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Lateral Movement of Unbraced Trusses During Construction

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Abstract. *Factors contributing to lateral buckling potential of trusses during construction are presented along with equations for determining maximum spacing of temporary lateral bracing.*

Keywords. Truss, Truss erection, Temporary truss bracing, Wood engineering, Buckling

Introduction

Wood trusses with spans up to and exceeding 80 feet are frequently utilized by post frame builders and have become a common feature in other types of construction. This increased use of long span trusses can be attributed to a number of factors including:

- Availability of MSR lumber and engineered wood products with relatively high strengths
- Past improvements in metal plate connectors
- Increased number and size of fabrication facilities
- Market demand for buildings with fewer or no interior supports
- Greater confidence in the use of long span trusses because of past performance, and
- Increases use and sophistication of truss design software

Although long span trusses have performed very well in service, improper or nonexistent bracing has resulted in a disproportionately greater number of long span truss collapses during construction. In many cases, this is simply because many builders are not aware of the substantial increased susceptibility of longer trusses to collapse when they are not properly braced.

The Fundamental Problem

The vast majority of agricultural trusses are simply-supported, gable trusses whose top chord is laterally supported by purlins. The spacing of these purlins dictates the slenderness ratio (L_e/d), and hence the lateral buckling potential of the top chord.

As trusses are set, their own dead weight is generally sufficient to buckle the compression chord as shown in figure 1a. To prevent such movement, the temporary lateral bracing (or some of the purlins) must be attached to the truss before it is released from hoisting equipment. Every time the unsupported length of the compression chord is cut in half by the addition of lateral bracing, the force required to buckle the chord increases by a factor of four (figures 1b and 1c).

For lateral bracing to be effective, it must be kept from shifting. This is generally accomplished by attaching the lateral braces to a rigid endwall and/or by installing temporary diagonal bracing as shown in figure 2a.

If lateral bracing is not anchored, the chord compressive forces will work to move the lateral bracing until the 1/2 sine-wave shape shown in figure 2b is obtained. As this occurs, the truss center of mass is shifted off the centerline of its supports, which makes it easier for gravitational forces to overturn/collapse the truss (figure 3). The collapse potential is much greater for longer span trusses because (1) the shift in center of truss mass increases at an increasing rate as span increases, and (2) truss weight generally increases with span.

Wind Effects

The potential for truss collapse from improper lateral bracing becomes significantly greater when there is a component of wind helping shift the truss laterally. Without roof sheathing, wind is able to apply a certain amount of lateral pressure to every truss in the roof.

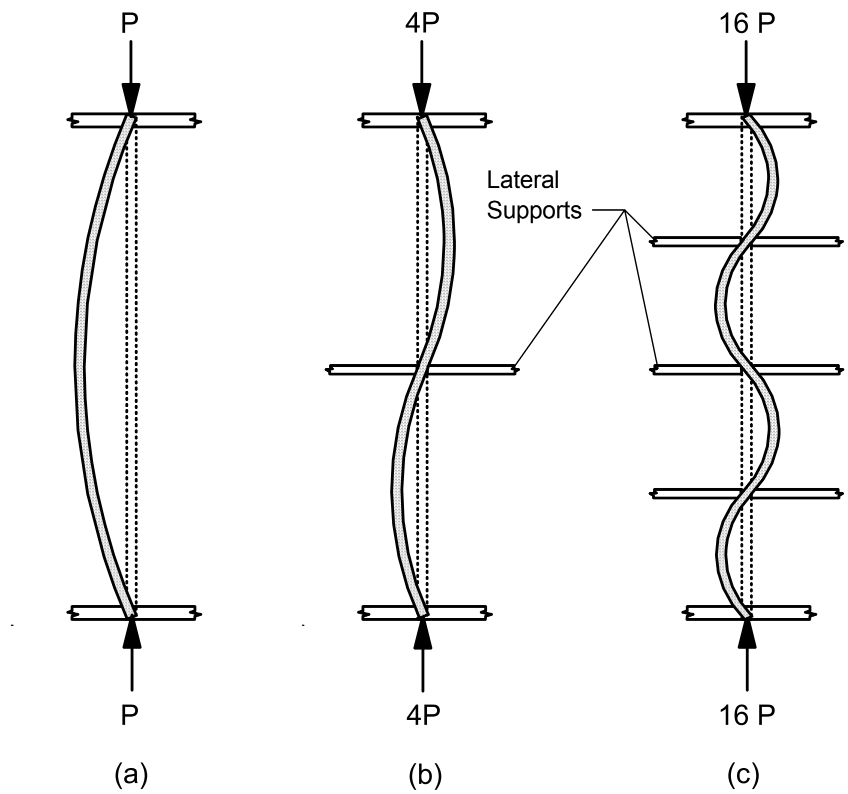

Figure 1. The force required to buckle a pin-ended column quadruples when the effective buckling length is halved.

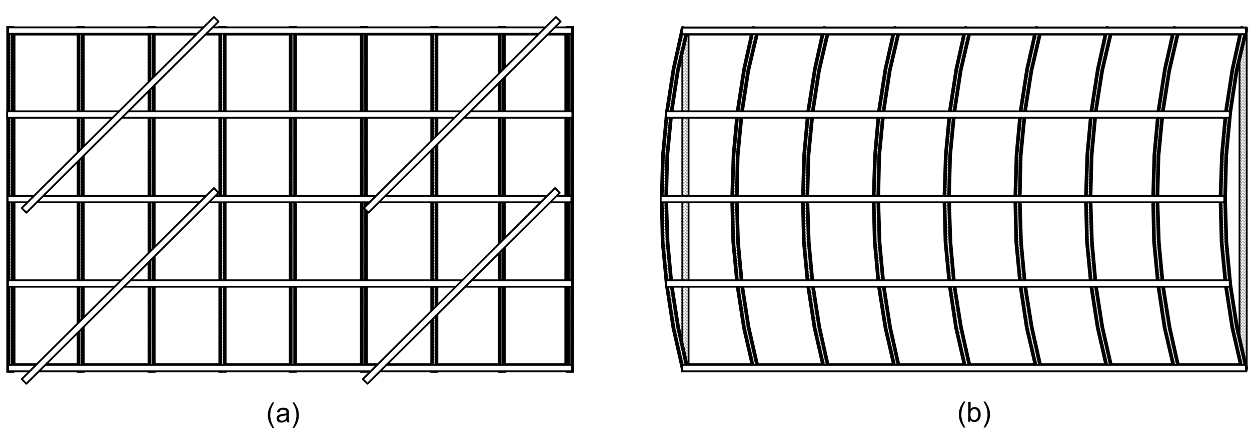

Figure 2. Top view of roof framing showing (a) with, and (b) without diagonal bracing to prevent simultaneous lateral shifting of trusses and lateral bracing.

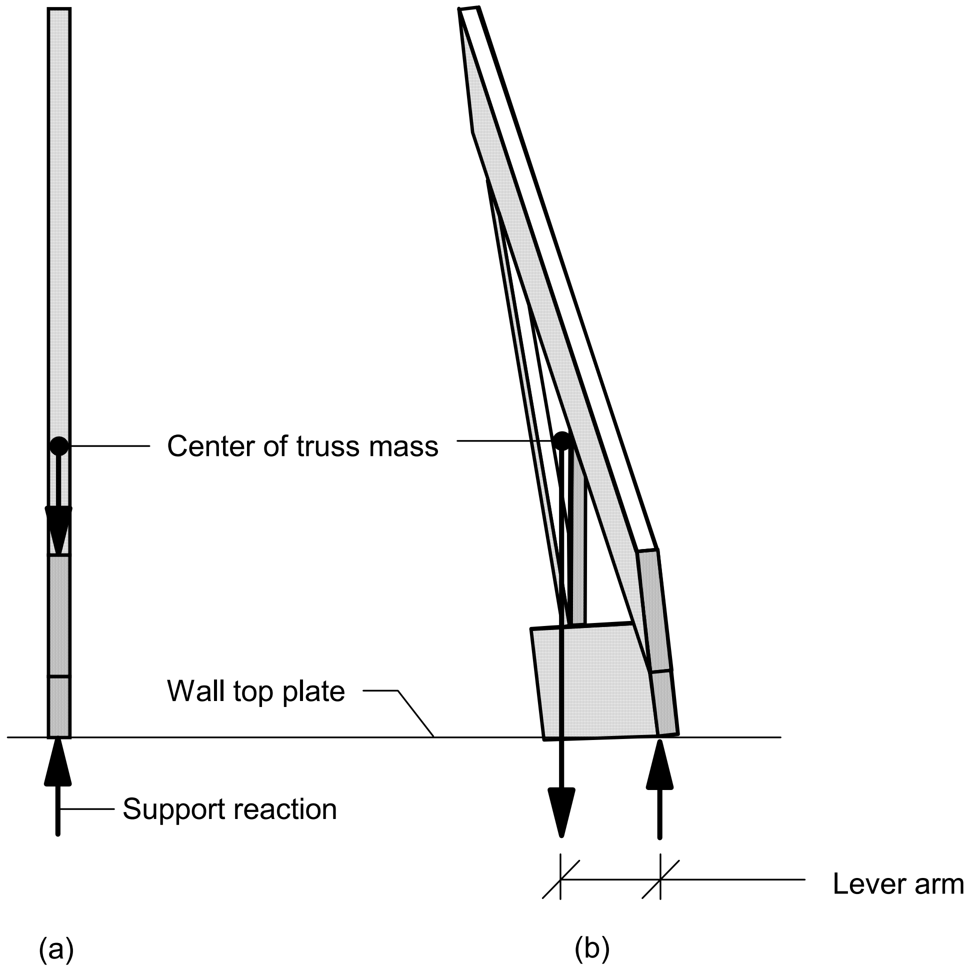

Figure 3. Truss end views (a) before, and (b) after lateral displacement. The shift in center of truss mass makes it easier for gravitational forces to overturn the truss.

The effect of wind forces on trusses can be approximated by direct application of the energy equation for fluid flow, which in one of its many forms basically states that if fluid with a velocity V is completely converted to static pressure, the pressure will equal $\rho \bullet V^2/(2 \bullet g)$ where ρ is the density of the fluid and g is the gravitational constant. If ρ is taken as 0.0766 lbm/ft^3 [the dry air mass density at 59 F (15C) and 29.92 inch Hg (101 kPa)] and g is given as 32.17 ft•lbm/(s^2•lbf), then:

$$\text{Pressure in lbf/ft}^2 = 0.00256 \bullet V^2 \text{ when } V \text{ is given in mph} \tag{1}$$

Theoretically, pressures calculated using equation 1 are only applicable to wind blowing normal to an infinite plane. For other objects, values from equation 1 must be adjusted by drag coefficients to account for friction and drag that results from complex fluid flow around the object. For infinitely long flat plates, this adjustment is on the order of 1.6 (Daugherty and Franzini,1965). Given that dimension lumber orientated with its wide face normal to wind can be modeled as an infinitely long flat plate, the effective pressure acting on truss members from winds blowing normal to the truss can be approximated as:

Pressure, lbf/ft^2 = 0.00435 V^2 when V is given in mph (2)

Or

Force, lbf = 0.00435 $V^2 A$ when V is given in mph and A is in ft^2 (3)

The surface areas of different sized, symmetric, gable trusses were approximated, and equation 3 then used to calculate the total force applied to them by 20, 40, 60 and 80 mph winds. These estimates, which are compiled in Table 1, are only applicable to trusses directly exposed to the wind. Forces on trusses that are shaded from the wind by other trusses or objects are likely to be considerably lower.

Table 1. Total Wind Force Applied to an Exposed Gable Truss

Truss length, feet	Nominal width of top and bottom chords, inches	Roof slope	Surface area, ft^2	Total force on truss in lbf for wind speed in mph of			
				20	40	60	80
20	4	3:12	14	24	96	215	383
		6:12	16	27	109	245	435
	6	3:12	20	34	137	309	550
		6:12	22	38	151	339	602
40	6	3:12	43	74	296	666	1184
		6:12	48	83	334	750	1334
	8	3:12	55	95	380	854	1518
		6:12	61	106	424	954	1696
	10	3:12	69	119	477	1073	1908
		6:12	75	130	521	1173	2086
60	8	3:12	86	149	597	1344	2390
		6:12	111	194	775	1745	3102
	10	3:12	107	186	744	1673	2974
		6:12	132	230	922	2074	3686
	12	3:12	127	221	883	1986	3531
		6:12	153	267	1068	2403	4271
80	10	3:12	153	266	1064	2393	4255
		6:12	206	358	1433	3225	5734
	12	3:12	179	311	1245	2801	4979
		6:12	234	407	1628	3664	6513

More important than the actual lateral force on a truss, is the amount of lateral movement of the center of the truss (relative to its ends) resulting from the lateral force. As previously show (figure 3), it is this movement that enables gravitational forces to work to overturn a truss.

When a uniform pressure is applied to a rectangular, simply-supported beam, the midspan deflection is given as:

$$\Delta = \frac{(Pressure)\, L^4}{6.4\, E\, d^3} \tag{4}$$

Where: L is the support spacing, E is modulus of elasticity, and d is beam depth. Since wind

pressure is a function of the square of the wind speed, a doubling of the wind speed will quadruple deflection. More importantly, when span length L is doubled, deflections increase by 1600%.

If pressure is calculated according to equation 2, and values of 1.5 inches and 1.9 million lbf/in^2 are substituted for d and E, respectively, the deflections compiled in Table 2 are obtained. These deflections represent lateral truss movement due to wind, when the only resistance to truss movement is lateral and vertical displacement of the truss at each end support. It is important to note that many of the deflections in Table 2 would not be geometrically obtainable, as the beam would be drawn off its supports well before the deflections are reached. To call attention to this, deflections in Table 2 that exceed $L/15$ have been lightly shaded, and those that exceed half the span length ($L/2$) have been darkly shaded.

Table 2. Deflections of a Simply Supported Beam Under Uniform Wind Pressure* (modulus of elasticity = 1.9 million lbf/in^2, depth = 1.5 inches)

Support spacing, feet	Midspan deflection, inches, due to wind with a velocity in mph of							
	5	10	15	20	30	40	60	80
10	0.00	0.02	0.03	0.06	0.14	0.24	0.55	0.98
12	0.01	0.03	0.07	0.13	0.28	0.51	1.1	2.0
16	0.03	0.10	0.23	0.40	0.90	1.6	3.6	6.4
20	0.06	0.24	0.55	0.98	2.2	3.9	8.8	16
24	0.13	0.51	1.1	2.0	4.6	8.1	18	32
30	0.31	1.2	2.8	4.9	11	21	45	79
40	0.98	3.9	8.8	16	35	63	140	250
60	4.9	20	44	79	180	320	710	1270
80	16	62	140	250	560	1000	2250	4001

* Shaded deflections exceed $L/15$ values. Heavily shaded values exceed $L/2$.

The deflections in Table 2 are only representative of situations where wind is blowing on a single truss. With several equally spaced trusses, the average wind pressure on each truss (and hence lateral truss deflection) will be less than that associated with a single truss. The relationship between this average pressure and the number of trusses is likely to be a complex function of truss geometry, chord size, truss spacing and wind direction. A very conservative approach would be to assume that only one truss in the entire roof is subjected to lateral wind pressure. Under this assumption, lateral deflection of the roof could be obtained by dividing the numbers in Table 2, by the number of trusses in the roof.

Although Table 2 implies that there is uniform lateral movement of the top and bottom chords as wind is applied to the side of a truss, this is unlikely. Bending forces will accentuate lateral displacements of compressive chords, and decrease that for tension chords (figure 3b). Also, as truss span increases, truss height increases, and the center of mass of the truss moves up. This makes it easier to move the top of the truss laterally.

Finally, because long, wide buildings take longer to construct, there is a greater probability of high-speed winds striking before the roof is sheathed, thereby increasing the probability of a wind related failure.

Diagonal Bracing

To prevent a simultaneous lateral shift of roof framing, one or more trusses and/or the lateral bracing connecting the trusses, must be kept from shifting. Often times endwalls and/or endwall columns are relied upon to keep the roof framing from shifting during construction. Unfortunately, endwalls and endwall columns are seldom rigid enough for the task. For example, the top of a newly-installed, nominal 6- by 6-inch, 10-foot high, earth-embedded, endwall column can generally be displaced one full inch with less than 100 pounds of force. Light wood-frame stud walls are even more flexible.

In the end, the only positive way to prevent movements during construction is to rely on diagonal bracing. Diagonal bracing is not only important to keep side- and end-walls from racking, but is really the only effective way to keep lateral truss braces, and hence trusses, from shifting laterally (figure 2).

HIB-98 Temporary Lateral Bracing Requirements

HIB-98 (TPI, 1998) contains maximum recommended spacings for temporary lateral bracing. These recommended spacings were developed by Mr. Patrick McGuire of the Borkholder Corporation, Nappanee, Indiana (McGuire, 2001). The HIB-98 spacings were developed for an assumed load of the truss weight, plus two workers and their equipment at a given time assumed to weigh 250 lbf, each. Footnotes in HIB-98 state that the bracing schedules do not provide for wind loads or for accidental overload, materials stacked on trusses during erection, or loads due to misuse or negligence.

In developing the HIB-98 spacings, McGuire took construction tolerances into account. Specifically, he assumed an overall bow in the chord equal to $L/200$, where L is the spacing between lateral supports. The $L/200$ bow is the maximum allowed by ANSI/TPI 1-1995 (TPI, 1995).

Spacing Calculations for Temporary Lateral Braces

In situations where the recommended spacings in HIB-98 may not apply, the following two equations can be used to calculate the maximum spacing of temporary diagonal bracing for a truss chord in compression.

For cases where there is no bow in the chord ($e = 0$):

$$L = \left[\frac{0.41\, b^2 A E}{P}\right]^{1/2} \tag{5}$$

For cases where there is bow in the chord ($e > 0$):

$$L = \left[\frac{b^2 A E}{6P}\right]^{1/2} \bullet \cos^{-1}\left[\frac{12\, e}{b\,(S A/P - 2)}\right] \tag{6}$$

Where:

L = maximum spacing between lateral supports

b = truss chord thickness (generally 1.5 inches)

A = truss chord cross-sectional area

E = truss chord modulus of elasticity

P = axial compressive force in truss chord due to truss dead weight and weight of workers

e = bow in unloaded chord

S = proportional limit stress for bending about the truss chord weak axis

Equation 5 is the Euler buckling equation and equation 6 is obtained from the secant formula for eccentrically loaded columns. A factor of safety of 2.0 has been incorporated into each equation. Equation 6 becomes equation 5 when e is set equal to zero. Note: if the inverse cosine function in equation 6 returns a value in degrees, it must be converted to radians by multiplying by $\pi/180$.

Equation 2 requires a value for the proportional limit stress for bending about the truss chord weak axis. Using the allowable stress design (ASD) maximum allowable bending stress for weak axis bending, F_{b2}' (AF&PA, 1997) is not recommended as it would be very conservative. This because resistance and load side safety factors are included in the ASD value, and neither should be included in S since a safety factor has already been applied to the axial load. A value closer to the proportional limit stress for bending about the weak axis would be provided by using the load and resistance factor (LRFD) adjusted bending strength, F_b', for weak axis bending (AF&PA, 1996).

If e is set equal to a function of L (e.g., $e = L/200$ = maximum bow allowed during installation by ANSI/TPI 1-1995), then equation 6 requires an iterative solution.

Truss Chord Axial Force, P

For simple-supported, triangular-shaped trusses, the maximum axial force, P, is located at the truss heel and can be calculated from the truss reaction, R, as:

$$P = \frac{R}{\sin\theta_t - \dfrac{\sin\theta_t \cos\theta_t}{\cos\theta_t}} \tag{7}$$

Where:

P = maximum compressive force in top chord of a simple-supported, symmetrical gable truss.

R = vertical truss reaction

θ_b = slope of bottom chord

θ_t = slope of top chord

The worst loading situation during construction occurs when the entire live load is concentrated near one of the truss supports. In equation form:

$$R = D + W \tag{8}$$

Where:

D = truss dead load tributary to support

W = construction live load

As previously noted, W was assigned a value of 500 lbf when developing the HIB-98 recommended lateral brace spacings.

Truss Dead Load

Included in the output from many truss design programs will be an estimate of the truss's weight. It is not known how these weights are determined. It is quite likely that there is variation from program to program.

To calculate truss weight in the absence of truss design software, most people begin with the species-dependent, wood specific gravity values compiled in the National Design Specifications (NDS) for Wood Construction (AF&PA, 1997) and in the LRFD Manual for Engineered Wood Construction (AF&PA, 1996). These AF&PA values are based on weight and volume when oven-dried. For more accurate weight estimates, use specific gravity values based on oven-dried weight and volume at the in-situ moisture content. The latter can be obtained from the former using the following, empirically derived conversion.

$$G_M = \frac{G}{1 + 0.256\, G\, (1 - a)} \tag{9}$$

Where:

G_M = specific gravity based on oven-dried weight and volume at moisture content M

G = specific gravity based on weight and volume when oven-dried

a = $(30 - M)/30$

M = moisture content of lumber, % dry basis

Table 3 contains G values for domestic softwood species as tabulated by AP&FA. The G_{12} values (G_M at M = 12%) in Table 3 were calculated from the G values using equation 5.

The Wood Handbook (Forest Products Laboratory, 1999) contains equations for estimating wood modulus of elasticity from specific gravity values. Rearranging these equations to obtain specific gravity as the dependent variable yields:

For softwoods:

$$G_{12} = (E\,/\,2973500)^{1.19} \tag{10}$$

For hardwoods:

$$G_{12} = (E\,/\,2393300)^{1.43} \tag{11}$$

Where:

G_{12} = specific gravity based on oven-dried weight and volume at 12% moisture content

E = modulus of elasticity in lbf/in^2

The preceding equations were used to calculate the values in Table 4. In cases were lumber with a relatively high MOE is used in a truss, the values in Table 4 may be more realistic then the average species value from Table 3. A good compromise in such situations may be to average the two values.

Table 3 - Specific Gravity Values For Domestic Softwoods

Species Combination	G	G_{12}
Coast Sitka Spruce	0.39	0.375
Douglas Fir-Larch	0.50	0.475
Douglas Fir-Larch (North)	0.49	0.47
Douglas Fir-South	0.46	0.44
Eastern Hemlock	0.41	0.39
Eastern Hemlock-Balsam Fir	0.36	0.35
Eastern Hemlock-Tamarack	0.41	0.39
Eastern Hemlock-Tamarack (North)	0.47	0.45
Eastern Softwoods	0.36	0.35
Eastern Spruce	0.41	0.39
Eastern White Pine	0.36	0.35
Hem-Fir	0.43	0.41
Hem-Fir(North)	0.46	0.44
Mixed Southern Pine	0.51	0.48
Mountain Hemlock	0.47	0.45
Northern Pine	0.42	0.40
Northern White Cedar	0.31	0.30
Ponderosa Pine	0.43	0.41
Red Pine	0.44	0.42
Redwood, close grain	0.44	0.42
Redwood, open grain	0.37	0.36
Sitka Spruce	0.43	0.41
Southern Pine	0.55	0.52
Spruce-Pine-Fir	0.42	0.40
Spruce-Pine-Fir (E of 2.0 million psi and higher grades of MSR & MEL)	0.50	0.475
Spruce-Pine-Fir (South)	0.36	0.35
Western Cedars	0.36	0.35
Western Cedars (North)	0.35	0.34
Western Hemlock	0.47	0.45
Western Hemlock (North)	0.46	0.44
Western White Pine	0.40	0.38
Western Woods	0.36	0.35

Table 4 – Specific gravity values as a function of wood modulus of elasticity

Modulus of elasticity, million lbf/in^2	G_{12}	
	Softwoods	Hardwoods
1.0	0.27	0.29
1.1	0.31	0.33
1.2	0.34	0.37
1.3	0.37	0.42
1.4	0.41	0.46
1.5	0.44	0.51
1.6	0.48	0.56
1.7	0.51	0.61
1.8	0.55	0.67
1.9	0.59	0.72
2.0	0.62	0.77
2.1	0.66	0.83

Multiplying the G_{12} value by density of water and by the actual volume of a piece of lumber whose moisture content is 12% yields the dry weight of the piece of lumber. To get the actual moist weight of the piece, its dry weight must be multiplied by 1.12 (i.e., increased by its moisture content of 12%). Although rather straightforward, the conversion from dry to moist weight is often overlooked by individuals not familiar with the different ways wood specific gravity values are tabulated.

The weight of the top and bottom chords for a typical gable truss can be quickly approximated from overall truss span and chord slopes. Considerably more time is required to determine the weight of all web members, web lateral bracing and metal connector plates. To diminish the time spent doing this, relationships between component weights and key truss characteristics can be developed. For example, the plot in figure 4 can be used to approximate the weight of all web members and associated lateral bracing for symmetrical gable trusses (regular heel configuration) with roof slopes between 3:12 and 6:12.

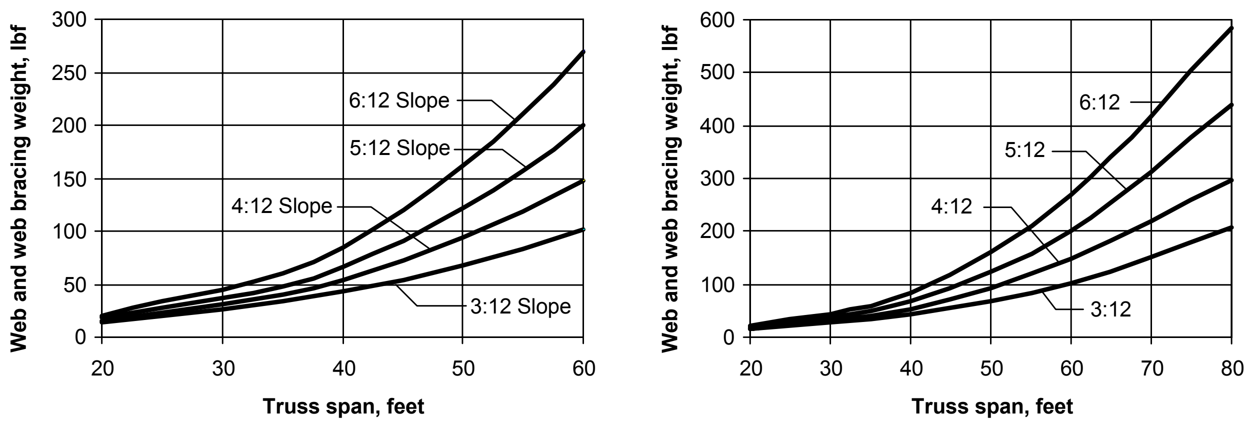

Figure 4. Weight of all webs and web bracing in a symmetrical gable truss as a function of truss span and roof slope.

Example Spacing Calculation

What is the maximum spacing of temporary lateral supports for a symmetrical gable truss with an 80-foot span and top chord slope of 4:12? Top chords are nominal 2- by 12-inch Dense Sel Str Southern Pine. The bottom chords are nominal 2- by 12-inch 1950F-1.7E Southern Pine. Determine spacings for cases where compression chords are installed with bows of 0, L/200, L/100, and L/50.

Step1: Specific gravity of lumber

Southern Pine has a G_{12} value of 0.52 (Table 3). Dense Sel Str Southern Yellow Pine has a MOE 1.9 million lbf/in^2. Table 4 lists a G_{12} value of 0.59 for softwood with this MOE, and a value of 0.51 for softwood with an MOE for the 1.7 million lbf/in^2. Averaging the values from Tables 3 and 4 yields G_{12} values of 0.555 for the top chords and 0.515 for the bottom chord.

Step 2: Truss dead weight

Wt. of top chord = 0.555(62.4 lbf/ft^3)(1.5 in.)(11.25 in.)(80 ft)(1.12)(ft^2/144 in^2)/cos(18.4)

= 383 lbf

Wt. of bottom chord = 0.515(62.4 lbf/ft^3)(1.5 in.)(11.25 in.)(80 ft)(1.12)(ft^2/144 in^2)

= 337 lbf

Wt. of web and web bracing from figure 4 = 148 lbf

Wt of metal plate connectors (assumed) = 50 lbf

Total truss dead weight = 383 + 337 + 148 + 50 = 918 lbf

Step 3: Maximum chord axial force

$P = R/\sin\theta$ = (500 lbf + 918 lbf / 2)/sin(18.4) = 3040 lbf

Step 4: Lateral brace spacing

Using equation 5 when e = 0 yields:

$$L = \sqrt{\frac{0.41\, b^2 A\, E}{P}} = \sqrt{\frac{0.41\left(1.5\, in.\right)^2\left(16.875\, in^2\right)\left(1900000\, lbf / in^2\right)}{3040\, lbf}} = 98.6\, in.$$

Equation 6 is used when e (chord bow) is non-zero, and requires an estimate of the proportional limit stress for bending about the truss chord weak axis. As previously noted, the LRFD adjusted bending strength, F_b', for weak axis bending (AF&PA, 1996) can be used for this purpose. For nominal 2- by 12-inch Dense Sel Str Southern Pine F_b' is equal to the product of the reference bending strength F_b (5210 lbf/in^2) and the flat use factor C_{fu} (1.20), or 6250 lbf/in^2.

For the case of L/200, equation 6 appears as:

$$L = \sqrt{\frac{\left(1.5\, in.\right)^2\left(16.9\, in.^2\right)\left(1900\, ksi\right)}{6\left(3.040\, kips\right)}} \cdot \cos^{-1}\left[\frac{12\left(L/200\right)}{\left(1.5\, in\right)\left((6250\ psi)(16.9\, in.^2)/(3040\, lbf)\ -\ 2\right)}\right]$$

Solving by iteration yields:

L = 91.7 in. for $e = L/200$ = 0.45 in.

Likewise use of equation 2 provided:

L = 85.5 in. for $e = L/100$ = 0.85 in.

L = 75.1 in. for $e = L/50$ = 1.5 in.

Limits Imposed by Design Specifications

Wood design specifications limit the slenderness ratio for solid columns to 75 during construction. Since the effective length of truss chords is equal to the distance between lateral supports (figure 1), this design requirement limits spacing between temporary lateral braces for nominally 2-inch thick compression chords to 75 x 1.5 inches or 112.5 inches. Realizing that design specifications must conservatively account for all situations – including measurable chord bow – an increase in the slenderness ratio (e.g., to 80) would appear justified when chord bow is accounted for in structural calculations.

Summary

Trusses require careful lateral bracing during construction to prevent lateral buckling of the compression chord(s) due to the combination of axial forces induced by the truss's own dead weight, and bending forces resulting from wind forces.

The probability of failure from compression chord buckling increases as truss span increases. This is due to a combination of the following interacting factors.

1. Chord axial forces due to truss dead weight increase with span.
2. Longer span trusses exhibit greater out-of-plane movement. Note: deflection of a simply supported beam subjected to a uniform load is directly proportional to the fourth power of the span when cross-sectional area remains constant with length.
3. Longer span trusses have larger chords and generally larger and longer webs. This translates into increased surface area and weight per foot of span. The greater the surface area, the greater the wind force that acts to laterally bow the truss out-of-plane.
4. The more weight per unit length, the greater the gravitational force that works to overturn/collapse the truss as it bows out-of-plane.
5. Longer trusses tend to be taller. Not only may this subject the top of the truss to higher wind forces, but for trusses only fixed from out-of-plane movement at their bases (i.e., heels), the overturning moment about the base is increased.
6. Longer trusses are more apt to be used in buildings that take more time to erect. Consequently, there is a greater probability of high-speed winds striking before the roof is sheathed.

Lateral buckling is prevented by ensuring that spacing of temporary lateral bracing is not too great, and that this lateral bracing is not allowed to shift. Shifting of lateral bracing is best prevented with the use of diagonal bracing.

Equations for calculating the maximum spacing of lateral bracing were presented along with an example analysis.

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