.06	10.75	10.75	13.44	13.44	16.13	16.13	18.81	18.81	21.5	21.5	24.19	24.19	26.88	26.88
	2.47	2.47	4.95	4.95	7.42	7.42	9.89	9.89	12.37	12.37	14.84	14.84	17.31	17.31	19.79	19.79	22.26	22.26	24.73	24.73
	2.34	2.34	4.67	4.67	7.01	7.01	9.34	9.34	11.68	11.68	14.01	14.01	16.35	16.35	18.69	18.69	21.02	21.02	23.36	23.36
	2.03	2.03	4.06	4.06	6.09	6.09	8.12	8.12	10.16	10.16	12.18	12.18	14.22	14.22	16.25	16.25	18.28	18.28	20.31	20.31
	1.76	1.76	3.53	3.53	5.29	5.29	7.05	7.05	8.82	8.82	10.58	10.58	12.34	12.34	14.11	14.11	15.87	15.87	17.63	17.63
	1.32	1.32	2.65	2.65	3.97	3.97	5.3	5.3	6.62	6.62	7.94	7.94	9.27	9.27	10.59	10.59	11.91	11.91	13.24	13.24
	0.927	0.927	1.85	1.85	2.78	2.78	3.71	3.71	4.63	4.63	5.56	5.56	6.49	6.49	7.41	7.41	8.34	8.34	9.27	9.27
	0.44	0.44	0.881	0.881	1.32	1.32	1.76	1.76	2.2	2.2	2.64	2.64	3.09	3.09	3.53	3.53	3.97	3.97	4.41	4.41

Table B3. **Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x8 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.**

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	1373		2746		4118		5491		6864		8237		9609		10982		12355		13728	
4	31.3	31.3	62.6	62.3	93.43	93.22	124.3	124	155	154.7	185.6	184.8	215.6	214.9	245.7	245.2	275.8	274.8	305.4	304.4
6	19.03	19.03	38.05	38.05	57.06	57.03	76.05	76.01	95.02	94.99	114	114	132.9	132.9	151.8	151.8	170.8	170.8	189.7	189.6
	19.03	19.03	38.05	38.05	57.06	57.03	76.05	76.01	95.02	94.99	114	114	132.9	132.9	151.8	151.8	170.8	170.8	189.7	189.6
8	11.43	11.43	22.86	22.91	34.36	34.35	45.81	45.95	57.44	57.29	68.75	68.85	80.32	80.3	91.78	91.9	103.4	103.6	115.1	115.3
	16.01	16.01	32.02	31.93	47.89	47.89	63.86	63.63	79.54	79.73	95.68	95.53	111.4	111.5	127.4	127.2	143.1	142.8	158.7	158.4
	11.43	11.43	22.86	22.91	34.36	34.35	45.81	45.95	57.44	57.29	68.75	68.85	80.32	80.3	91.78	91.9	103.4	103.6	115.1	115.3
12	5.49	5.49	10.99	10.99	16.48	16.48	21.97	21.95	27.44	27.54	33.05	33.07	38.58	38.64	44.17	44.11	49.62	49.77	55.3	55.03
	9.61	9.61	19.22	19.22	28.82	28.82	38.43	38.46	48.08	47.94	57.53	57.57	67.16	67.06	76.65	76.76	86.36	86.14	95.71	96.05
	10.98	10.98	21.95	21.95	32.92	32.92	43.9	43.87	54.84	54.97	65.96	65.87	76.84	76.94	87.93	87.79	98.76	99	110	109.7
	9.61	9.61	19.22	19.22	28.82	28.82	38.43	38.46	48.08	47.94	57.53	57.57	67.16	67.06	76.65	76.76	86.36	86.14	95.71	96.05
	5.49	5.49	10.99	10.99	16.48	16.48	21.97	21.95	27.44	27.54	33.05	33.07	38.58	38.64	44.17	44.11	49.62	49.77	55.3	55.03
16	3.15	3.15	6.3	6.3	9.44	9.43	12.58	12.57	15.71	15.76	18.91	18.92	22.07	22.04	25.19	25.22	28.37	28.33	31.48	31.59
	5.95	5.95	11.89	11.89	17.84	17.86	23.81	23.82	29.77	29.71	35.66	35.67	41.61	41.63	47.58	47.55	53.49	53.58	59.54	59.37
	7.72	7.72	15.45	15.45	23.16	23.14	30.86	30.89	38.62	38.62	46.35	46.33	54.05	54.07	61.79	61.83	69.56	69.41	77.13	77.32
	8.35	8.35	16.7	16.7	25.05	25.06	33.42	33.36	41.7	41.7	50.08	50.09	58.44	58.4	66.74	66.69	75.03	75.2	83.56	83.35
	7.72	7.72	15.45	15.45	23.16	23.14	30.86	30.89	38.62	38.62	46.35	46.33	54.05	54.07	61.79	61.83	69.56	69.41	77.13	77.32
	5.95	5.95	11.89	11.89	17.84	17.86	23.81	23.82	29.77	29.77	35.66	35.67	41.61	41.63	47.58	47.55	53.49	53.58	59.54	59.37
	3.15	3.15	6.3	6.3	9.44	9.43	12.58	12.57	15.71	15.71	18.91	18.92	22.07	22.04	25.19	25.22	28.37	28.33	31.48	31.59
20	2.11	2.11	4.22	4.22	6.33	6.33	8.45	8.45	10.56	10.56	12.67	12.69	14.81	14.77	16.88	16.93	19.04	19.03	21.15	21.17
	3.9	3.9	7.8	7.8	11.7	11.7	15.6	15.6	19.5	19.5	23.4	23.37	27.26	27.34	31.24	31.18	35.07	35.09	38.99	38.94
	5.54	5.54	11.07	11.07	16.6	16.6	22.14	22.14	27.68	27.68	33.21	33.23	38.76	38.69	44.22	44.26	49.79	49.75	55.28	55.37
	6.25	6.25	12.5	12.5	18.74	18.74	24.99	24.99	31.24	31.24	37.48	37.51	43.76	43.78	50.04	50.04	56.3	56.37	62.63	62.51
	6.85	6.85	13.7	13.7	20.55	20.55	27.4	27.4	34.26	34.26	41.11	41.06	47.9	47.9	54.74	54.72	61.56	61.47	68.3	68.42
	6.25	6.25	12.5	12.5	18.74	18.74	24.99	24.99	31.24	31.24	37.48	37.51	43.76	43.78	50.04	50.04	56.3	56.37	62.63	62.51
	5.54	5.54	11.07	11.07	16.6	16.6	22.14	22.14	27.68	27.68	33.21	33.23	38.76	38.69	44.22	44.26	49.79	49.75	55.28	55.37
	3.9	3.9	7.8	7.8	11.7	11.7	15.6	15.6	19.5	19.5	23.4	23.37	27.26	27.34	31.24	31.18	35.07	35.09	38.99	38.94
	2.11	2.11	4.22	4.22	6.33	6.33	8.45	8.45	10.56	10.56	12.67	12.69	14.81	14.77	16.88	16.93	19.04	19.03	21.15	21.17
24	1.49	1.49	2.98	2.98	4.46	4.46	5.95	5.95	7.44	7.44	8.92	8.91	10.4	10.4	11.88	11.9	13.39	13.42	14.91	14.93
	2.69	2.69	5.37	5.37	8.06	8.06	10.74	10.74	13.43	13.43	16.11	16.14	18.83	18.83	21.52	21.5	24.19	24.15	26.83	26.83
	4.02	4.02	8.03	8.03	12.04	12.04	16.06	16.06	20.07	20.07	24.09	24.06	28.07	28.07	32.08	32.11	36.12	36.15	40.16	4.14
	5.13	5.13	10.26	10.26	15.39	15.39	20.52	20.52	25.65	25.65	30.78	30.78	35.91	35.91	41.04	41	46.13	46.12	51.25	51.27
	5.17	5.17	10.34	10.34	15.5	15.5	20.67	20.67	25.84	25.84	31.01	31.04	36.21	36.21	41.39	41.42	46.6	46.58	51.76	51.78
	5.7	5.7	11.4	11.4	17.1	17.1	22.8	22.8	28.5	28.5	34.2	34.15	39.84	39.84	45.53	45.51	51.2	51.22	56.91	56.87
	5.17	5.17	10.34	10.34	15.5	15.5	20.67	20.67	25.84	25.84	31.01	31.04	36.21	36.21	41.39	41.42	46.6	46.58	51.76	51.78
	5.13	5.13	10.26	10.26	15.39	15.39	20.52	20.52	25.65	25.65	30.78	30.78	35.91	35.91	41.04	41	46.13	46.12	51.25	51.27
	4.02	4.02	8.03	8.03	12.04	12.04	16.06	16.06	20.07	20.07	24.09	24.06	28.07	28.07	32.08	32.11	36.12	36.15	40.16	40.14
	2.69	2.69	5.37	5.37	8.06	8.06	10.74	10.74	13.43	13.43	16.11	16.14	18.83	18.83	21.52	21.5	24.19	24.15	26.88	26.83
	1.49	1.49	2.98	2.98	4.46	4.46	5.95	5.95	7.44	7.44	8.92	8.91	10.4	10.4	11.88	11.9	13.39	13.42	14.91	14.93
28	1.08	1.08	2.16	2.16	3.24	3.24	4.32	4.32	5.4	5.4	6.48	6.48	7.56	7.54	8.62	8.62	9.7	9.7	10.78	10.78
	1.96	1.96	3.92	3.92	5.88	5.88	7.84	7.84	9.8	9.8	11.75	11.75	13.71	13.76	15.72	15.72	17.69	17.7	19.67	19.67
	3.47	3.47	6.94	6.94	10.41	10.41	13.88	13.88	17.35	17.35	20.82	20.82	24.29	24.26	27.73	27.73	31.2	31.16	34.62	34.61
	3.44	3.44	6.89	6.89	10.32	10.32	13.77	13.77	17.22	17.22	20.66	20.66	24.1	24.05	27.48	27.48	30.92	30.99	34.43	34.46

Table B3 continued. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x8 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	1373		2746		4118		5491		6864		8237		9609		10982		12355		13728	
	4.01	4.01	8.02	8.02	12.03	12.03	16.04	16.04	20.05	20.05	24.07	24.07	28.07	28.23	32.26	32.26	36.29	36.21	40.23	40.19
	5.13	5.13	10.25	10.25	15.38	15.38	20.5	20.5	25.63	25.63	30.76	30.76	35.88	35.69	40.78	40.78	45.88	45.94	51.05	51.11
	4.6	4.6	9.21	9.21	13.81	13.81	18.41	18.41	23.01	23.01	27.61	27.61	32.21	32.41	37.04	37.04	41.67	41.64	46.27	46.19
	5.13	5.13	10.25	10.25	15.38	15.38	20.5	20.5	25.63	25.63	30.76	30.76	35.88	35.69	40.78	40.78	45.88	45.94	51.05	51.11
	4.01	4.01	8.02	8.02	12.03	12.03	16.04	16.04	20.05	20.05	24.07	24.07	28.07	28.23	32.26	32.26	36.29	36.21	40.23	40.19
	3.44	3.44	6.89	6.89	13.32	13.32	13.77	13.77	17.22	17.22	20.66	20.66	24.1	24.05	27.48	27.48	30.92	30.99	34.43	34.46
	3.47	3.47	6.94	6.94	10.41	10.41	13.88	13.88	17.35	17.35	20.82	20.82	24.29	24.26	27.73	27.73	31.2	31.16	34.62	34.61
	1.96	1.96	3.92	3.92	5.88	5.88	7.84	7.84	9.8	9.8	11.75	11.75	13.71	13.76	15.72	15.72	17.69	17.7	19.67	19.67
	1.08	1.08	2.16	2.16	3.24	3.24	4.32	4.32	5.4	5.4	6.48	6.48	7.56	7.54	8.62	8.62	9.7	9.7	10.78	10.78
32	0.852	0.852	1.7	1.7	2.56	2.56	3.41	3.41	4.26	4.26	5.11	5.11	5.96	5.96	6.82	6.81	7.67	7.67	8.52	8.49
	1.44	1.44	2.89	2.89	4.33	4.33	5.77	5.77	7.21	7.21	8.65	8.65	10.1	10.1	11.54	11.54	12.99	12.99	14.43	14.48
	2.56	2.56	5.11	5.11	7.66	7.66	10.22	10.22	12.77	12.77	15.33	15.33	17.88	17.88	20.44	20.42	22.97	22.97	25.52	25.48
	2.89	2.89	5.78	5.78	8.66	8.66	11.55	11.55	14.44	14.44	17.33	17.33	20.22	20.22	23.1	23.15	26.05	26.05	28.94	28.93
	3.97	3.97	7.94	7.94	11.91	11.91	15.88	15.88	19.85	19.85	23.81	23.81	27.78	27.79	31.76	31.7	35.66	35.66	39.62	39.67
	3.46	3.46	6.92	6.92	10.38	10.38	13.84	13.84	17.3	17.3	20.76	20.76	24.22	24.19	27.65	27.7	31.16	31.16	34.63	34.57
	4	4	7.99	7.99	11.98	11.98	15.98	15.98	19.98	19.98	23.97	23.97	27.97	28.03	32.03	31.99	35.99	35.99	39.99	40.03
	4.57	4.57	9.15	9.15	13.72	13.72	18.3	18.3	22.87	22.87	27.44	27.44	32.02	31.93	36.49	36.54	41.11	41.11	45.68	45.63
	4	4	7.99	7.99	11.98	11.98	15.98	15.98	19.98	19.98	23.97	23.97	27.97	28.03	32.03	31.99	35.99	35.99	39.99	40.03
	3.46	3.46	6.92	6.92	10.38	10.38	13.84	13.84	17.3	17.3	20.76	20.76	24.22	24.19	27.65	27.7	31.16	31.16	34.63	34.57
	3.97	3.97	7.94	7.94	11.91	11.91	15.88	15.88	19.85	19.85	23.81	23.81	27.78	27.79	31.76	31.7	35.66	35.66	39.62	39.67
	2.89	2.89	5.78	5.78	8.66	8.66	11.55	11.55	14.44	14.44	17.33	17.33	20.22	20.22	23.1	23.15	26.05	26.05	28.94	28.93
	2.56	2.56	5.11	5.11	7.66	7.66	10.22	10.22	12.77	12.77	15.33	15.33	17.88	17.88	20.44	20.42	22.97	22.97	25.52	25.48
	1.44	1.44	2.89	2.89	4.33	4.33	5.77	5.77	7.21	7.21	8.65	8.65	10.1	10.1	11.54	11.54	12.99	12.99	14.43	14.48
	0.852	0.852	1.7	1.7	2.56	2.56	3.41	3.41	4.26	4.26	5.11	5.11	5.96	5.96	6.82	6.81	7.67	7.67	8.52	8.49
36	0.572	0.572	1.14	1.14	1.71	1.71	2.29	2.29	2.86	2.86	3.43	3.43	4	4	4.57	4.57	5.14	5.14	5.71	5.71
	1.2	1.2	2.4	2.4	3.61	3.61	4.81	4.81	6.01	6.01	7.21	7.21	8.41	8.41	9.61	9.61	10.82	10.82	12.02	12.02
	1.72	1.72	3.43	3.43	5.15	5.15	6.87	6.87	8.58	8.58	10.3	10.3	12.02	12.02	13.73	13.73	15.45	15.45	17.17	17.17
	2.29	2.29	4.57	4.57	6.86	6.86	9.14	9.14	11.43	11.43	13.72	13.72	16	16	18.29	18.29	20.57	20.57	22.86	22.86
	2.63	2.63	5.27	5.27	7.9	7.9	10.54	10.54	13.17	13.17	15.8	15.8	18.44	18.44	21.07	21.07	23.71	23.71	26.34	26.34
	3.03	3.03	6.06	6.06	9.08	9.08	12.11	12.11	15.14	15.14	18.17	18.17	21.19	21.19	24.22	24.22	27.25	27.25	30.28	30.28
	3.21	3.21	6.42	6.42	9.62	9.62	12.83	12.83	16.04	16.04	19.25	19.25	22.45	22.45	25.66	25.66	28.87	28.87	32.08	32.08
	3.48	3.48	6.97	6.97	10.45	10.45	13.94	13.94	17.42	17.42	20.9	20.9	24.39	24.39	27.87	27.87	31.36	31.36	34.84	34.84
	3.44	3.44	6.88	6.88	10.31	10.31	13.75	13.75	17.19	17.19	20.62	20.62	24.06	24.06	27.5	27.5	30.93	30.93	34.37	34.37
	3.48	3.48	6.97	6.97	10.45	10.45	13.94	13.94	17.42	17.42	20.9	20.9	24.39	24.39	27.87	27.87	31.36	31.36	34.84	34.84
	3.21	3.21	6.42	6.42	9.62	9.62	12.83	12.83	16.04	16.04	19.25	19.25	22.45	22.45	25.66	25.66	28.87	28.87	32.08	32.08
	3.03	3.03	6.06	6.06	9.08	9.08	12.11	12.11	15.14	15.14	18.17	18.17	21.19	21.19	24.22	24.22	27.25	27.25	30.28	30.28
	2.63	2.63	5.27	5.27	7.9	7.9	10.54	10.54	13.17	13.17	15.8	15.8	18.44	18.44	21.07	21.07	23.71	23.71	26.34	26.34
	2.29	2.29	4.57	4.57	6.86	6.86	9.14	9.14	11.43	11.43	13.72	13.72	16	16	18.29	18.29	20.57	20.57	22.86	22.86
	1.72	1.72	3.43	3.43	5.15	5.15	6.87	6.87	8.58	8.58	10.3	10.3	12.02	12.02	13.73	13.73	15.45	15.45	17.17	17.17
	1.2	1.2	2.4	2.4	3.61	3.61	4.81	4.81	6.01	6.01	7.21	7.21	8.41	8.41	9.61	9.61	10.82	10.82	12.02	12.02
	0.572	0.572	1.14	1.14	1.71	1.71	2.29	2.29	2.86	2.86	3.43	3.43	4	4	4.57	4.57	5.14	5.14	5.71	5.71

Table B4. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x10 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																	
Length (ft)	1721		3442		5163		6884		8604		10325		12046		13767		15488		17209	
4	38.85	39.02	77.35	77.69	115.5	116	153.2	154	190.8	191.6	229	228.9	264.2	267.1	299.8	302	334.5	337.3	377.5	371.7
6	23.84	23.84	47.69	47.64	71.46	71.41	95.21	95.16	118.9	118.9	142.7	142.6	166.3	166.2	190	189.9	213.6	213.4	237.2	237
	23.84	23.84	47.69	47.64	71.46	71.41	95.21	95.16	118.9	118.9	142.7	142.6	166.3	166.2	190	189.9	213.6	213.4	237.2	237
8	14.36	14.34	28.83	28.73	43.19	43.25	57.63	57.58	72.05	72.03	86.63	86.47	101.4	101.1	115.5	115.9	130.1	129.9	144.8	144.6
	20	20.04	39.83	39.99	59.81	59.75	79.65	79.75	99.49	99.55	119.1	119.4	138.5	139	158.8	158.3	178.3	178.7	198	198.1
	14.36	14.34	28.83	28.73	43.19	43.25	57.63	57.58	72.05	72.03	86.63	86.47	101.4	101.1	115.5	115.9	130.1	129.9	144.8	144.6
12	6.88	6.88	13.77	13.8	20.7	20.68	27.58	27.63	34.53	34.54	41.44	41.53	48.45	48.53	55.46	55.43	62.35	62.25	69.17	69.32
	12.04	12.04	24.08	24.05	36.07	36.12	48.16	48.1	60.11	60.16	72.19	72.16	84.19	84.01	96.02	96.12	108.1	108.3	120.3	120.2
	13.77	13.77	27.54	27.56	41.34	41.27	55.03	55.08	68.84	68.76	82.52	82.48	96.23	96.44	110.2	110.1	123.8	123.6	137.4	137.5
	12.04	12.04	24.08	24.05	36.07	36.12	48.16	48.1	60.11	60.16	72.19	72.16	84.19	84.01	96.02	96.12	108.1	108.3	120.3	120.2
	6.88	6.88	13.77	13.8	20.7	20.68	27.58	27.63	34.33	34.54	41.44	41.53	48.45	48.53	55.46	55.43	62.35	62.25	69.17	69.32
16	3.95	3.95	7.89	7.89	11.84	11.82	15.76	15.75	19.69	19.75	23.7	23.76	27.72	27.66	31.61	31.67	35.63	35.65	39.61	39.71
	7.45	7.45	14.91	14.91	22.36	22.4	29.87	29.87	37.33	37.27	44.73	44.66	52.11	52.23	59.69	59.63	67.08	67.07	74.53	74.4
	9.68	9.68	19.36	19.36	29.04	29.03	38.7	38.73	48.41	48.39	58.06	58.12	67.81	67.66	77.32	77.42	87.1	87.06	96.74	96.88
	10.47	10.47	20.94	20.94	31.4	31.4	41.86	41.81	52.25	52.33	62.79	62.74	73.19	73.34	83.82	83.69	94.15	94.21	104.7	104.5
	9.68	9.68	19.36	19.36	29.04	29.03	38.7	38.73	48.41	48.39	58.06	58.12	67.81	67.66	77.32	77.42	87.1	87.06	96.74	96.88
	7.45	7.45	14.91	14.91	22.36	22.4	29.87	29.87	37.33	37.27	44.73	44.66	52.11	52.23	59.69	59.63	67.08	67.07	74.53	74.4
	3.95	3.95	7.89	7.89	11.84	11.82	15.76	15.75	19.69	19.75	23.7	23.76	27.72	27.66	31.61	31.67	35.63	35.65	39.61	39.71
20	2.65	2.65	5.29	5.29	7.94	7.94	10.58	10.57	13.21	13.24	15.89	15.91	18.56	18.52	21.16	21.17	23.82	23.71	26.35	26.53
	4.89	4.89	9.78	9.78	14.68	14.68	19.57	19.6	24.49	24.44	29.33	29.32	34.21	34.3	39.2	39.16	44.06	44.32	49.24	48.91
	6.94	6.94	13.87	13.87	20.81	20.81	27.74	27.71	34.64	34.67	41.6	41.6	48.54	48.42	55.34	55.45	62.38	62.03	68.93	69.27
	7.84	7.84	15.67	15.67	23.51	23.51	31.34	31.36	39.2	39.22	47.07	47.06	54.91	55.05	62.92	62.73	70.57	70.87	78.74	78.52
	8.59	8.59	17.17	17.17	25.76	25.76	34.34	34.32	42.89	42.84	51.41	51.42	59.99	59.82	68.37	68.58	77.15	76.92	85.46	85.61
	7.84	7.84	15.67	15.67	23.51	23.51	31.34	31.36	39.2	39.22	47.07	47.06	54.91	55.05	62.92	62.73	70.57	70.87	78.74	78.52
	6.94	6.94	13.87	13.87	20.81	20.81	27.74	27.71	34.64	34.67	41.6	41.6	48.54	48.42	55.34	55.45	62.38	62.03	68.93	69.27
	4.89	4.89	9.78	9.78	14.68	14.68	19.57	19.6	24.49	24.44	29.33	29.32	34.21	34.3	39.2	39.16	44.06	44.32	49.24	48.91
	2.65	2.65	5.29	5.29	7.94	7.94	10.58	10.57	13.21	13.24	15.89	15.91	18.56	18.52	21.16	21.17	23.82	23.71	26.35	26.53
24	1.86	1.86	3.73	3.73	5.59	5.59	7.46	7.46	9.32	9.31	11.17	11.21	13.08	13.08	14.95	14.95	16.82	16.8	18.67	18.71
	3.37	3.37	6.73	6.73	10.1	10.1	13.46	13.46	16.83	16.86	20.23	20.18	23.54	23.53	26.89	26.92	30.29	30.32	33.69	33.61
	5.04	5.04	10.07	10.07	15.11	15.11	20.15	20.15	25.18	25.15	30.19	30.23	35.27	35.3	40.35	40.29	45.32	45.3	50.34	50.43
	6.42	6.42	12.85	12.85	19.27	19.27	25.7	25.7	32.12	32.12	38.54	38.5	44.92	44.89	51.3	51.33	57.75	57.74	64.16	64.1
	6.49	6.49	12.97	12.97	19.46	19.46	25.94	25.94	32.42	32.45	38.94	38.99	45.49	45.47	51.97	52.02	58.52	58.54	65.05	65.04
	7.14	7.14	14.28	14.28	21.42	21.42	28.56	28.56	35.7	35.66	42.8	42.73	49.85	49.9	57.03	56.94	64.06	64.03	71.14	71.19
	6.49	6.49	12.97	12.97	19.46	19.46	25.94	25.94	32.42	32.45	38.94	38.99	45.49	45.47	51.97	52.02	58.52	58.54	65.05	65.04
	6.42	6.42	12.85	12.85	19.27	19.27	25.7	25.7	32.12	32.12	38.54	38.5	44.92	44.89	51.3	51.33	57.75	57.74	64.16	64.1
	5.04	5.04	10.07	10.07	15.11	15.11	20.15	20.15	25.18	25.15	30.19	30.23	35.27	35.3	40.35	40.29	45.32	45.3	50.34	50.43
	3.37	3.37	6.73	6.73	10.1	10.1	13.46	13.46	16.83	16.86	20.23	20.18	23.54	23.53	26.89	26.92	30.29	30.32	33.69	33.61
	1.86	1.86	3.73	3.73	5.59	5.59	7.46	7.46	9.32	9.31	11.17	11.21	13.08	13.08	14.95	14.95	16.82	16.8	18.67	18.71
28	1.35	1.35	2.71	2.71	4.06	4.06	5.42	5.42	6.77	6.76	8.11	8.11	9.46	9.44	10.79	10.77	12.12	12.11	13.45	13.45
	2.46	2.46	4.92	4.92	7.38	7.38	9.84	9.84	12.29	12.32	14.79	14.79	17.26	17.31	19.78	19.81	22.29	22.31	24.79	24.79
	4.35	4.35	8.69	8.69	13.04	13.04	17.38	17.38	21.73	21.7	26.04	26.04	30.38	30.32	34.65	34.62	38.95	38.92	43.25	43.25
	4.32	4.32	8.63	8.63	12.95	12.95	17.26	17.26	21.58	21.57	25.89	25.89	30.21	30.24	34.56	34.57	38.89	38.39	43.21	43.21
	5.03	5.03	10.07	10.07	15.1	15.1	20.14	20.14	25.17	25.24	30.29	30.29	35.34	35.33	40.37	40.37	45.41	45.48	50.53	50.53
	6.42	6.42	12.83	12.83	19.25	19.25	25.67	25.67	32.08	31.96	38.35	38.35	44.74	44.74	51.13	51.15	57.54	57.41	63.79	63.79
	5.78	5.78	11.56	11.56	17.34	17.34	23.11	23.11	28.89	29.03	34.84	34.84	40.65	40.66	46.47	46.43	52.24	52.39	58.22	58.22

Table B4 continued. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x10 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	1721		3442		5163		6884		8604		10325		12046		13767		15488		17209	
	6.42	6.42	12.83	12.83	19.25	19.25	25.67	25.67	32.08	31.96	38.35	38.35	44.74	44.74	51.13	51.15	57.54	57.41	63.79	63.79
	5.03	5.03	10.07	10.07	15.1	15.1	20.14	20.14	25.17	25.24	30.29	30.29	35.34	35.33	40.37	40.37	45.41	45.48	50.53	50.53
	4.32	4.32	8.63	8.63	12.95	12.95	17.26	17.26	21.58	21.57	25.89	25.89	30.21	30.24	34.56	34.57	38.89	38.39	43.21	43.21
	4.35	4.35	8.69	8.69	13.04	13.04	17.38	17.38	21.73	21.7	26.04	26.04	30.38	30.32	34.65	34.62	38.95	38.92	43.25	43.25
	2.46	2.46	4.92	4.92	7.38	7.38	9.84	9.84	12.29	12.32	14.79	14.79	17.26	17.31	19.78	19.81	22.29	22.31	24.79	24.79
	1.35	1.35	2.71	2.71	4.06	4.06	5.42	5.42	6.77	6.76	8.11	8.11	9.46	9.44	10.79	10.77	12.12	12.11	13.45	13.45
32	1.07	1.07	2.13	2.13	3.2	3.2	4.26	4.26	5.33	5.33	6.4	6.4	7.46	7.47	8.54	8.51	9.57	9.55	10.61	10.61
	1.81	1.81	3.62	3.62	5.44	5.44	7.25	7.25	9.06	9.06	10.87	10.87	12.68	12.64	14.45	14.53	16.34	16.41	18.23	18.22
	3.2	3.2	6.39	6.39	9.59	9.59	12.79	12.79	15.98	15.98	19.18	19.18	22.38	22.47	25.68	25.56	28.76	28.68	31.86	31.9
	3.63	3.63	7.26	7.26	10.89	10.89	14.52	14.52	18.15	18.14	21.77	21.77	25.4	25.29	28.9	29.02	32.65	32.72	36.36	36.31
	4.97	4.97	9.93	9.93	14.9	14.9	19.86	19.86	24.82	24.83	29.79	29.79	34.76	34.86	39.85	39.73	44.7	44.65	49.61	49.66
	4.35	4.35	8.69	8.69	13.04	13.04	17.38	17.38	21.72	21.7	26.04	26.04	30.38	30.29	34.62	34.72	39.06	39.11	43.46	43.4
	5.01	5.01	10.01	10.01	15.02	15.02	20.03	20.03	25.03	25.1	30.12	30.12	35.14	35.19	40.22	40.15	45.17	45.11	50.13	50.2
	5.73	5.73	11.47	11.47	17.2	17.2	22.93	22.93	28.66	28.57	34.28	34.28	40	39.96	45.67	45.72	51.44	51.5	57.23	57.14
	5.01	5.01	10.01	10.01	15.02	15.02	20.03	20.03	25.03	25.1	30.12	30.12	35.14	35.19	40.22	40.15	45.17	45.11	50.13	50.2
	4.35	4.35	8.69	8.69	13.04	13.04	17.38	17.38	21.72	21.7	26.04	26.04	30.38	30.29	34.62	34.72	39.06	39.11	43.45	43.4
	4.97	4.97	9.93	9.93	14.9	14.9	19.86	19.86	24.82	24.83	29.79	29.79	34.76	34.86	39.85	39.73	44.7	44.65	49.61	49.66
	3.63	3.63	7.26	7.26	10.89	10.89	14.52	14.52	18.15	18.14	21.77	21.77	25.4	25.29	28.9	29.02	32.65	32.72	36.36	36.31
	3.2	3.2	6.39	6.39	9.59	9.59	12.79	12.79	15.98	15.98	19.18	19.18	22.38	22.47	25.68	25.56	28.76	28.68	31.86	31.9
	1.81	1.81	3.62	3.62	5.44	5.44	7.25	7.25	9.06	9.06	10.87	10.87	12.68	12.64	14.45	14.53	16.34	16.41	18.23	18.22
	1.07	1.07	2.13	2.13	3.2	3.2	4.26	4.26	5.33	5.33	6.4	6.4	7.46	7.47	8.54	8.51	9.57	9.55	10.61	10.61
36	0.716	0.716	1.43	1.43	2.15	2.15	2.86	2.86	3.58	3.58	4.3	4.3	5.01	5.01	5.73	5.73	6.44	6.44	7.16	7.16
	1.51	1.51	3.01	3.01	4.52	4.52	6.03	6.03	7.53	7.53	9.04	9.04	10.55	10.55	12.05	12.05	13.56	13.56	15.07	15.07
	2.15	2.15	4.3	4.3	6.46	6.46	8.61	8.61	10.76	10.76	12.91	12.91	15.06	15.06	17.22	17.22	19.37	19.37	21.52	21.5
	2.86	2.86	5.73	5.73	8.59	8.59	11.46	11.46	14.32	14.32	17.19	17.19	20.05	20.05	22.92	22.91	25.77	25.77	28.63	28.69
	3.3	3.3	6.61	6.61	9.91	9.91	13.21	13.21	16.51	16.51	19.82	19.82	23.12	23.12	26.42	26.45	29.75	29.75	33.06	33
	3.79	3.79	7.59	7.59	11.38	11.38	15.18	15.18	18.97	18.97	22.77	22.77	26.56	26.56	30.36	30.32	34.11	34.11	37.9	37.95
	4.02	4.02	8.05	8.05	12.07	12.07	16.09	16.09	20.11	20.11	24.14	24.14	28.16	28.16	32.18	32.22	36.25	36.25	40.28	40.25
	4.37	4.37	8.73	8.73	13.1	13.1	17.46	17.46	21.83	21.83	26.19	26.19	30.56	30.56	34.93	34.89	39.25	39.25	43.61	43.63
	4.31	4.31	8.62	8.62	12.93	12.93	17.24	17.24	21.55	21.55	25.86	25.86	30.17	30.17	34.48	34.51	38.83	38.83	43.14	43.13
	4.37	4.37	8.73	8.73	13.1	13.1	17.46	17.46	21.83	21.83	26.19	26.19	30.56	30.56	34.93	34.89	39.25	39.25	43.61	43.63
	4.02	4.02	8.05	8.05	12.07	12.07	16.09	16.09	20.11	20.11	24.14	24.14	28.16	28.16	32.18	32.22	36.25	36.25	40.28	40.25
	3.79	3.79	7.59	7.59	11.38	11.38	15.18	15.18	18.97	18.97	22.77	22.77	26.56	26.56	30.36	30.32	34.11	34.11	37.9	37.95
	3.3	3.3	6.61	6.61	9.91	9.91	13.21	13.21	16.51	16.51	19.82	19.82	23.12	23.12	26.42	26.45	29.75	29.75	33.06	33
	2.86	2.86	5.73	5.73	8.59	8.59	11.46	11.46	14.32	14.32	17.19	17.19	20.05	20.05	22.92	22.91	25.77	25.77	28.63	28.69
	2.15	2.15	4.3	4.3	6.46	6.46	8.61	8.61	10.76	10.76	12.91	12.91	15.06	15.06	17.22	17.22	19.37	19.37	21.52	21.5
	1.51	1.51	3.01	3.01	4.52	4.52	6.03	6.03	7.53	7.53	9.04	9.04	10.55	10.55	12.05	12.05	13.56	13.56	15.07	15.07
	0.716	0.716	1.43	1.43	2.15	2.15	2.86	2.86	3.58	3.58	4.3	4.3	5.01	5.01	5.73	5.73	6.44	6.44	7.16	7.16
40	0.573	0.573	1.15	1.15	1.72	1.72	2.29	2.29	2.87	2.87	3.44	3.44	4.01	4.01	4.59	4.59	5.16	5.15	5.72	5.72
	1.08	1.08	2.15	2.15	3.23	3.23	4.3	4.3	5.37	5.37	6.45	6.45	7.52	7.52	8.6	8.6	9.68	9.69	10.77	10.77
	1.58	1.58	3.16	3.16	4.74	4.74	6.32	6.32	7.9	7.9	9.48	9.48	11.06	11.06	12.64	12.64	14.22	14.21	15.79	15.79
	2.15	2.15	4.29	4.29	6.44	6.44	8.58	8.58	10.73	10.73	12.88	12.88	15.02	15.02	17.17	17.17	19.31	19.32	21.46	21.46
	2.44	2.44	4.89	4.89	7.33	7.33	9.77	9.77	12.21	12.21	14.66	14.66	17.1	17.1	19.54	19.54	21.99	21.98	24.43	24.43
	2.86	2.86	5.73	5.73	8.59	8.59	11.46	11.46	14.32	14.32	17.19	17.19	20.05	20.05	22.92	22.92	25.78	25.8	28.66	28.66
	3.16	3.16	6.31	6.31	9.47	9.47	12.63	12.63	15.79	15.79	18.94	18.94	22.1	22.1	25.26	25.26	28.42	28.4	31.56	31.56

Table B4 continued. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x10 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	1721		3442		5163		6884		8604		10325		12046		13767		15488		17209	
	3.37	3.37	6.74	6.74	10.1	10.1	13.47	13.47	16.84	16.84	20.21	20.21	23.57	23.57	26.94	26.94	30.31	30.31	33.67	33.67
	3.45	3.45	6.89	6.89	10.34	10.34	13.78	13.78	17.23	17.23	20.67	20.67	24.12	24.12	27.56	27.56	31.01	31.01	34.46	34.46
	3.58	3.58	7.16	7.16	10.74	10.74	14.33	14.33	17.9	17.9	21.49	21.49	25.07	25.07	28.65	28.65	32.23	32.22	35.8	35.8
	3.45	3.45	6.89	6.89	10.34	10.34	13.78	13.78	17.23	17.23	20.67	20.67	24.12	24.12	27.56	27.56	31.01	31.01	34.46	34.46
	3.37	3.37	6.74	6.74	10.1	10.1	13.47	13.47	16.84	16.84	20.21	20.21	23.57	23.57	26.94	26.94	30.31	30.31	33.67	33.67
	3.16	3.16	6.31	6.31	9.47	9.47	12.63	12.63	15.79	15.79	18.94	18.94	22.1	22.1	25.26	25.26	28.42	28.4	31.56	31.56
	2.86	2.86	5.73	5.73	8.59	8.59	11.46	11.46	14.32	14.32	17.19	17.19	20.05	20.05	22.92	22.92	25.78	25.8	28.66	28.66
	2.44	2.44	4.89	4.89	7.33	7.33	9.77	9.77	12.21	12.21	14.66	14.66	17.1	17.1	19.54	19.54	21.99	21.98	24.43	24.43
	2.15	2.15	4.29	4.29	6.44	6.44	8.58	8.58	10.73	10.73	12.88	12.88	15.02	15.02	17.17	17.17	19.31	19.32	21.46	21.46
	1.58	1.58	3.16	3.16	4.74	4.74	6.32	6.32	7.9	7.9	9.48	9.48	11.06	11.06	12.64	12.64	14.22	14.21	15.79	15.79
	1.08	1.08	2.15	2.15	3.23	3.23	4.3	4.3	5.37	5.37	6.45	6.45	7.52	7.52	8.6	8.6	9.68	9.69	10.77	10.77
	0.573	0.573	1.15	1.15	1.72	1.72	2.29	2.29	2.87	2.87	3.44	3.44	4.01	4.01	4.59	4.59	5.16	5.15	5.72	5.72

Table B5. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x12 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	2054		4108		6162		8216		10270		12323		14377		16431		18485		20539	
4	46.36	46.04	92.72	91.98	138	137.1	182.8	181.9	227.4	225.5	270.6	268.8	313.6	310.9	355.4	352.4	396.5	391.3	429.3	419.1
6	28.42	28.42	56.84	56.79	85.19	85.11	113.5	113.4	141.7	141.6	169.9	169.8	198.1	197.9	226.2	226	254.3	254	282.2	281.8
	28.42	28.42	56.84	56.79	85.19	85.11	113.5	113.4	141.7	141.6	169.9	169.8	198.1	197.9	226.2	226	254.3	254	282.2	281.8
8	17.11	17.11	34.23	34.21	51.32	51.6	68.81	69.08	86.35	85.8	103	103.5	120.8	120.8	138.1	138.4	155.7	156.1	173.5	173.7
	23.91	23.91	47.81	47.79	71.69	71.26	95.02	94.59	118.2	119	142.8	141.9	165.5	165.4	189	188.4	212	211.4	234.9	234.5
	17.11	17.11	34.23	34.21	51.32	51.6	68.81	69.08	86.35	85.8	103	103.5	120.8	120.8	138.1	138.4	155.7	156.1	173.5	173.7
12	8.22	8.22	16.43	16.44	24.66	24.69	32.91	33.02	41.28	41.37	49.64	49.66	57.93	58.04	66.33	66.18	74.45	74.8	83.11	82.75
	14.37	14.37	28.73	28.76	43.14	43.12	57.5	57.39	71.73	71.69	86.03	85.99	100.3	100.2	114.5	114.9	129.2	128.7	143	143.5
	16.43	16.43	32.87	32.82	49.23	49.22	65.63	65.71	82.13	82.1	98.51	98.54	115	115.1	131.5	131.1	147.5	147.9	164.4	163.9
	14.37	14.37	28.73	28.76	43.14	43.12	57.5	57.39	71.73	71.69	86.03	85.99	100.3	100.2	114.5	114.9	129.2	128.7	143	143.5
	8.22	8.22	16.43	16.44	24.66	24.69	32.91	33.02	41.28	41.37	49.64	49.66	57.93	58.04	66.33	66.18	74.45	74.8	83.11	82.75
16	4.71	4.71	9.42	9.4	14.1	14.18	18.9	18.84	23.55	23.67	28.41	28.36	33.09	33.08	37.8	37.86	42.59	42.68	47.43	47.43
	8.9	8.9	17.79	17.84	26.76	26.66	35.55	35.66	44.57	44.39	53.26	53.35	62.24	62.32	71.23	71.15	80.04	79.89	88.77	88.77
	11.55	11.55	23.11	23.06	34.59	34.66	46.21	46.13	57.66	57.83	69.39	69.31	80.86	80.75	92.29	92.35	103.9	104.1	115.7	115.7
	12.49	12.49	24.99	25.02	37.53	37.49	49.99	50.04	62.54	62.39	74.86	74.92	87.41	87.49	99.99	99.94	112.4	112.2	124.7	124.7
	11.55	11.55	23.11	23.06	34.59	34.66	46.21	46.13	57.66	57.83	69.39	69.31	80.86	80.75	92.29	92.35	103.9	104.1	115.7	115.7
	8.9	8.9	17.79	17.84	26.76	26.66	35.55	35.66	44.57	44.39	53.26	53.35	62.24	62.32	71.23	71.15	80.04	79.89	88.77	88.77
	4.71	4.71	9.42	9.4	14.1	14.18	18.9	18.84	23.55	23.67	28.41	28.36	33.09	33.08	37.8	37.86	42.59	42.68	47.43	47.43
20	3.15	3.15	6.31	6.31	9.46	9.46	12.61	12.61	15.77	15.81	18.97	19	22.17	22.08	25.23	25.29	28.45	28.4	31.56	31.61
	5.84	5.84	11.69	11.69	17.53	17.54	23.39	23.38	29.23	29.18	35.02	34.98	40.31	40.98	46.83	46.73	52.58	52.68	58.54	58.55
	8.27	8.27	16.54	16.54	24.81	24.81	33.09	33.07	41.34	41.37	49.64	49.67	57.94	57.76	66.02	66.13	74.4	74.3	82.55	82.42
	9.36	9.36	18.72	18.72	28.08	28.06	37.41	37.48	46.85	46.81	56.17	56.2	65.56	65.67	75.06	74.98	84.35	84.38	93.75	93.91
	10.24	10.24	20.48	20.48	30.72	30.73	40.98	40.87	51.09	51.15	61.38	61.31	71.52	71.47	81.68	81.71	91.93	91.95	102.2	102
	9.36	9.36	18.72	18.72	28.08	28.06	37.41	37.48	46.85	46.81	56.17	56.2	65.56	65.67	75.06	74.98	84.35	84.38	93.75	93.91
	8.27	8.27	16.54	16.54	24.81	24.81	33.09	33.07	41.34	41.37	49.64	49.67	57.94	57.76	66.02	66.13	74.4	74.3	82.55	82.42
	5.84	5.84	11.69	11.69	17.53	17.54	23.39	23.38	29.23	29.18	35.02	34.98	40.31	40.98	46.83	46.73	52.58	52.68	58.54	58.55
	3.15	3.15	6.31	6.31	9.46	9.46	12.61	12.61	15.77	15.81	18.97	19	22.17	22.08	25.23	25.29	28.45	28.4	31.56	31.61
24	2.23	2.23	4.45	4.45	6.68	6.68	8.9	8.9	11.13	11.09	13.31	13.36	15.58	15.58	17.81	17.83	20.06	20.02	22.24	22.2
	4.02	4.02	8.03	8.03	12.05	12.05	16.06	16.06	20.08	20.16	24.19	24.1	28.12	28.15	32.17	32.15	36.16	36.25	40.28	40.31
	6.01	6.01	12.03	12.03	18.04	18.04	24.06	24.07	30.08	30	36	36.12	42.14	42.09	48.1	48.12	54.14	54.07	60.07	60.07
	7.66	7.66	15.32	15.32	22.98	22.98	30.64	30.61	38.26	38.31	45.97	45.87	53.52	53.51	61.15	61.16	68.81	68.83	76.48	76.43
	7.75	7.75	15.49	15.49	23.24	23.24	30.99	31.09	38.86	38.81	46.57	46.59	54.36	54.48	62.25	62.19	69.97	69.96	77.73	77.83
	8.51	8.51	17.03	17.03	25.54	25.54	34.06	33.93	42.41	42.47	50.95	50.97	59.46	59.28	67.75	67.86	76.34	76.36	84.84	84.71
	7.75	7.75	15.49	15.49	23.24	23.24	30.99	31.09	38.86	38.81	46.57	46.59	54.36	54.48	62.25	62.19	69.97	69.96	77.73	77.83
	7.66	7.66	15.32	15.32	22.98	22.98	30.64	30.61	38.26	38.31	45.97	45.87	53.52	53.51	61.15	61.16	68.81	68.83	76.48	76.43
	6.01	6.01	12.03	12.03	18.04	18.04	24.06	24.07	30.08	30	36	36.12	42.14	42.09	48.1	48.12	54.14	54.07	60.07	60.07
	4.02	4.02	8.03	8.03	12.05	12.05	16.06	16.06	20.08	20.16	24.19	24.1	28.12	28.15	32.17	32.15	36.16	36.25	40.28	40.31
	2.23	2.23	4.45	4.45	6.68	6.68	8.9	8.9	11.13	11.09	13.31	13.36	15.58	15.58	17.81	17.83	20.06	20.02	22.24	22.2
28	1.61	1.61	3.22	3.22	4.83	4.83	6.45	6.45	8.06	8.04	9.65	9.62	11.22	11.2	12.8	12.78	14.38	14.36	15.96	16.09
	2.94	2.94	5.89	5.89	8.83	8.83	11.77	11.77	14.71	14.76	17.71	17.77	20.73	20.77	23.74	23.79	26.76	26.8	29.78	29.6
	5.18	5.18	10.36	10.36	15.54	15.54	20.72	20.72	25.9	25.86	31.02	30.96	36.12	36.07	41.23	41.19	46.34	46.27	51.41	51.51
	5.15	5.15	10.31	10.31	15.46	15.46	20.62	20.62	25.77	25.77	30.92	30.94	36.09	36.13	41.29	41.24	46.39	46.51	51.67	51.72
	6.81	6.81	12.02	12.02	18.04	18.04	24.05	24.05	30.06	30.15	36.17	36.23	42.27	42.22	48.26	48.44	54.5	54.36	60.4	60.25

Table B5 continued. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x12 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																	
Length (ft)	2054		4108		6162		8216		10270		12323		14377		16431		18485	20539	
	7.65	7.65	15.3	15.3	22.95	22.95	30.6	30.6	38.25	38.11	45.73	45.61	53.21	53.28	60.89	60.62	68.19	68.32	75.92	76.11
	6.91	6.91	13.81	13.81	20.72	20.72	27.63	27.63	34.53	34.7	41.63	41.77	48.73	48.64	55.59	55.9	62.88	62.76	69.74	69.53
	7.65	7.65	15.3	15.3	22.95	22.95	30.6	30.6	38.25	38.11	45.73	45.61	53.21	53.28	60.89	60.62	68.19	68.32	75.92	76.11
	6.81	6.81	12.02	12.02	18.04	18.04	24.05	24.05	30.06	30.15	36.17	36.23	42.27	42.22	48.26	48.44	54.5	54.36	60.4	60.25
	5.15	5.15	10.31	10.31	15.46	15.46	20.62	20.62	25.77	25.77	30.92	30.94	36.09	36.13	41.29	41.24	46.39	46.51	51.67	51.72
	5.18	5.18	10.36	10.36	15.54	15.54	20.72	20.72	25.9	25.86	31.02	30.96	36.12	36.07	41.23	41.19	46.34	46.27	51.41	51.51
	2.94	2.94	5.89	5.89	8.83	8.83	11.77	11.77	14.71	14.76	17.71	17.77	20.73	20.77	23.74	23.79	26.76	26.8	29.78	29.6
	1.61	1.61	3.22	3.22	4.83	4.83	6.45	6.45	8.06	8.04	9.65	9.62	11.22	11.2	12.8	12.78	14.38	14.36	15.96	16.09
32	1.27	1.27	2.54	2.54	3.81	3.81	5.08	5.08	6.35	6.36	7.63	7.63	8.9	8.85	10.12	10.1	11.36	11.37	12.63	12.6
	2.17	2.17	4.33	4.33	6.5	6.5	8.66	8.66	10.83	10.81	12.98	12.95	15.11	15.25	17.42	17.46	19.65	19.62	21.8	21.88
	3.81	3.81	7.63	7.63	11.44	11.44	15.26	15.26	19.07	19.09	22.9	22.95	26.77	26.59	30.39	30.34	34.13	34.18	37.98	37.84
	4.33	4.33	8.65	8.65	12.98	12.98	17.31	17.31	21.63	21.66	25.99	25.94	30.27	30.42	34.76	34.82	39.18	39.13	43.48	43.66
	5.94	5.94	11.88	11.88	17.82	17.82	23.75	23.75	29.69	29.62	35.54	35.55	41.48	41.39	47.31	47.24	53.15	53.16	59.07	58.89
	5.17	5.17	10.33	10.33	15.5	15.5	20.67	20.67	25.83	25.92	31.1	31.1	36.28	36.32	41.51	41.55	46.75	46.74	51.93	52.07
	6	6	12.01	12.01	18.01	18.01	24.01	24.01	30.01	29.94	35.93	35.94	41.93	41.93	47.92	47.94	53.93	53.96	59.95	59.87
	6.81	6.81	13.62	13.62	20.43	20.43	27.24	27.24	34.05	34.11	40.93	40.92	47.74	47.71	54.53	54.48	61.29	61.25	68.06	68.12
	6	6	12.01	12.01	18.01	18.01	24.01	24.01	30.01	29.94	35.93	35.94	41.93	41.93	47.92	47.94	53.93	53.96	59.95	59.87
	5.17	5.17	10.33	10.33	15.5	15.5	20.67	20.67	25.83	25.92	31.1	31.1	36.28	36.32	41.51	41.55	46.75	46.74	51.93	52.07
	5.94	5.94	11.88	11.88	17.82	17.82	23.75	23.75	29.69	29.62	35.54	35.55	41.48	41.39	47.31	47.24	53.15	53.16	59.07	58.89
	4.33	4.33	8.65	8.65	12.98	12.98	17.31	17.31	21.63	21.66	25.99	25.94	30.27	30.42	34.76	34.82	39.18	39.13	43.48	43.66
	3.81	3.81	7.63	7.63	11.44	11.44	15.26	15.26	19.07	19.09	22.9	22.95	26.77	26.59	30.39	30.34	34.13	34.18	37.98	37.84
	2.17	2.17	4.33	4.33	6.5	6.5	8.66	8.66	10.83	10.81	12.98	12.95	15.11	15.25	17.42	17.46	19.65	19.62	21.8	21.88
	1.27	1.27	2.54	2.54	3.81	3.81	5.08	5.08	6.35	6.36	7.63	7.63	8.9	8.85	10.12	10.1	11.36	11.37	12.63	12.6
36	0.855	0.855	1.71	1.71	2.56	2.56	3.42	3.42	4.27	4.27	5.13	5.13	5.98	5.98	6.84	6.84	7.69	7.7	8.55	8.55
	1.8	1.8	3.6	3.6	5.4	5.4	7.2	7.2	8.99	8.99	10.79	10.79	12.59	12.59	14.39	14.39	16.19	16.16	17.96	17.94
	2.57	2.57	5.14	5.14	7.71	7.71	10.27	10.27	12.84	12.84	15.41	15.41	17.98	17.98	20.55	20.55	23.12	23.18	25.76	25.78
	3.42	3.42	6.84	6.84	10.26	10.26	13.67	13.67	17.09	17.09	20.51	20.51	23.93	23.92	27.34	27.34	30.76	30.68	34.09	34.08
	3.94	3.94	7.89	7.89	11.83	11.83	15.77	15.77	19.72	19.72	23.66	23.66	27.6	27.61	31.56	31.56	35.5	35.58	39.53	39.51
	4.53	4.53	9.06	9.06	13.58	13.58	18.11	18.11	22.64	22.64	27.16	27.16	31.69	31.67	36.19	36.19	40.72	40.66	45.18	45.2
	4.8	4.8	9.61	9.61	14.41	14.41	19.21	19.21	24.01	24.01	28.82	28.82	33.62	33.65	38.46	38.46	43.27	43.31	48.12	48.12
	5.21	5.21	10.42	10.42	15.63	15.63	20.84	20.84	26.05	26.05	31.25	31.25	36.46	36.42	41.63	41.63	46.83	46.81	52.01	52
	5.15	5.15	10.29	10.29	15.44	15.44	20.58	20.58	25.73	25.73	30.87	30.87	36.02	36.06	41.21	41.21	46.36	46.38	51.53	51.54
	5.21	5.21	10.42	10.42	15.63	15.63	20.84	20.84	26.05	26.05	31.25	31.25	36.46	36.42	41.63	41.63	46.83	46.81	52.01	52
	4.8	4.8	9.61	9.61	14.41	14.41	19.21	19.21	24.01	24.01	28.82	28.82	33.62	33.65	38.46	38.46	43.27	43.31	48.12	48.12
	4.53	4.53	9.06	9.06	13.58	13.58	18.11	18.11	22.64	22.64	27.16	27.16	31.69	31.67	36.19	36.19	40.72	40.66	45.18	45.2
	3.94	3.94	7.89	7.89	11.83	11.83	15.77	15.77	19.72	19.72	23.66	23.66	27.6	27.61	31.56	31.56	35.5	35.58	39.53	39.51
	3.42	3.42	6.84	6.84	10.26	10.26	13.67	13.67	17.09	17.09	20.51	20.51	23.93	23.92	27.34	27.34	30.76	30.68	34.09	34.08
	2.57	2.57	5.14	5.14	7.71	7.71	10.27	10.27	12.84	12.84	15.41	15.41	17.98	17.98	20.55	20.55	23.12	23.18	25.76	25.78
	1.8	1.8	3.6	3.6	5.4	5.4	7.2	7.2	8.99	8.99	10.79	10.79	12.59	12.59	14.39	14.39	16.19	16.16	17.46	17.94
	0.855	0.855	1.71	1.71	2.56	2.56	3.42	3.42	4.27	4.27	5.13	5.13	5.98	5.98	6.84	6.84	7.69	7.7	8.55	8.55
40	0.683	0.683	1.37	1.37	2.05	2.05	2.73	2.73	3.41	3.41	4.1	4.1	4.78	4.78	5.46	5.46	6.14	6.15	6.83	6.83
	1.29	1.29	2.57	2.57	3.86	3.86	5.14	5.14	6.43	6.43	7.71	7.71	9	9	10.28	10.28	11.57	11.57	12.85	12.86
	1.88	1.88	3.77	3.77	5.65	5.65	7.54	7.54	9.42	9.42	11.31	11.31	13.19	13.19	15.08	15.08	16.96	16.97	18.85	18.82
	2.56	2.56	5.12	5.12	7.68	7.68	10.24	10.24	12.8	12.8	15.36	15.36	17.93	17.93	20.49	20.49	23.05	23.02	25.58	25.65
	2.92	2.92	5.83	5.83	8.75	8.75	11.67	11.67	14.59	14.59	17.5	17.5	20.42	20.42	23.34	23.34	26.25	26.31	29.24	29.15

Table B5 continued. Spring forces (lbs) produced in the chord and CLB nail connections in SAP2000 (CSI, 1995) for a 2x12 No. 2 Southern Pine chord braced by n-Spruce-Pine-Fir CLB's connected by 2-16d Common nail connections.

	Axial load in compression chord, Fc' (lbs)																			
Length (ft)	2054		4108		6162		8216		10270		12323		14377		16431		18485		20539	
	3.42	3.42	6.84	6.84	10.25	10.25	13.67	13.67	17.09	17.09	20.51	20.51	23.93	23.93	27.34	27.34	30.76	30.7	34.11	34.19
	3.77	3.77	7.54	7.54	11.31	11.31	15.08	15.08	18.84	18.84	22.61	22.61	26.38	26.38	30.15	30.15	33.92	33.96	37.73	37.68
	4.02	4.02	8.04	8.04	12.06	12.06	16.07	16.07	20.09	20.09	24.11	24.11	28.13	28.13	32.15	32.15	36.17	36.14	40.16	40.18
	4.11	4.11	8.23	8.23	12.34	12.34	16.45	16.45	20.57	20.57	24.68	24.68	28.79	28.79	32.9	32.9	37.02	37.03	41.15	41.14
	4.27	4.27	8.55	8.55	12.82	12.82	17.09	17.09	21.36	21.36	25.64	25.64	29.91	29.91	34.18	34.18	38.45	38.44	42.72	42.71
	4.11	4.11	8.23	8.23	12.34	12.34	16.45	16.45	20.57	20.57	24.68	24.68	28.79	28.79	32.9	32.9	37.02	37.03	41.15	41.14
	4.02	4.02	8.04	8.04	12.06	12.06	16.07	16.07	20.09	20.09	24.11	24.11	28.13	28.13	32.15	32.15	36.17	36.14	40.16	40.18
	3.77	3.77	7.54	7.54	11.31	11.31	15.08	15.08	18.84	18.84	22.61	22.61	26.38	26.38	30.15	30.15	33.92	33.96	37.73	37.68
	3.42	3.42	6.84	6.84	10.25	10.25	13.67	13.67	17.09	17.09	20.51	20.51	23.93	23.93	27.34	27.34	30.76	30.7	34.11	34.19
	2.92	2.92	5.83	5.83	8.75	8.75	11.67	11.67	14.59	14.59	17.5	17.5	20.42	20.42	23.34	23.34	26.25	26.31	29.24	29.15
	2.56	2.56	5.12	5.12	7.68	7.68	10.24	10.24	12.8	12.8	15.36	15.36	17.93	17.93	20.49	20.49	23.05	23.02	25.58	25.65
	1.88	1.88	3.77	3.77	5.65	5.65	7.54	7.54	9.42	9.42	11.31	11.31	13.19	13.19	15.08	15.08	16.96	16.97	18.85	18.82
	1.29	1.29	2.57	2.57	3.86	3.86	5.14	5.14	6.43	6.43	7.71	7.71	9	9	10.28	10.28	11.57	11.57	12.85	12.86
	0.683	0.683	1.37	1.37	2.05	2.05	2.73	2.73	3.41	3.41	4.1	4.1	4.78	4.78	5.46	5.46	6.14	6.15	6.83	6.83

Appendix C

Spring forces produced in the chord and diagonal nail connections for a system analysis in SAP2000 (CSI, 1995) for Southern Pine Chords braced by n-Spruce-Pine-Fir webs and one or two Spruce-Pine-Fir diagonals

Table C1. X-components of joint forces (lbs) produced in the SAP2000 (CSI, 1995) analysis of j-truss chords braced by multiple CLB's and one or two diagonals.

Jt	5-8 ft. chords, 3 CLB's, 1 diagonal					6-20 ft. chords, 9 CLB's, 2 diagonals					11-20 ft. chords, 9 CLB's, 2 diagonals				
	10% to 50% of the allowable load level (lbs)*					10% to 50% of the allowable load level (lbs)*					10% to 50% of the allowable load level (lbs)*				
	684	1368	2053	2737	3421	684	1368	2053	2737	3421	684	1368	2053	2737	3421
A	-38	-43	-31	-0.5	44	62	124	183	243	301	110	217	319	412	491
B	-29	-58	-87	-116	-145	-2	-2	0.09	3	9	2	12	30	62	117
C	-41	-83	-125	-167	-209	-14	-29	-45	-62	-79	-28	-58	-90	-127	-167
D	-21	-41	-60	-79	-99	-17	-34	-52	-70	-88	-33	-66	-102	-139	-180
E	129	225	303	363	408	-22	-43	-63	-83	-103	-37	-73	-106	-139	-174
F						-7	-15	-23	-32	-40	-15	-32	-50	-69	-87
G						-7	-15	-23	-32	-40	-15	-32	-50	-69	-87
H						-22	-43	-63	-83	-103	-38	-73	-106	-139	-174
I						-17	-34	-52	-70	-88	-32	-66	-102	-139	-180
J						-14	-29	-45	-62	-79	-28	-58	-90	-127	-167
K						-2	-2	0.09	3	9	2	12	30	62	117
L						62	124	183	243	301	110	217	319	412	491

* Allowable load level was based on 2x4 No. 2 Southern Pine and an l_e/d of 16.

Vita

Catherine Richardson Underwood was born in Radford, Virginia, on April 23, 1976. She is the daughter of Mr. Robert L. Richardson and Mrs. Nancy C. Richardson (deceased) both of Giles County, Virginia. She was preceded in birth by her three brothers David, John, and Jim Richardson who were there to help guide her through life's twists and turns. She graduated from Radford High School in June 1994 and obtained a Bachelor of Science degree in Biological Systems Engineering from Virginia Polytechnic Institute and State University in May 1998. During the summer of 1998 she married a young man by the name of Casey Wayne Underwood before going on to pursue a Masters of Science degree from Virginia Polytechnic Institute and State University in Biological Systems Engineering. She is a member of the American Society of Agricultural Engineers, the Forest Products Society, and the honor society Alpha Epsilon.