T-brace design for MPC wood truss webs

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Abstract

T-bracing is a prescriptive construction practice to reinforce compression web members of metal-plate-connected wood trusses. However, a rational analysis and design method for T-braced web members has not been published. Reinforcement of the truss web with a brace increases the effective stiffness of the composite section, and results in an increased axial load capacity of the web. Based on laboratory tests, the increase in stiffness of a T-braced 2 by 4 web member was documented and a design method for T-braced truss webs was proposed.

Prefabricated metal-plate-connected (MPC) wood trusses are widely used in residential and low-rise commercial buildings. Their popularity is partly due to their ease of construction and cost effectiveness. The trusses come in various shapes and sizes, and often include long, slender compression web members. When a compression web member exceeds the allowable stress for a specific grade and size of the member, lateral bracing is introduced to reduce the effective buckling length of the web. It is commonly accomplished by bracing the webs of a series of adjacent trusses with continuous lateral bracing (CLB) at the center of the webs (or 1/3 points) or reinforcing the web with an additional member. When a web is reinforced by attaching a side member to form a T-shape, it is called T-bracing, as shown in **Figure 1**. The additional member increases the stiffness of the composite web, and increases the buckling capacity.

T-braces have been in use for several decades with satisfactory field performance; however, a rational design procedure for T-braced webs has not been established. The objectives of this research were to:

1. Evaluate the increase in the stiffness of a member with T-bracing;
2. Propose a simple design procedure for T-braced truss webs;
3. Validate the proposed design procedure to the extent possible using laboratory test data on unbraced and braced webs.

Background

The analysis and design of MPC wood trusses are primarily based on the proprietary software of a truss-plate company. The software incorporates the design requirements of ANSI/TPI 1-1995 (TPI 1995) and the National Design Specification for Wood Construction (NDS) (AF&PA 1997a). Although there are other programs (e.g. Cramer et al. 1993, Foschi 1977) for the analysis of MPC wood trusses, the truss industry widely uses the Purdue Plane Structures Analyzer (PPSA) program (Suddarth and Wolfe 1984). The analysis is based on the static analysis of individual trusses with varying degrees of complexity at the joints. The truss designer selects the members and the connector plates based on the results of the analysis. The truss designer also specifies the discrete locations of the lateral bracing if necessary. A building designer is responsible for the overall installation of the trusses and the structural integrity of the assembly.

In lieu of the CLB at discrete locations as specified in the truss design, the field engineer may choose to reinforce the member in different ways. A prescriptive field practice uses a T-brace instead of CLB attached to a series of webs. It generally consists of nominal 2 by 4 dimension lumber symmetrically nailed on the narrow face of the web to form a T-shaped member. Similar to

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T-braces, L-braces and I-braces are also occasionally used. Mitek Industries has recently introduced a patented steel section as an alternative to the wood T-brace. The steel section is mounted as a crown on the edge (narrow face) of the web member during fabrication of the truss.

Discrete lateral bracing has traditionally been used to improve the axial load capacity of compression members. Different models are used to analyze and design the discrete lateral braces (Plaut and Yang 1993, Yura 1996, Miles et al. 2000). Leichti et al. (2002) used finite element modeling to evaluate the performance of T-braced columns and used full-scale compression test results to validate the model. Glued and nailed assemblies with varying web and brace length were investigated. They quantified the effects of brace length and attachment method on the effectiveness of the T-brace.

Column design equation

In the United States, wood structures design is governed by locally adopted building codes that rely on the provisions of the NDS (AF&PA 1997a). The NDS design of a wood column is based on the nonlinear interaction between its crushing strength and its buckling strength. The effect of slenderness (buckling) is accounted for by the column stability factor C_p.

$$C_p = \frac{1+(F_{cE}/F_c{}^*)}{2c} - \sqrt{\left[\frac{1+(F_{cE}/F_c{}^*)}{2c}\right]^2 - \frac{F_{cE}/F_c{}^*}{c}} \qquad [1]$$

where $F_c{}^*$ = compression design value adjusted by all applicable modification factors except C_p; $F_{cE} = \frac{K_{cE}E'}{(L_e/d)^2}$; K_{cE} = 0.510 – 0.839(COV_E), 0.3 for visually graded lumber, 0.384 for machine-evaluated lumber, 0.418 for products with $COV_E \leq 0.11$; $c = 0.8$ for sawn lumber and 0.9 for glued-laminated timber: COV_E = coefficient of variation of modulus of elasticity; E' = allowable design value of modulus of elasticity adjusted by all applicable modification factors; L_e = effective buckling length; d = least dimension of a rectangular section that permits buckling (1.5 in. for a 2 by 4 truss web).

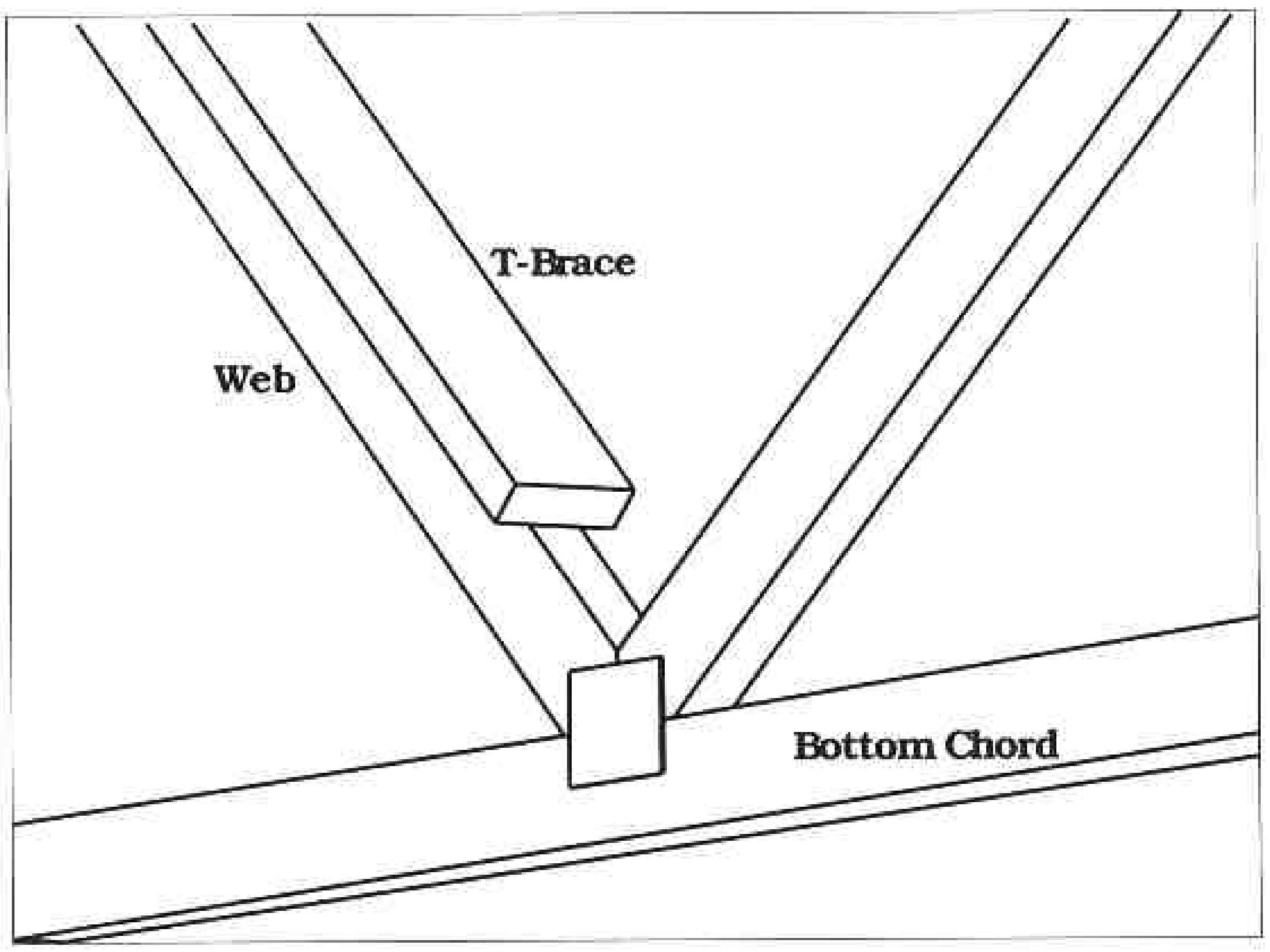

Figure 1. — Sketch of T-braced compression web of wood truss.

The equation for the column stability factor was adopted from Ylinen's (1956) model for dimension lumber. The model has been extensively investigated to establish the different values of the parameter c for engineered wood products (Rammer and Zahn 1997, Zahn and Rammer 1995, Zahn 1991).

Truss web design with a T-brace

The addition of a T-brace on the web increases the stiffness of the web. Hence, for the design of a T-braced web, Equation [1] must be modified to include the stiffening effect of the T-brace on the web (enhanced E') and the slenderness ratio must be adjusted to account for a non-rectangular T-section. We propose the following design equation for (dry in-service) truss webs:

$$f_c < F'_c \qquad [2]$$

or

$$P/A_W < F_c\, C_p\, C_D \qquad [3]$$

where P = compressive design load in the web; A_W = cross-sectional area of the web (not including the brace); F_c = tabulated allowable compressive stress parallel to the grain; C_D = load duration factor; C_p = column stability factor based on the enhanced E of a T-section discussed in the next section of this paper.

The proposed design procedure is limited to 2 by 4 webs braced by a single 2 by 4 centered on the truss web. For general column design, L_e/d must be less than 50 for a rectangular section (AF&PA 1997a), where L_e is the effective column buckling length and d is the corresponding depth of the section. For a non-rectangular section, $L_e/d < 50$ is equivalent to $L_e/r < 173$ where r is the radius of gyration. The effective column length L_e is given by:

$$L_e = K_e\, L_W \qquad [4]$$

where K_e accounts for the boundary conditions of the web ends (such as pinned or fixed); L_W is the actual length of the truss web.

For the case of truss webs without T-braces, it is a common design practice to use K_e equal to 0.8 (Grant et al. 1986). We feel that using 0.8 in Equation [4] for T-braced webs in conjunction with the proposed design procedure is a reasonable design practice. The stiffening effect of the T-brace on the web is due to the increase in the effective radius of gyration with the addition of the brace. Assuming complete composite action between the web and brace, the assembly will buckle about the axis having the lower L_e/r-value. For a T-braced web composed of two 2 by 4's the "weak axis" of the truss web will produce the lowest L_e/r-value. Assuming complete composite action between the two members, and further assuming that the members do not twist under load, the calculated radius of gyration is equal to 0.777.

Using a K_e factor of 0.8 for a truss web, the maximum length of a T-braced web is given by:

Table 1. — Summary of selected lumber properties.

Test span	Specific gravity[a]				Modulus of elasticity			
	Average	COV	Range		Average	COV	Range	
		(%)	----- (min./max.) -----		(million psi)	(%)	------- (million psi) -------	
5-foot edge	0.451	11.8	0.381	0.581	1.379	19.0	0.911	1.758
6-foot flat	0.483	9.3	0.412	0.560	1.757	16.6	1.299	2.291
8-foot edge	0.474	6.0	0.433	0.552	1.516	18.6	1.051	2.086
9-foot flat	0.470	8.4	0.388	0.536	1.561	20.8	0.849	1.992

[a] The specific gravity (based on ovendry weight and volume) was derived from gross density measurements of full-size specimens conditioned to 12 percent MC using the procedure given in Section 3.13 of the NDS Supplement (AF&PA 1997b).

Table 2. — Comparison of T-braced web stiffness to flatwise (unbraced) web stiffness.

Web test span	Measured stiffness			
	Web member EI_W	Brace member EI_B	T-braced web EI_T	EI_T/EI_W
(ft.)	-------------- (million lb.-in.^{2}) --------------			
6	1.805 (15%)[a]	7.486 (19%)	5.955 (12%)	3.327 (12%)
9	1.602 (21%)	8.493 (17%)	7.936 (13%)	5.124 (19%)

[a] Numbers in parentheses are COVs.

$$\frac{L_e}{r} = \frac{K_e L_W}{r} = \frac{0.8 L_W}{0.777} < 173 \qquad [5]$$

Therefore, L_W must be less than 168 inches (14 ft.) to meet this criterion. In other words, based on the proposed design procedure, 2 by 4 webs longer than 14 feet cannot be braced by a 2 by 4 T-brace due to the NDS slenderness limitation.

In the next sections, laboratory test data on T-braced webs are presented that form the basis for an E enhancement to account for the stiffening effect of the T-brace. Our proposed design procedure is based on the concept that the E of the truss web is effectively increased by the brace, but the web area resisting the axial stress is not increased, thus in Equation [3], A_W is defined as the truss web area only. In proposing the E enhancement in the NDS column design procedure, we anticipate a 2 by 4 brace that covers the truss web except for 6 inches on each end and it is securely nailed to the truss web with 16d box nails (0.135-in. diameter by 3.5-in. long) at 6 inches on-center spacing.

Experimental methods

A local lumber manufacturer donated nominal 2 by 4, 10-foot-long, Utility grade spruce-pine-fir (SPF) lumber for this study. The lumber was conditioned to equilibrium moisture content of approximately 12 percent (dry basis) in a room maintained at 65 percent relative humidity and 72°F. It was then randomly sorted and labeled into four groups of 15 pieces. Groups of lumber were trimmed to 9-foot 6-inch, 8-foot 6-inch, 6-foot 6-inch, and 5-foot 6-inch lengths. Static modulus of elasticity (MOE) was determined by subjecting the specimens to the static bending test protocol of ASTM D 198-99 standard (ASTM 1999). The lumber was subjected to a four-point bending test with the load-span approximately equal to 20 percent of the span. The main members (simulated truss webs) were tested in a flatwise orientation at 9- and 6-feet center-to-center span, while the side members (braces) were tested in an edgewise (joist) orientation at 8- and 5-feet center-to-center span. The specimens were loaded at a constant crosshead speed to induce 0.5-inch mid-span deflection in approximately 3 minutes of loading. The load-deflection data were used to compute the stiffness of the web members in a flatwise position and the brace members in an edgewise position. Specific gravity (based on ovendry weight and volume) was derived from the gross density measurements of full-size specimens conditioned to 12 percent moisture content, using the procedure given in Section 3.13 of the NDS Supplement (AF&PA 1997b).

The measured specific gravity and E data are summarized in **Table 1** for the 60 pieces of lumber used in the experiment. The ranges reported in **Table 1** demonstrate that a wide range of the variable E was included in the subsequent stiffness test of the T-braced webs. A wide range of E data was desired for input to the subsequent multiple linear regression analyses so that in using the results for design, various lumber grades selected by the bracing designer would be represented by the regression equation.

Following the static bending test, the brace members were trimmed to 8- and 5-foot lengths, and were symmetrically attached onto the edge of the 9- and 6-foot web members, respectively, to form T-braced web specimens. The brace members were attached with 16d box nails (0.135-in. diameter by 3.5-in. long) spaced at 6 inches on center with the first nail placed 3 inches from the end of the brace. The T-braced web specimens were tested with the web member mounted in a flatwise position. The load was applied on the web member only, without directly loading the brace member. Two LVDTs were mounted to monitor the mid-span deflections at the edge of the brace member and the web member. Two LVDTs were used to account for any unsymmetrical deflections. The average deflection was used to compute the stiffness of the T-braced web.

Test results and discussion

The objective of the testing program was to determine an effective E when a truss web having length L_W was braced in a specific manner by another 2 by 4 brace having length L_B. Assuming complete composite action between the two members, and further assuming that the members do not twist under load, the effective EI of the composite T-section is

Table 3. — Comparison of the predicted T-braced web efficiency with the measured efficiency.

Web length and ratio of brace-to-web length	Calculated allowable load of web without brace P^a	Calculated allowable load of web with T-brace P^{Ta}	Predicted bracing efficiency P^T/P	Ult. load of web without brace P_U [b]	Ult. load of web with T-brace P^T_U [b]	Measured bracing efficiency P^T_U/P_U
	(lb.)			(lb.)		
L_W = 6-ft. R = 5/6	1,628	5,002	3.07	3,507 (47%) [c]	10,251 (29%)	2.92
L_W = 10-ft. R = 8/9	606	2,828	4.67	1,063 (37%)	4,968 (21%)	4.67

[a] $E_W = E_B$ = 1.6 million psi; F_c = 1,350 psi for Douglas-fir-larch; C_D = 1.15; K_e = 0.8.
[b] P_U and P^T_U are from Leichti et al. (2002).
[c] Numbers in parentheses are COVs.

the sum of the stiffness of the members. In our proposed design procedure, we choose to define an enhanced fictitious E for the web, E'_T, that accounts for the stiffening effect of the T-brace. Hence, we define the T-braced web composite stiffness as follows:

$$E'_T I_W = E_W I_W + E_B I_B \qquad [6]$$

where E'_T = enhanced fictitious E of the truss web with T-brace; E_W = measured E of the test web; I_W = measured I (weak axis) of the test web; E_B = measured E of the brace; I_B = measured I (strong axis) of the brace.

However, Equation [**6**] relates to an idealized condition because the nailing between the two members does not result in complete composite action due to nail slip and the fact that the brace length (L_B) is less than the truss web length (L_W). Data of this type are well suited for multiple linear regression analysis involving the elements of Equation [**6**] plus an additional term to account for the effect of the brace length being less that the web length. Therefore, the following linear model was fit to the test data:

$$E'_T I_W = b_1 E_W I_W + b_2 E_B I_B + b_3 R + \varepsilon \qquad [7]$$

where b_1, b_2, and b_3 = regression parameters estimated from the test data; $R = L_B/L_W$; ε = standard residual error of the regression.

The multiple linear regression analysis resulted in parameter estimates with a coefficient of determination of 0.89. Since we desire a fictitious E for the web that is buckling about the weak axis, the effective E'_T is obtained by dividing the fitted regression equation by the weak

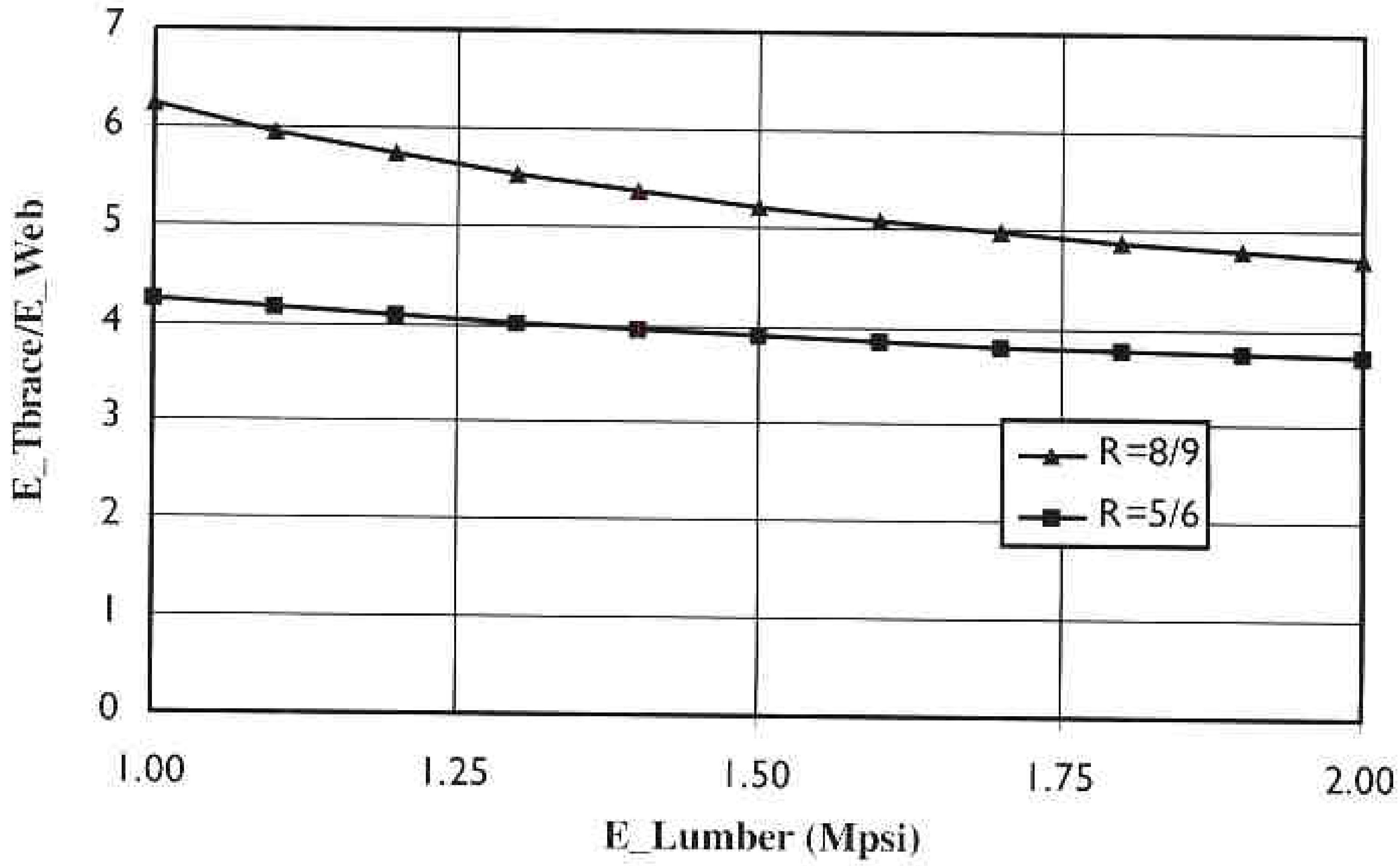

Figure 2. — E enhancement factor for T-brace for 6- and 9-foot webs.

axis I of a 2 by 4 web (0.984 in.^{4}) as follows:

$$E'_T = (1.20\ E_W I_W + 0.363\ E_B I_B + 34.8\ R - 27.9)/0.984 \qquad [8]$$

where the units of E_W and E_B are million psi; the units of I_W and I_B are in.^{4}; when $R > 8/9$, then use $R = 8/9$. The resulting units on E'_T are million psi.

To clarify how Equation [**8**] can be used in T-brace design, an example calculation follows, assuming E_W = 1.4 million psi and E_B = 1.2 million psi, and L_W = 54 inches. Because the brace is assumed to extend within 6 inches of the 54-inch web ends, $R = (54 - 6 - 6)/54 = 0.778$; $E'_T = [(1.2 \times 1.4 \times 0.984) + (0.363 \times 1.2 \times 5.359) + (34.8 \times 0.778) - 27.9]/0.984$; E'_T = 3.21 million psi.

Equation [8] is recommended for predicting E'_T in Equation [7] provided the T-brace design meets the same conditions of the test data: the stress-rated 2 by 4 brace covers the entire web except for 6 inches on each end and the brace is nailed with 16d box nails (0.135-in. diameter by 3.5-in. long) at 6 inches on-center (minimum size and spacing). The R-ratio in Equation [**8**] is conservatively limited to 8/9 since it was the largest value of R used in the regression analysis.

Our test results show that a T-brace enhances the stiffness of a web by a factor of 3.3 to 5.1 (**Table 2**). The stiffness enhancement is higher for longer webs. A plot of the E enhancement factor (E'_T/E_W) versus E_W for a 6- and 9-foot web is shown in **Figure 2**. For this plot, it was assumed that the web and brace members have the same published E-values. **Figure 2** clearly depicts the impact of R: shorter webs having a lower R ratio are stiffened less by the application of the T-brace.

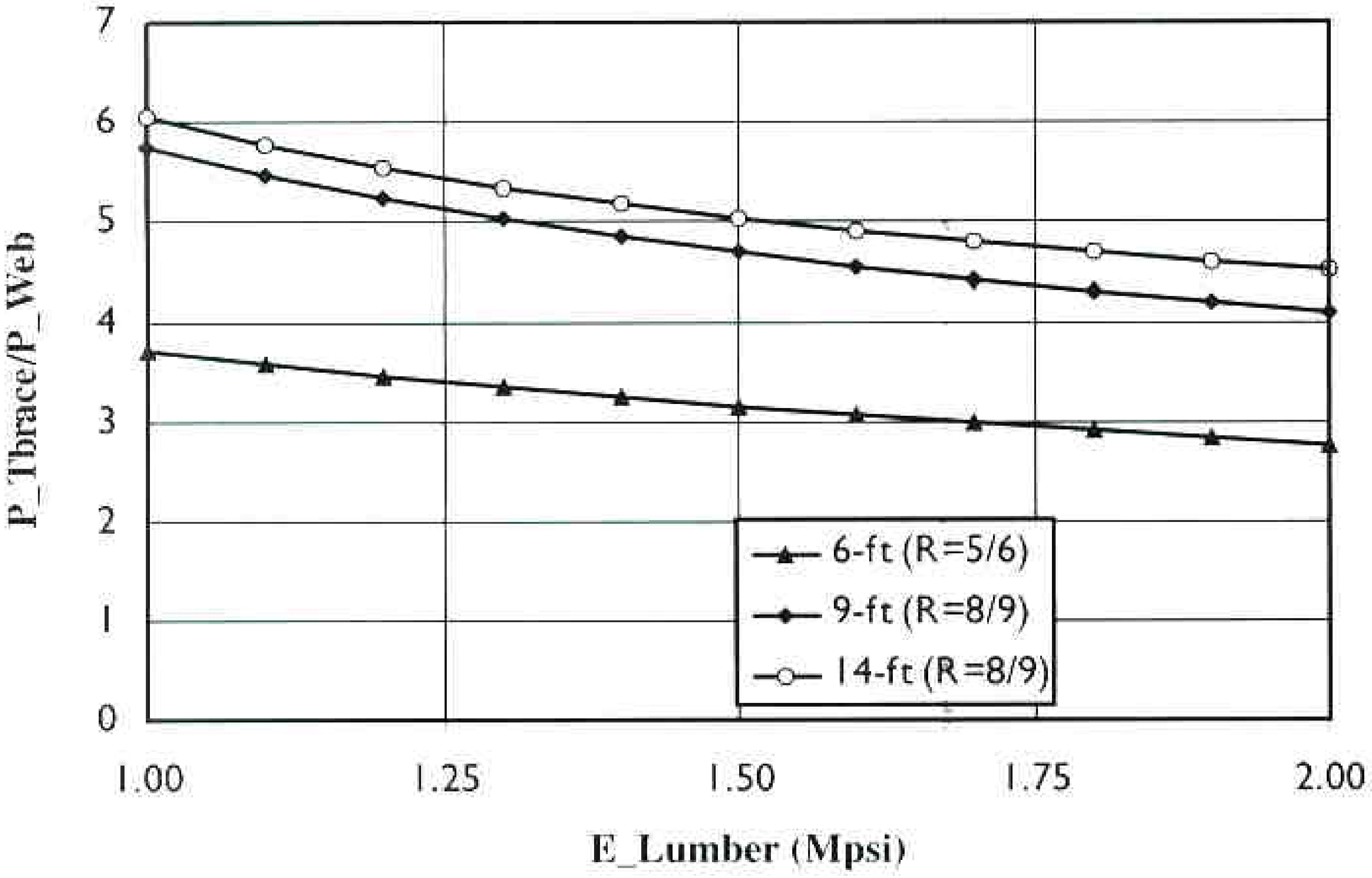

Figure 3. — T-Brace efficiency versus E of the web for 6-, 9-, and 14-foot webs.

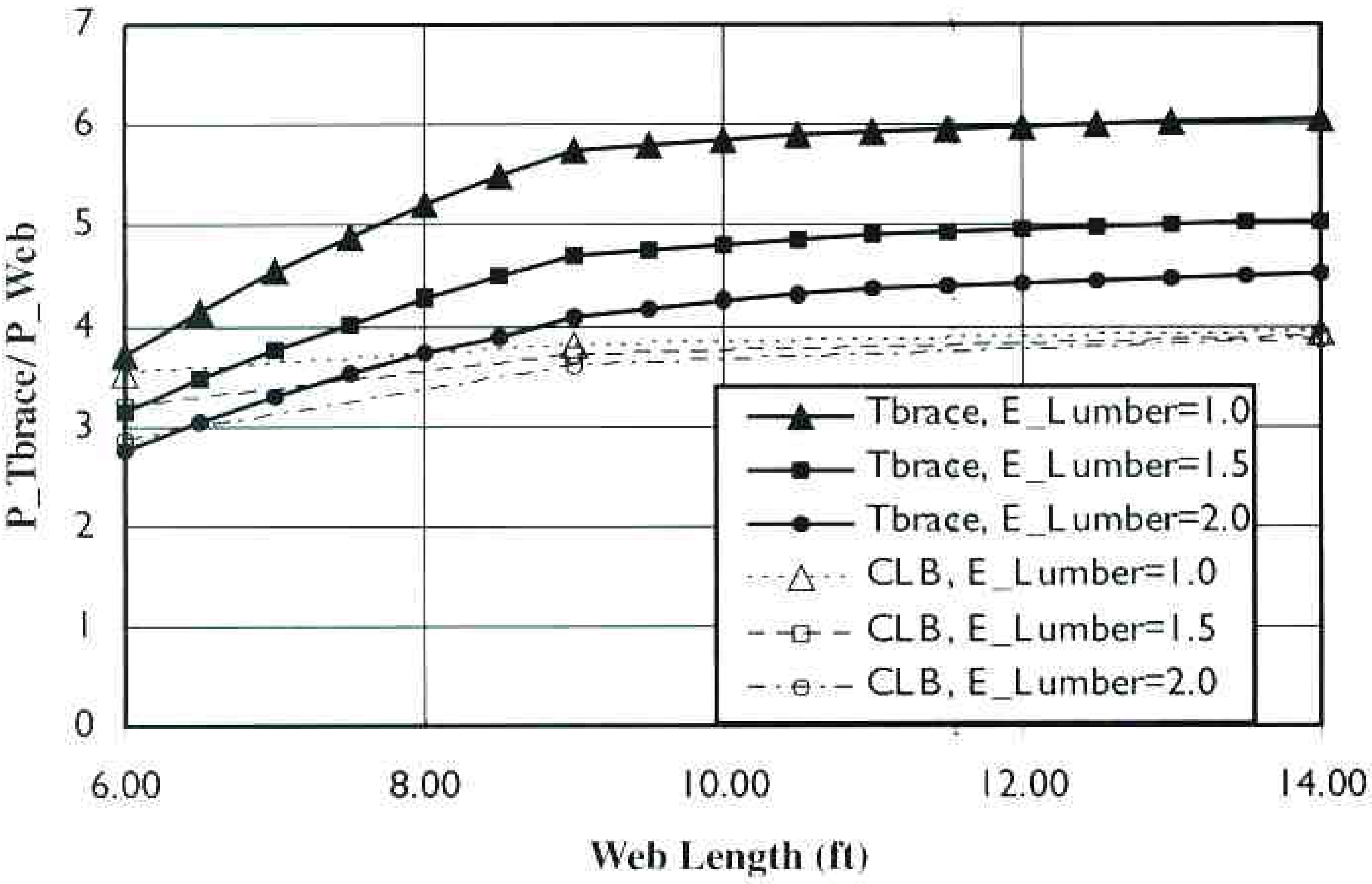

Figure 4. — Brace efficiency versus web length for T-Brace and CLB at midspan.

Once we established the enhanced E of a T-braced web (E'_T), the design capacity of a T-braced web can be evaluated using the NDS column design method using the enhanced E and the modified slenderness limitation. The allowable design loads (P_T) of 6- and 10-foot T-braced webs consisting of Douglas-fir-larch No. 2 2 by 4's were calculated using the proposed method. The corresponding design load (P) of the unbraced web was calculated using the NDS (AF&PA 1997a) guidelines excluding the slenderness limitation of 50. The design load included a load duration factor (C_D) of 1.15, and an end condition factor (K_e) of 0.8. A comparison between the computed T-brace efficiency at design level and the measured ultimate T-brace efficiency (Leichti et al. 2002) is shown in **Table 3**. The T-brace efficiency is defined as the ratio of the axial load design capacity (or ultimate load) of a T-braced web to the corresponding capacity of an unbraced web. The predicted bracing efficiency is in close agreement with the measured bracing efficiency. It should be noted that the experimental ratios from the ultimate load tests are based on sample sizes of 3 and 10 for the unbraced and braced members, respectively (Leichti et al. 2002). A discrepancy in the two ratios may be expected because comparisons are being made at two different points in the distributions. In one case, the ratio being formed is at about the 50th percentile of the distribution, whereas for our design numbers, the comparison is approximately at the first percentile of the strength distribution.

A plot of the bracing efficiency with respect to the lumber E is shown in **Figure 3** for 6-, 9-, and 14-foot-long webs. The brace length to web length ratio R was set to 5/6 for the 6-foot web, and 8/9 for the 9- and 14-foot webs. Hence, we do not observe much difference in the brace efficiency when the length is increased from 9 to 14 feet. **Figure 4** shows a comparison of bracing efficiencies for T-bracing versus one CLB at the midspan of the web, over a range of web lengths. The T-brace results in threefold to sixfold increases in load-carrying capacity of the web compared to threefold to fourfold increases with one CLB. The increase in capacity is higher for longer members with lower assumed E values. Full-scale axial load tests of T-braced webs with different configurations has shown the capacity of webs to increase by a factor of 1.4 to 5.4 depending upon the configuration of the T-brace and the ratio of the brace length to web length (Leichti et al. 2002).

Summary

In this study, we tested 2 sets with 15 replicated T-braced web specimens under flexural load at 6- and 9-foot spans. The specimens consisted of nominal 2 by 4 SPF simulated truss webs braced by a 2 by 4 SPF T-brace using 16d box nails (0.135-in. diameter by 3.5-in. long) at 6 inches on-center. The stiffness of the T-braced web assembly was compared with the original stiffness of the web member. The effectiveness of the T-brace was found to be a function of the lengths of the web and brace, and the stiffnesses of the web and brace members. When the T-braced webs were compared with the flatwise bending stiffness of the corresponding web member, the braced sections were on average 3.3 to 5.1 times stiffer.

Based on our test results, we proposed a multiple linear regression equation to

predict the stiffness of a T-braced web as a function of lumber stiffness and the ratio of brace to web lengths. We use this T-braced web stiffness to define a fictitious enhanced E for the web, which can then be used to calculate the axial design load capacity of the braced web. It should be noted that our regression coefficients to compute enhanced E were based on the test results limited to T-brace assemblies fabricated with 2 by 4 Utility SPF lumber (which varied in E from 0.849 to 2.29 million psi), where the brace was symmetrically attached to the edge of the web with 16d box nails at 6-inch spacing.

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