

Exploratory study of small timber trusses constructed with through-bolt and cross-pipe heel connectors

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Abstract

Throughout the world, there is a need for simple, strong, yet inexpensive connectors that can be used to fabricate trusses from natural small-diameter tree stems as well as squared stems without extensive premachining of the joint area. A connector that might satisfy these requirements is the through-bolt with cross-pipe heel connector. Tests were conducted, accordingly, to determine the load carrying capacity of a variety of trusses constructed with these connectors. The primary purpose of the tests was to obtain first estimates of the peak load carrying capacity of representative trusses constructed with through-bolt and cross-pipe heel joints and to determine the modes of joint failures to be expected. Cross pipes were cut from commercially available 1-1/2-, 2-, and 4-inch diameter schedule 40 and 80 black pipe. Truss members measured a nominal 2 by 4, 4 by 4, or 4 by 6 inches. A number of trusses were also fabricated from round small-diameter tree stems. Load carrying capacities of the trusses ranged from 4,500 to 30,000 pounds. Overall, results of the tests indicate that trusses with useful load carrying capacities can be easily constructed with relatively inexpensive cross-pipe heel joints. Of particular importance, the trusses do not fail catastrophically when the cross pipes begin to yield but continue to carry load. Trusses in which the top chords frame into the bottom chord are able to carry substantially higher loads than are those in which the bottom chord frames into the top chords. Use of close-fitting pipe inserts or wood disk inserts provides a simple and effective way of reinforcing cross pipes.

Throughout many regions of the world, there is a need for simple, strong, yet inexpensive connectors that can be used to fabricate trusses for homes, farm buildings, light industrial buildings, and footbridges, among others. Ideally, such trusses could be fabricated from natural small-diameter tree stems as well as squared stems. The most important characteristic of such a connector is that it be well suited for joining together members of irregular cross section at the heels of a truss without extensive premachining of the joint area.

Previous research has shown that through-bolt with cross-pipe connectors can be used to fabricate high strength timber beam end connections (Eckelman 2004). This work also suggests that these connectors might be used as “keys” in the fabrication of heel joints in light timber trusses (Fig. 1) or in the heel joints of rafter to ceiling-joist connections in a manner somewhat similar to the applications shown by Holtman (1929) and Brown et al. (1952). The load vs. deflection characteristics of a number of such cross pipes investigated in the previous study (Eckelman, 2004), when loaded as force rings, are shown in Figure 2. As can be seen, the cross pipes do not

suddenly “collapse” but continue to carry load even after substantial yielding has occurred.

If it is assumed that the mode of failure of cross pipes used as connectors in the heel of a truss would be crushing under the action of axial rafter forces, the results shown in Figure 2 may be used to obtain first estimates of the load carrying capacity of trusses constructed with these connectors. In the case of a truss with a 30 degree slope, the axial force exerted on a heel cross pipe by a rafter would be equal to the peak load acting on the truss (Fig. 3b). Thus, as a first estimate, it would be expected that a truss with 30 degree slope and cross-pipe

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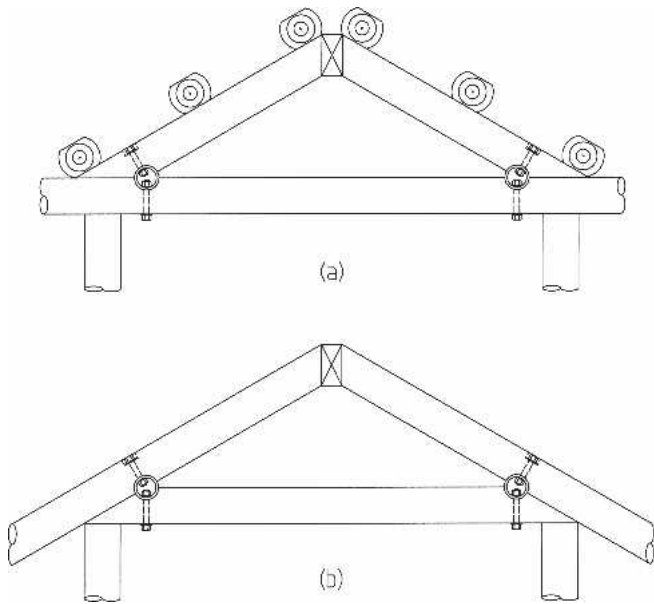


Figure 1. — Illustration showing possible use of cross pipe connectors in the construction of heel joints in light timber trusses.

heel connectors should be able to carry a peak load, F , as great as the cross pipe crushing (yield) loads¹ shown in Figure 2. In terms of equivalent roof loads, a uniform line load, with magnitude $w = F/L$, acting along the entire length, L , of a truss generates an axial rafter force only 62.5 percent as great as that produced by an equivalent peak load (Fig. 3a). Thus, for purposes of analysis, such trusses would be expected to carry a total uniform load, wL , that is 60 percent greater than the maximum peak load.

Assuming a 20-foot length as the upper limit for small-diameter logs (Wolfe and Murphy 2005) used as rafters, then for a 30 degree slope and an overhang of little more than a foot, a half-span of 16 feet appears reasonable—for a total span of 32 feet. Based on the results shown in Figure 2, as a first approximation, a 32-foot truss with 2.375-inch diameter (nominal 2-inch pipe) by 6-inch long schedule 80 cross pipe connectors would be expected to carry a uniform vertical line load of about $(7,750/0.625)/32$, or 388 pound/ft. Thus, for a roof system with a 10-foot truss spacing and a corresponding projected roof area of 320 ft², a 32-foot truss could carry a uniform vertical load of 388/10, or, 38.8 psf. Even with allowances for necessary safety factors, it appears that such trusses could be designed to provide useful levels of strength.

Cost is another consideration. Presently, the cost of 2.375-inch diameter schedule 80 pipe is about \$3.00/ft; cost of 1/2-by 6-inch bolts is about \$0.33 each. Thus, the cost of hardware for a joint would be expected to be about \$1.50 for a 6-inch-long cross pipe, plus \$0.66 for the bolts, plus about \$0.34 for washers and nuts for a total cost of about \$2.50/joint, or about \$0.32/kip of peak load.

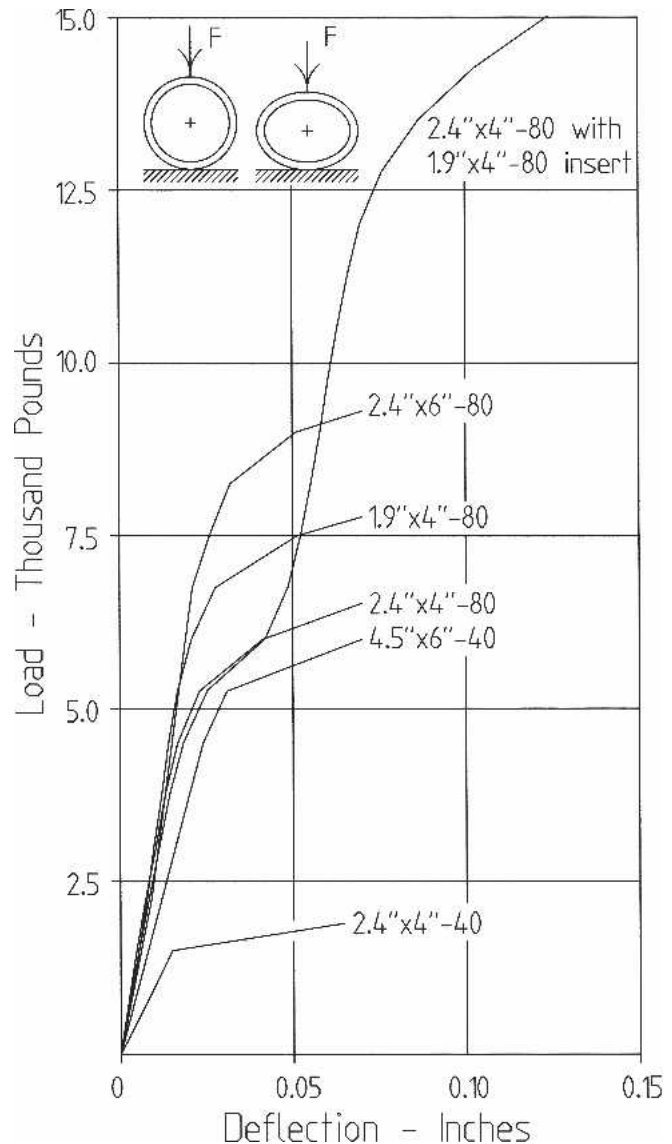


Figure 2. — Deflection behavior of 4- and 6-inch long 1.9-, 2.4-, and 4.5-inch (nominal 1 1/2-, 2-, and 3 1/2 inch, respectively) schedule 40 and 80 cross pipes.

These considerations led to the conclusion that the use of cross pipes as heel joint connectors justified further investigation. Exploratory tests were conducted, accordingly, both with round, square, or rectangular timbers, to obtain additional information concerning the performance and feasibility of the use of cross pipes in heel joints. The primary purpose of the tests was to obtain first estimates of the load-carrying capacity of representative trusses constructed with through-bolt and cross-pipe heel joints and to determine the modes of joint failures to be expected—specifically, do the joints fail in a “safe” as opposed to catastrophic manner. Results of these tests are presented below.

Materials and constructions

Two types of truss heel-joint configurations were considered in the study—one in which the top chords frame into the bottom chord (Fig. 1a), and one in which the bottom chord frames into the top chords (Fig. 1b). Typical configurations of the trusses that represented these two types of trusses are

¹ Presumably, the load capacities of these cross pipes could be calculated (Seeley and Smith, 1952) for use in truss design calculations; however, the yield stress of the material must be known, which is both a function of the yield point of the material itself and of the forming operations used to fabricate the pipe (Karren, 1967).

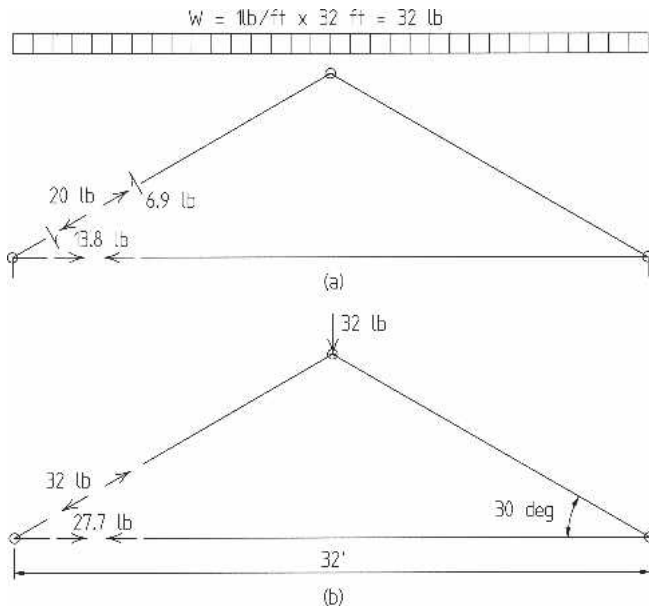


Figure 3. — Rafter “thrust” acting on heel joint of truss with 30 degree slope under the action of a uniform load, (a), and a single peak load, (b).

shown in Figure 4. Variations in heel construction and support conditions are shown in Figure 5. All of the trusses had a 30 degree slope. Three trusses of each type were constructed.

Wood species used in construction of the trusses included no. 1 and no. 2 & better southern yellow pine (*Pinus sp.*), preservative treated no. 2 red pine (*Pinus resinosa*), no. 2 & better eastern pine (*Pinus strobus*), ungraded yellow-poplar (*Liriodendron tulipifera*), small stem white ash (*Fraxinus americana*), and small stem red elm (*Ulmus rubra*). The white ash had a nominal diameter of 5.5 inches, whereas the red elm had diameters of 3.5 and 4.5 inches; the graded material measured a nominal 1.5 by 3.5 inches and 3.5 by 3.5 inches in cross section; the ungraded yellow-poplar measured a full 4 by 6 inches. All of the material had a nominal MC of 12 percent. Essentially all of the material contained boxed heart.

Holes for the cross pipes were drilled with Forstner bits. Typical center to center spacing of the cross pipes was 48 inches for the cross pipe locations shown in Figure 4.

Cross pipes (Fig. 6a) were cut from commercially available black pipe. Sizes included 1.90-inch outside diameter (nominal 1-1/2-inch) schedule 80 pipe, 2.375-inch outside diameter (nominal 2-inch) schedule 40 and schedule 80 pipe, and 4.0-inch outside diameter (nominal 3-1/2-inch) schedule 40 pipe. All of the cross-pipe connectors were attached to the truss members with 1/2-inch bolts.

A 2-, 3-, or 4-inch diameter hole was drilled crossways through the peak of each truss to accommodate a steel cylinder through which loads could be applied to the trusses (Fig. 4). The top surface of this cylinder coincided with the intersection point of the top surfaces of the upper chords.

Details of construction are summarized in Table 1. Specific details are given below.

Top chord frames into bottom chord

Truss sets 1 to 3 were of essentially identical construction, Figure 4a, except for the species of the chords, namely, (1) eastern pine, (2) red pine, and (3) southern yellow pine. Cross-

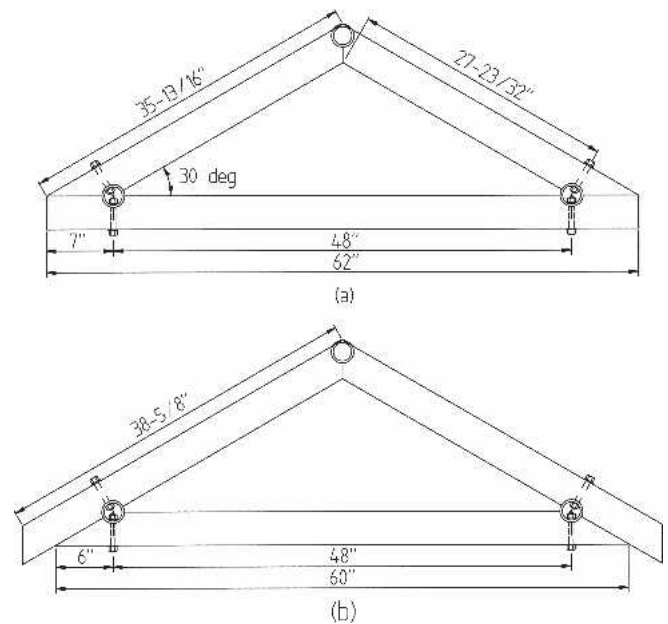


Figure 4. — Typical truss configurations used in the tests: (a) top chords frame into lower chord, (b) lower chord frames into top chords.

pipe joint connectors, Figure 6, were constructed of 2.375-inch diameter by 4-inch long schedule 80 pipe; these were located in the heels as shown in Figure 5a.

Truss set 4a was constructed of nominal 3.5- by 3.5-inch no. 2 southern yellow pine with 1.90-inch diameter by 4-inch long schedule 80 cross pipes located in the heels as shown in Figure 5a. Truss set 4b was identical to 4a except for the cross pipes, which were reinforced with two 1.469-inch by 0.1-inch (nominal 9/16-inch) washers, Figure 6c.

Truss set 5a (6 specimens) was constructed with 2&B Eastern pine chords and 2.375-inch diameter by 4-inch long schedule 80 cross pipes that were centered at the intersection of the lower surface of the top chord with the upper surface of the bottom chord, Figure 5b. Truss set 5b differed only in that the cross pipes were reinforced with two 1.90-inch by 1.5-inch schedule 80 cross pipes, Figure 6b. Truss set 5c was constructed with schedule 40 as opposed to schedule 80 cross pipes.

Truss set 6 was constructed of 5.5-inch diameter round white ash members with 2.375-inch diameter by 6-inch long schedule 80 cross pipes and two 1.90-inch diameter by 2.5-inch long schedule 80 inserts (similar to Figure 6b) located in the heels as shown in Figure 5b. A half-inch thick slab was sawn off one side (the inside truss surfaces) of the members to provide a reference surface for alignment of the holes in the members.

Truss set 7a was constructed of 4- by 6-inch yellow-poplar members with 4.0-inch outside (nominal 3.5-inch) diameter by 6-inch long schedule 40 cross pipes that were centered at the intersection of the lower surface of the top chord with the upper surface of the bottom chord (Fig. 5b). Truss set 7b differed from 7a in that each cross pipe was reinforced with two 3.5-inch outside diameter by 0.117-inch thick (nominal 1-1/2-inch) washers in a manner similar to that shown in Figure 6c. Truss set 7c differed from 7a in that each cross pipe was reinforced with two white ash disks that measured

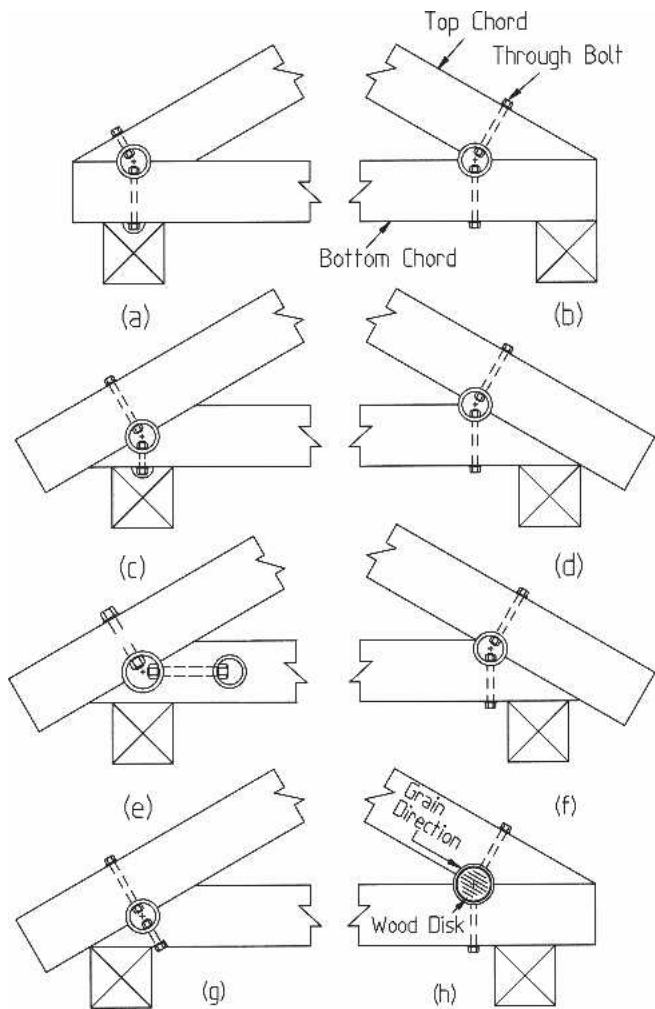


Figure 5. — Typical heel configuration used in construction of trusses and heel support positions used in testing of trusses.

3.5 inches in diameter by 2 inches thick. These disks were inserted in each end of a cross pipe with their grain direction parallel to that of the top chord (Fig. 5h).

Bottom chord frames into top chord

Truss set 8a was constructed (Fig. 4b) of nominal 3.5- by 3.5-inch no. 2 & better eastern pine with 2.375-inch diameter by 4-inch long schedule 80 cross pipes centered at the intersection of the lower surface of the top chord with the upper surface of the bottom chord, Figure 5d. Truss set 8b was identical except that the cross pipes were reinforced with two 1.90-inch diameter by 1.5-inch long inserts (Fig. 6b). Truss set 8c differed from 8a in that the cross pipes were constructed of schedule 40 pipe, Table 1.

Truss set 9 was constructed of 5.5-inch diameter white ash members with 2.375-inch diameter by 6-inch long schedule 80 cross pipes and two 1.90-inch diameter by 2.5-inch long schedule 80 inserts (similar to Figure 6b); these were located in the heels of the truss as shown in Figure 5f.

Truss set 10a (1 truss) was constructed of nominal 4.5-inch diameter red elm members with 2.375-inch diameter by 6-inch long schedule 80 cross pipes located in the heels as shown in Figure 5g. This heel configuration was used to position the bolt through the bottom chord at a greater distance from the end of the chord. Truss set 10b (1 truss) was con-

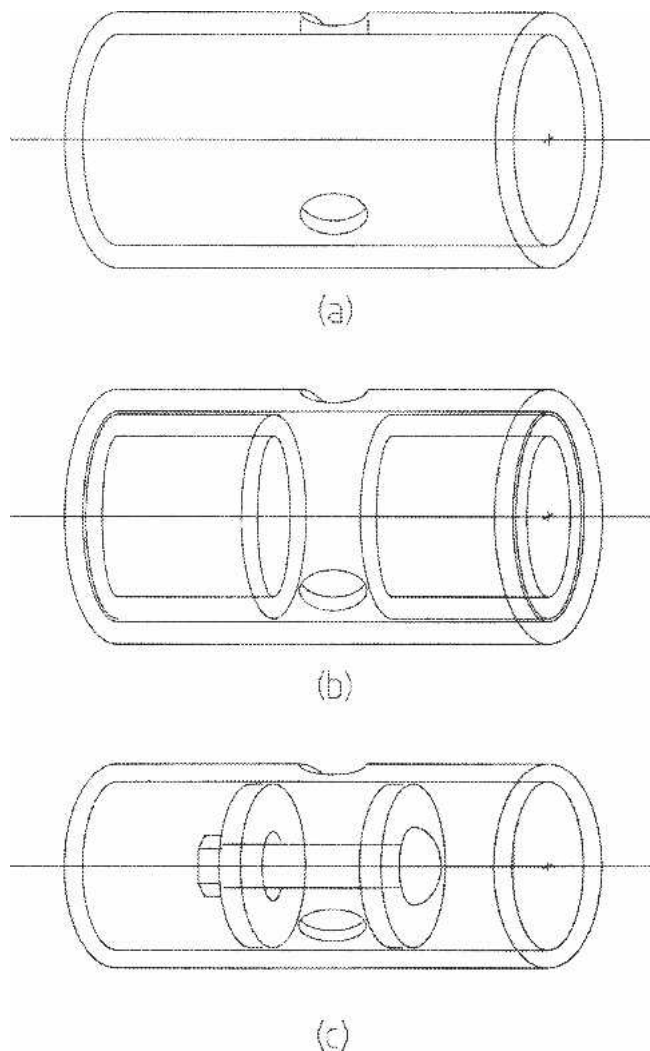


Figure 6. — Typical cross pipe configurations used in construction of trusses. (a): 2.375" D × 4" long schedule 80; (b): 2.375" D × 4" long schedule 80 with 1.9" D × 1.5" long schedule 80 inserts; (c): 1.9" D × 4" long schedule 80 cross pipe with two 1.469" D washers and 0.438" bolt.

structed of 3.5-inch diameter (average) red elm members with 2.375-inch diameter by 4-inch long schedule 80 cross pipes. Truss set 10c was constructed of nominal 3.5-inch square 2&B eastern pine with 2.375-inch by 4-inch schedule 80 cross pipes located in the heels as shown in Figure 5c. Truss set 10d was identical to truss set 10c except for the cross pipes, which were constructed of schedule 40 pipe.

Truss set 11a was constructed of nominal 1.5- by 3.5-inch southern yellow pine with 2.375-inch diameter by 2-inch long schedule 40 cross pipes centered at the midpoint along the length of the bottom chord heel taper as shown in Figure 5e. In addition, each heel cross pipe was attached to a second cross pipe (1.90-inch outside diameter by 2-inch long schedule 80), embedded in the bottom chord, by means of a length of threaded rod (Fig. 5e). Truss set 11b was constructed with schedule 80 instead of schedule 40 cross pipes.

Test procedure

All the tests were conducted on a 30,000-lb capacity Riehle universal testing machine. Rate of loading was 0.125 inches/

Table 1. — Truss construction, cross pipe, and heel support details along with peak loads and SDs. EPine = eastern pine, RPine = red pine, sypine = southern yellow pine.

Truss set	Mem. dimension	Member species and grade	Heel detail figure	Cross pipe diam.	Len.	Pipe schedule	Type of insert	Pipe insert no.-diameter (in) by length (in)-schedule	Max load avg.	Std. dev.	Load @ 5 percent yield	Slope
(No.)	(in)			----- (in) -----					----- (lb) -----			(pound/in)
1	3.5 by 3.5	#2&B EPine	5a	2.375	4	80	none	none	8,183	2,627	7,500 ^f	--
2	3.5 by 3.5	#2 RPine	5a	2.375	4	80	none	none	6,150	2,215	7,500 ^f	--
3	1.5 by 3.5	#1 SYPine	5a	2.375	4	80	none	none	7,783	76	7,500 ^f	--
4a	3.5 by 3.5	#2 SYPine	5a	1.9	4	80	none	none	11,500	na ^c	10,500	--
4b	3.5 by 3.5	#2 SYPine	5a	1.9	4	80	washer ^b	na	12,233	404	12,000	--
5a	3.5 by 3.5	#2&B EPine	5b	2.375	4	80	none	none	9,540	430	7,500	3.9 by 10 ⁻⁵
5b	3.5 by 3.5	#2&B EPine	5b	2.375	4	80	pipe	two-1.90 by 1.5-80	13,400	721	12,500	--
5c	3.5 by 3.5	#2&B EPine	5b	2.375	4	40	none	none	5,500	na	3,250	6.6 by 10 ⁻⁵
6	5.5"D ^a	White ash	5b	2.375	6	80	pipe	two -1.90 by 2.5-80	25,167	2,517	25,000	1.9 by 10 ⁻⁵
7a	4 by 6	Y-pop	5b	4.0	6	40	none	none	11,000	na	7,000	3.1 by 10 ⁻⁵
7b	4 by 6	Y-pop	5b	4.0	6	40	washer ^c	na	24,117	2,518	21,500	1.8 by 10 ⁻⁵
7c	4 by 6	Y-pop	5b	4.0	6	40	ash disk ^d	na	30,000	na	29,000	1.5 by 10 ⁻⁵
8a	3.5 by 3.5	#2&B EPine	5d	2.375	4	80	none	none	6,500	433	4,500	5.8 by 10 ⁻⁵
8b	3.5 by 3.5	#2&B EPine	5d	2.375	4	80	pipe	two -1.9 by 1.5-80	8,250	na	7,500	7.5 by 10 ⁻⁵
8c	3.5 by 3.5	#2&B EPine	5d	2.375	4	40	none	none	3,000	na	2,100	1.56 by 10 ⁻⁴
9	5.5"D	White ash	5f	2.375	6	80	pipe	two -1.9 by 2.5-80	12,250	433	10,500	5.4 by 10 ⁻⁵
10a	4.5"D	Red Elm	5c	2.375	6	80	none	none	10,000	na		--
10b	3.5"D	Red Elm	5c	2.375	4	80	none	none	6,250	na	5,400	1.05 by 10 ⁻⁴
10c	3.5 by 3.5	#2&B EPine	5 g	2.375	4	80	none	none	9,000	na	8,000	5.6 by 10 ⁻⁵
10 days	3.5 by 3.5	#2&B EPine	5 g	2.375	4	40	none	none	6,250	na	5,250	1.15 by 10 ⁻⁴
11a	1.5 by 3.5	#2 SYPine	5e	2.375	2	40	none	none	4,500	na	--	--
11b	1.5 by 3.5	#2 SYPine	5e	2.375	2	80	none	none	7,500	na	--	--

^aD = diameter.

^bTwo-1.469" diameter by 0.109" thick washers.

^cTwo 3.5" by 0.180" thick washers.

^dTwo 3.5" diameter by 1.95" thick white ash disks.

^ena = not applicable.

^fTests terminated at this load level.

minute. Loads were applied to a steel cylinder located in the peak of the truss. Trusses were supported at each end by 4-inch square by 6-inch long steel blocks as shown in **Figure 5**—normally centered directly below the cross pipes or at the ends of the bottom chord. Testing machine load-head movement—corresponding to gross deflection of the peak of a truss—was measured by means of an electronic digital gage. Testing was continued until a member failure occurred or there was no increase in load owing to yielding of the cross pipes.

Results and discussion

The ultimate load capacities of the trusses are given in **Table 1** and are presented graphically in **Figure 7**. Lower chord failures occurred in the heel area of the first three sets of trusses and in the second group of the fourth set. In the remaining trusses, tests were terminated when the applied load ceased to increase owing to non-linear deformation of the cross pipes. For purposes of comparison, load capacities at 5 percent yielding are also given in **Table 1**. These values were determined by fitting a linear expression to the central linear portion of the deflection data and then determining the maxi-

mum load at which test deflections deviated from predicted deflections by 5 percent. Although they are based on an arbitrarily selected deflection criterion, these values provide a basis for comparing the “useable” load capacity of the joints.

The load capacities of trusses in which the top chords framed into the top surface of the bottom chord (**Fig. 1a**) were substantially greater than that of trusses in which the ends of the bottom chord framed into the interior sides of the top chords (**Fig. 1b**). Comparing truss sets 6 and 9, for example, the load capacity of the first configuration was essentially twice that of the second (**Table 1**). Differences in the load vs. deflection characteristics of these two sets of trusses are illustrated in **Figure 9**.

Top chord frames into bottom chord

In the first three sets of trusses, constructed of 2&B eastern pine, the bottom chord fractured immediately below the heel cross pipe (**Fig. 8a**) at an average load of 8,183 pounds. The first truss of this set exhibited a brash wood fracture; the remaining two trusses exhibited more jagged breaks. The average value obtained for the second set of trusses in which the

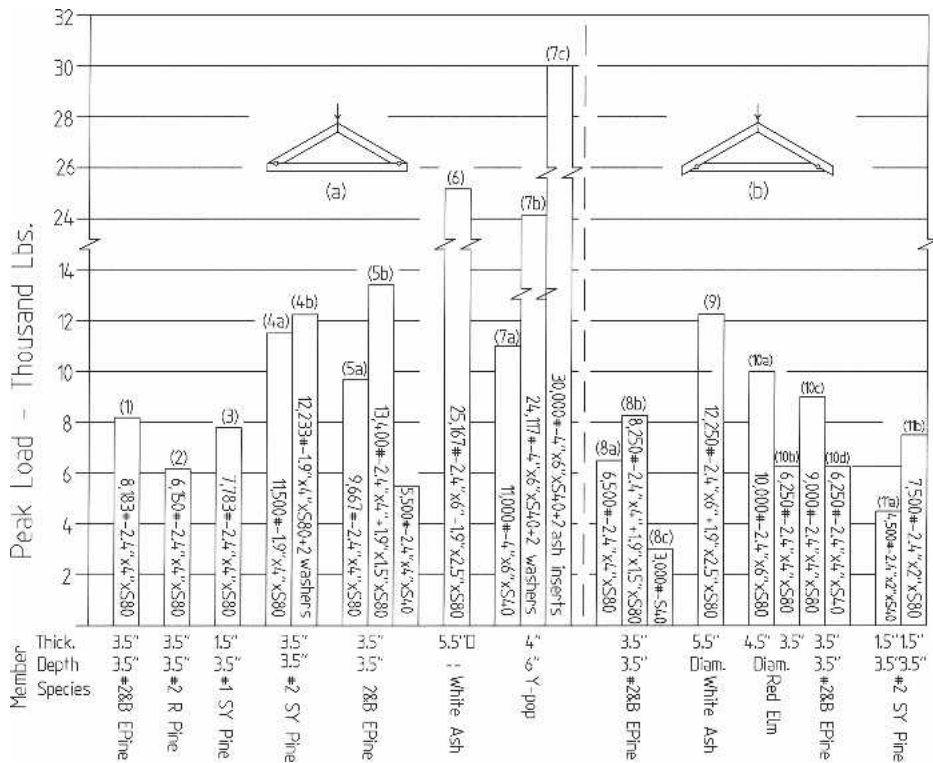


Figure 7. — Average peak loads obtained for trusses in which the top chords frame into the bottom chord (a), and the bottom chord frames into the top chords (b).

bottom chord was constructed of treated red pine was 6,150 pounds. All these trusses failed owing to brash wood fracture of the bottom chord immediately below the cross pipe (Fig. 8a). Average ultimate load obtained for the third set of trusses in which the bottom chords were constructed of nominal 1.5-by 3.5-inch no.1 southern yellow pine was 7,783 pounds. Two of the specimens failed owing to shearing of the heel of the bottom chord (Fig. 8b), whereas the third failed owing to fracture of the lower chord beneath the cross pipe. Overall, the results obtained with these three sets of trusses reflect differences in material quality and the manner in which the trusses were supported for testing. Specifically, the brash character of the woods used in the first two sets of trusses resulted in bending failures of the heels of the lower chords, whereas two of the three failures in the third set resulted from shear failures in the heel. In addition, the higher quality material used in the third set resulted in higher peak values even though the members were smaller in cross section. Non-linear pipe deformation was not observed at loads below 7,500 pound.

When the heel joints were constructed with 1.90 inch by 4-inch long cross pipes (truss set 4), positioned as shown in Figure 5a, (truss sets 4a & 4b) non-linear deformation was not observed below 10,500 pounds but was clearly observed at 11,500 pounds. Capacity of the cross pipes reinforced with washers was not determined owing to heel failures in the lower chord, but the washers exhibited linear behavior until the lower chords failed at an average of 12,233 pounds.

Likewise, when the heel joints were constructed with 2.375 inch by 4-inch long schedule 40 cross pipes, the trusses deflected linearly through 3,250 pounds. In contrast, when the heel joints were constructed with schedule 80 cross pipes (truss set 5) located as shown in Figure 5b, the trusses de-

flected linearly through 7,500 pounds. When each cross pipe was reinforced with two 1.90-inch by 1.5-inch schedule 80 inserts, the trusses deflected linearly through 12,500 pounds. Similarly, when 2.375-inch by 6-inch long cross pipes were reinforced with two 1.90-inch by 2.5-inch schedule 80 inserts (truss set 6), the pipes deflected linearly through 25,000 pounds.

Finally, when the heel joints were constructed with 4.0-inch diameter by 6-inch long schedule 40 cross pipes (truss set 7) as shown in Figure 5b, the trusses deflected linearly through 7,000 pounds. When the pipes were reinforced with two wrought iron washers, the trusses deflected linearly through 21,500 pounds. Finally, when the cross pipes were reinforced with two white ash wood disks, the trusses deflected linearly through 29,000 pounds.

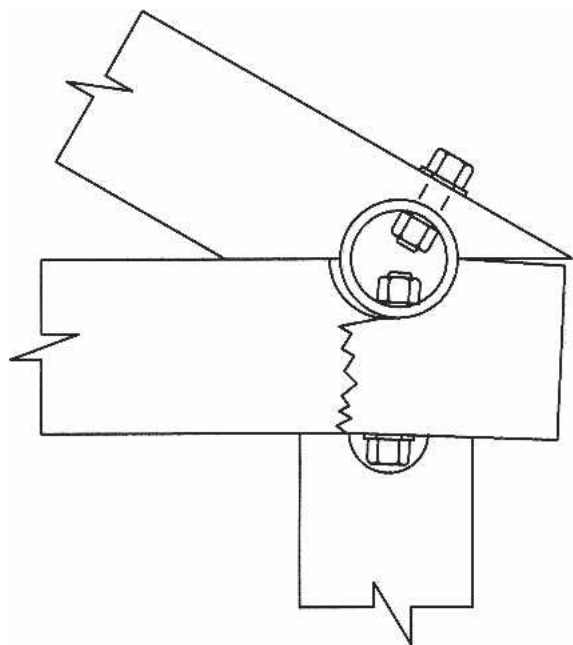
Overall, these results indicate that for a truss with 30 degree slope, a 1.90- by 4-inch schedule 80 cross

pipe has a linear load capacity of about 10,500 pounds. The same pipes, when reinforced with two 1.469-inch (9/16-inch) washers have a load capacity of at least 12,000 pounds. Larger diameter 2.375-inch by 4-inch long schedule 40 cross pipes have a linear load capacity of 3,250 pounds. Likewise, 2.375-inch by 4-inch long schedule 80 cross pipes have a load capacity of about 7,500 pounds, and, when reinforced with two 1.90-inch by 1.5-inch long schedule 80 inserts, have a linear load capacity of about 12,500 pounds. Similarly, 2.375-inch by 6-inch long schedule 80 cross pipes reinforced with two 1.90-inch by 2.5-inch long inserts have a linear load capacity of about 25,000 pounds. Finally, 4.0-inch diameter by 6-inch long schedule 40 cross pipes have a load capacity of about 7,000 pounds. When reinforced with two 3.5-inch (1-1/2-inch) washers, their capacity is increased to about 21,500 pounds. Similarly, when they are reinforced with two wood disks (as described), their linear load capacity increases to about 29,000 pounds.

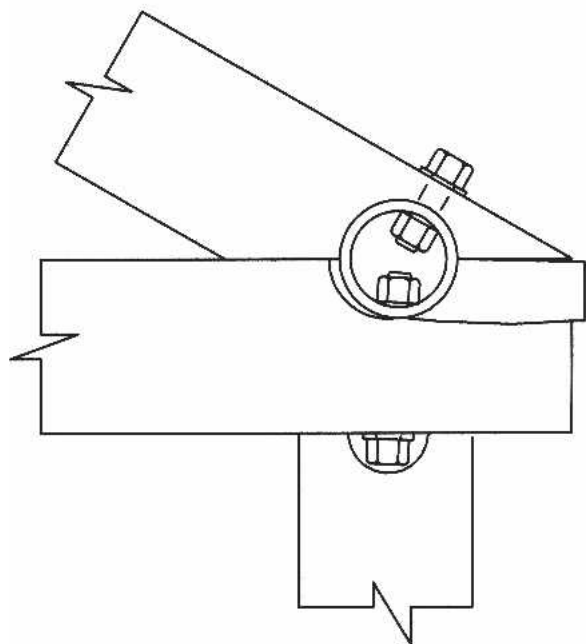
Bottom chord frames into top chord

In contrast, when the joints (truss set 11) were constructed as shown in Figure 5e with 2.375-inch by 2-inch long schedule 40 pipes, non-linear deformation occurred at about 4,500 pounds. In similar joints constructed with schedule 80 cross pipes, non-linear deformation occurred at about 7,500 pounds. Deformation of the cross pipe occurs principally in the short arc formed between the top chord bolt and the lower chord through-bolt. Presumably, therefore, the through-bolt in the bottom chord contributes to the strength of this connection by minimizing this arc and provides greater load capacity than the typical bolted heel connection shown in Figure 5d.

When the heel joints (truss set 8c) were constructed as shown in Figure 5d, with 2.375 inch by 4-inch long schedule



(a)



(b)

Figure 8. — Diagram showing fracture of the bottom chord beneath the cross pipe connector (a), and shear of the seat support of the cross pipe in the end of the bottom chord (b).

40 cross pipes, non-linear deformation occurred above 2,100 pounds; testing was discontinued at 3,000 pounds owing to substantial ovalization of the cross pipes. Similarly, when the joints were constructed with 2.375-inch by 4-inch long schedule 80 cross pipes (truss set 8a), non-linear deformation oc-

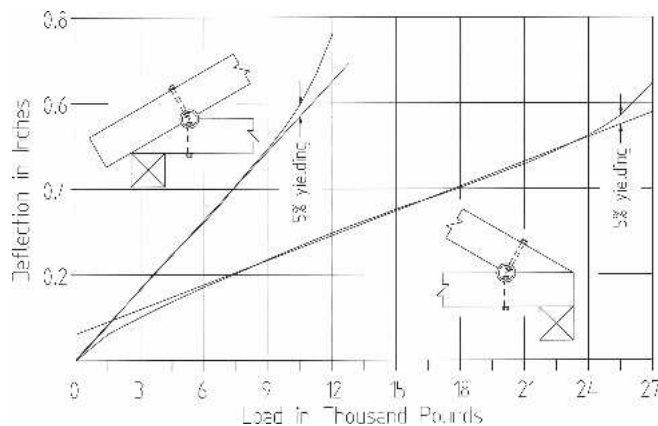


Figure 9. — Diagram showing deflection characteristics of truss set 9 with bottom chord framing into top chords, left; and truss set 6 with top chords framing into bottom chord, right.

curred above 4,500 pounds; testing was stopped at an average load of 6,500 pounds. Identical joints constructed with 2.375 inch by 4-inch long schedule 80 cross pipes and two 1.90-inch by 1.5-inch long schedule 80 inserts (truss set 8b) exhibited linear behavior through 7,500 pounds; testing was discontinued at an average of 8,250 pounds.

The white ash trusses (truss set 9) constructed as shown in **Figure 5d** with 2.375-inch diameter by 6-inch long schedule 80 cross pipes and two 1.90-inch diameter by 2.5-inch long schedule 80 inserts deflected linearly through 10,500 pounds. Testing was discontinued at an average peak load of 12,250 pounds owing to continued deformation of the cross pipes without increase in load.

When the heel (truss set 10a, 10b) was constructed as shown in **Figure 5c**, tests were discontinued at the 10,000 and 6,000 pounds levels owing to deformation of the heels of the truss even though the cross pipes had not substantially deformed—presumably because the continuous length of threaded rod carried part of the load and reinforced the cross pipe. Likewise, when the heel was constructed with 2.375-inch diameter by 4-inch long schedule 40 cross pipes (truss set 10c) and supported as shown in **Figure 5g**, non-linear deformation occurred above 5,750 pounds; testing was discontinued at 6,250 pounds owing to substantial deformation without increase in load capacity. In the case of identical joints constructed with schedule 80 pipe (truss set 10c), non-linear deformation occurred above 8,000 pounds, and testing was terminated at 9,000 pounds because of deformation without increase in load.

Overall, these results indicate that for a truss with 30 degree slope, a 2.375-inch schedule 40 cross pipe has a linear load capacity of about 2,100 pounds. Similarly, a 2.375-inch schedule 80 cross pipe has a linear load capacity of about 4,500 pounds; when reinforced with two 1.90-inch by 1.5-inch long schedule 80 inserts, the linear load capacity is increased to 7,500 pounds. Likewise, a 2.375-inch by 6-inch long schedule 80 cross pipe with two 1.90-inch by 2.5-inch long schedule 80 inserts has a linear load capacity of about 10,500 pounds. For the heel support detail shown in **Figure 5g**, a 2.375-inch diameter by 4-inch long schedule 40 cross pipe has a linear load capacity of about 5,250 pounds, whereas a comparable schedule 80 cross pipe has a linear load capacity

of about 8,000 pounds. Finally, for the heel detail shown in **Figure 5e**, a 2.375-inch by 2-inch long schedule 40 cross pipe has an estimated load capacity of about 4,500 pounds, whereas a comparable schedule 80 cross pipe has an estimated load capacity of 7,500 pounds.

Effect of cross pipe reinforcement

The potential value of cross pipe reinforcement with standard type A plain washers (Oberg and Jones, 1970) is seen in the results obtained for truss sets 4 and 7. In the case of truss set 4 (two 9/16-inch washers), only a small increase in load capacity was noted owing to fractures of the bottom chord, but non-linear deformation of the cross pipes was avoided. In truss set 7 (1-1/2-inch washers), however, use of two washers in each heel joint increased load capacity by 220 percent.

Likewise, the potential value of cross-pipe inserts is demonstrated by the results obtained for truss sets 5 and 8—use of two 1.9-inch diameter by 1.5-inch long inserts in the 2.375-inch by 4-inch long cross pipes of truss set 5 gave an increase in load capacity of 140 percent and an increase of 127 percent in truss set 8. Further, a load capacity of 25,167 pounds was obtained in truss set 6—which illustrates the increased load capacity that can be obtained with longer cross pipes and longer inserts. Based on the results obtained with truss sets 1 through 4, a first estimate for the load capacity of this construction (with 6-inch cross pipes and 2.5-inch inserts) would be $6/4 \times 7,500$ pounds + $5/4 \times 10,500$ pounds, or, 24,375 pounds. As can be seen, relatively close agreement was obtained, which tends to indicate that the cross pipe behavior is predictable.

Finally, truss set 7 demonstrates the potential value of the use of solid wood inserts in larger diameter cross pipes. The ultimate load capacity of the trusses could not be determined owing to the limited capacity of the testing machine, but within the limits of machine capacity, an increase of 270 percent was obtained.

Construction of the heel joints of truss set 10 is of interest because the threaded rod used to attach the cross pipe to the chords, initially at least, applies a compressive force to the cross pipe that presumably tends to counteract the effect of the force applied by the upper chord. Thus, the heel joint was able to carry a load of 10,000 pounds without ovalization of the cross pipe. The test was stopped because of embedment of the washers beneath the nuts in the faces of the top and bottom chords and because of fracture of one end of the bottom chord in tension perpendicular to the grain. Thus, larger washers with adequate seats in the chords are needed to develop maximum load capacity in this construction.

Discussion

For purposes of discussion, 32-foot trusses with cross pipe heel joints spaced at 5- or 10-foot intervals would have projected roof areas of 160- and 320-sq. ft, respectively. For a conservative roof load of 50 psf, the corresponding load acting on the roof section would be 8,000 pounds and 16,000 pounds, respectively; the corresponding uniform line loads acting on the truss would amount to 250 pounds and 500 pounds, respectively. As was shown in the introduction, a uniform line load acting on the truss produces a heel thrust 62.5 percent as great as that produced by a single peak load of equal magnitude. Thus, to be satisfactory for 5- and 10-foot spacings, the corresponding peak loads would amount to 8,000 by 0.625, or 5,000 pounds and 16,000 by 0.625, or, 10,000

pounds. Thus, for trusses in which the top chord frames into the bottom chord, 2.375-inch diameter by 4-inch long schedule 80 cross pipes or 4.0-inch diameter by 6-inch long schedule 40 cross pipes would satisfy the criteria for 5-foot truss spacings. Similarly, 2.375-inch diameter by 6-inch long schedule 80 cross pipes or 1.90-inch diameter by 4-inch long schedule 80 cross pipes would satisfy the criteria for 10-foot spacings. Trusses with 2.375-inch by 4-inch long schedule 40 cross pipes would not satisfy the criteria for either 5- or 10-foot truss spacings. They would, however, satisfy the criteria for say 2-foot spacings of 2,000 pounds.

For trusses in which the bottom chord frames into the sides of the top chords, 2.375-inch diameter by 4-inch long cross pipes would satisfy the criteria for 4-foot truss spacings, whereas similar cross pipes reinforced with two 1.90-inch by 1.5-inch long inserts would satisfy the criteria for 5-foot spacings. Likewise, 2.375-inch by 6-inch long schedule 80 cross pipes with two 1.90-inch by 2.5-inch long inserts would satisfy the criteria for 10-foot spacings. Somewhat improved results are obtained with the joint construction detail shown in **Figures 5c and 5g** in which a single threaded rod passes through the adjoining chord members and the cross pipe. For this construction, 2.375-inch diameter by 4-inch long schedule 80 cross pipes would meet the criteria for a 5-foot truss spacing, whereas similar 6-inch long pipes would nearly meet the criteria for a 10-foot spacing. Further research is needed to identify the performance characteristics of this construction. Attachment of the threaded rod to the cross pipe with nuts located on the outside of the cross pipes deserves investigation, for example, since this would load the cross pipe in compression along the axis of the threaded rod and tend to counteract the thrust imposed by the rafter on the side of the cross pipe.

Use of 2.375-inch diameter pipe (2-inch pipe) with 1.9-inch inserts (1-1/2-inch pipe) may prove to be an “optimum” combination for maximum load capacity at minimum cost. The cost of the connectors for these trusses based on current prices amounts to $\$2.50 + (\$2.40 \times 5/12) = \$2.50 + \$1.00 = \$3.50$ per heel.

Overall, the load capacity of trusses with larger diameter cross pipes—after wall thickness is taken into account—would be expected to be less than for the 2.375-inch diameter pipes. Various cross pipe/insert combinations may prove feasible, however, when use of larger cross pipes is desirable. Thus, 3.5-inch outside diameter pipe inserts (3-inch pipe, schedule 40) can be used with 4-inch diameter cross pipe (3-1/2-inch pipe, schedule 40). Likewise, 4-inch diameter pipe inserts (3-1/2-inch pipe, schedule 40) can be used with 4.5-inch diameter cross pipes (4-inch pipe). Also, 2.875-inch inserts (2-1/2-inch, schedule 80) can be used with 3.5-inch diameter cross pipes (3-inch, schedule 80). Furthermore, it may be feasible to use 3-, 3.5-, and 4-inch washers as force ring reinforcements in 3.5-inch (3-inch pipe), 4-inch (3-1/2-inch pipe), and 4.5-inch (4-inch pipe) cross pipes, respectively. Finally, use of solid wood inserts, particularly with the larger diameter cross pipes, appears to provide a feasible alternative method of reinforcement. If produced with a lip, these inserts could be used to “hide” the ends of the pipe. Also, washers could be attached to the inside face of inserts to ensure long-term strength where potential insert decay might be a factor.

Finally, in trusses in which the top chords frame into the lower chord, the end of the lower chord must extend a suffi-

cient distance beyond the seat for the cross pipe to prevent shear failures of the seat. Similarly, the lower chord must be sufficiently deep to provide sufficient material below the seat to prevent bending failures of the lower chord at this point. Support points for the trusses must be taken into consideration since placement of supports directly below the cross pipes—as opposed to points nearer the ends of the bottom chords—results in higher moments acting on the section of chord directly below a cross pipe.

Conclusions

Overall, results of the tests indicate that trusses with useful load carrying capacities can be constructed with cross-pipe heel joints. Of particular importance, the trusses do not fail catastrophically when the cross pipes begin to yield but continue to carry load. Trusses in which the top chords frame into the bottom chord are able to carry substantially higher loads than are those in which the bottom chord frames into the top chords. Furthermore, it appears advantageous to locate the longitudinal axes of the cross pipes at the point of intersection of the lower surface of the upper chords with the upper face of the bottom chord, **Figures 5b and d**, because this provides more material in the heel area and positions the connections further from potential end splits.

Bottom chords with limited cross section should be supported near the ends of the bottom chord, to prevent bending failure in the area beneath the cross pipes. Use of close-fitting pipe inserts provides a simple and effective way of reinforcing cross pipes as does the use of force ring type inserts (Eckelman 2004) and wood disk inserts. For a given wall thickness, higher load carrying capacities can be obtained with smaller

diameter cross pipes; however, the load capacities of trusses constructed with various cross pipe and insert or force ring combinations remain to be investigated.

Finally, for wide truss spacings, cross pipes constructed of schedule 80 pipe, often with pipe inserts constructed of schedule 80 pipe, are needed. For typical rafter spacings of 16 to 24 inches, schedule 40 cross pipes provide sufficient capacity.

Safety factors for these trusses should likely be based on the tendency of the bolt connections to loosen owing to shrinking and swelling of the members in service along with the tendency of the ends of the members to develop splits. Special drying practices may be needed (Karlsen 1967, Eckelman 2004) to force drying splits to develop in desired locations to avoid weakening the connections.

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