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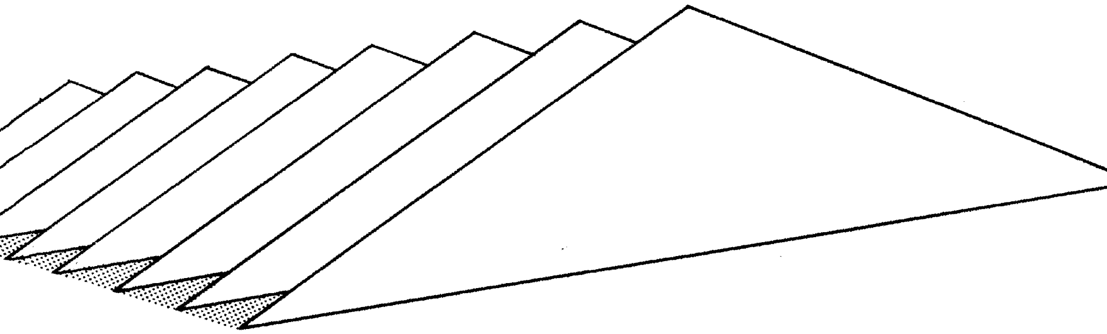

Lightweight / Trussed Rafters

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CONTENTS

ABSTRACT

A developmental and load-testing program is described and results that led to a design for a lightweight trussed rafter assembled from 1″ undressed lumber are presented. Experiment data on the structural performance under load of the lightweight design in several common spans and slopes are presented, analyzed and, in the instance of 24-foot span and 5 in 12 slope, are compared with the performance of trussed rafters assembled from 2-inch dressed lumber.

The lightweight design was found to perform as well as or better than similar designs assembled from 2-inch dressed lumber, and to possess advantages in ease of erection and efficient use of lumber. There was some reduction in lateral stability, but this did not affect the in-place stiffness of the trussed rafters when either spaced nailers or a solid roof deck was used to support the roof covering.

Related experiments on the strength of lap joints of 1-inch lumber in single shear, and on the effect of nailed joint design on the ultimate strength and stiffness of a lightweight trussed rafter are described and the results analyzed.

LIGHTWEIGHT / Trussed Rafters

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Trussed rafters and light trusses have been found to be advantageous for erection of farm shelter buildings, residences, and light commercial and industrial buildings. For example, Esmay and Boyd (1) have developed the use of standardized, light wooden trusses principally of 2-inch lumber for farm and utility buildings in Michigan. Friday and others (2) have developed and tested a 40-foot span truss rigidly connected to supporting poles. Luxford and Heyer (3) found that light glued and nailed roof trusses had certain advantages in simplifying house construction and reducing costs. Percival (4) developed the use of low-grade, hardwood lumber for fabrication of light trusses for farm building erection.

Beginning in 1949, Oklahoma State University recommended and demonstrated light trusses and trussed rafters for erection of dairy buildings; livestock, poultry, hay, and machinery shelters; and farm residences. The designs were based on published design data and recommendations. Fastenings at joints included split-ring and toothed ring connectors, nails, bolts, and glued-on gussets.

Informal appraisals of rural building practices during this work revealed widespread hesitancy on the part of rural builders, material dealers, and farmers to adopt and use these conventional designs for trussed rafters. Some reasons appeared to be the supposed difficulty in assembly of trussed rafters according to an engineered design, lack of acceptance of glue as an adequate fastening material, or the inability

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Cooperation in assembly and erection studies was received from the Poultry Science Department and the Dairy Department. Mr. Zivojin Kojic conducted the study on strength of nailed joints in lightweight trussed rafters.

Research reported herein was done under Oklahoma Agricultural Experiment Station Project No. 633.

of small builders and farmers to obtain the special connectors and installation tools required in some designs.

This indicated a need for a trussed rafter design that would offer improvements in assembly and fastening methods, in use of lumber, and in installation in the structure.

The present report is based on the results of development and testing work conducted the past four years at the Oklahoma Agricultural Experiment Station to arrive at an improved trussed rafter design for erection of farm shelter buildings.

Development Research

The first developmental work consisted of experiments to evaluate the structural performance of conventional types or designs of trussed rafters. It was thought that such data would serve as a basis for comparisons of performance of improved designs.

Structural loading experiments were performed later on several variations of a "light-weight" trussed rafter design that was developed after the first series of experiments with conventional designs.

Loading Experiments with Conventional Designs

Designs and joint treatments—Structural load testing experiments were conducted with trussed rafters built according to a design typical of those generally recommended for farm shelter erection. It employed the conventional "W" arrangement of members, and was assembled from dressed 2x4-inch (actual 1⅝x3⅝-inch) No. 1 Douglas Fir for the upper and lower chords. The top chord slope was 5 in 12. Span was 24 feet. Three different joint fastening treatments were used to obtain three variations of the basic design. These included (1) 2½-inch split

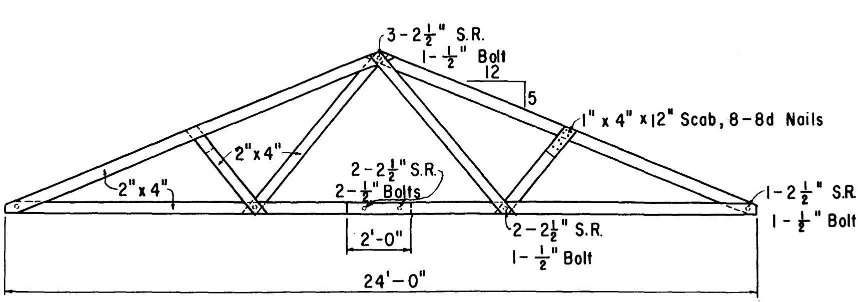


Fig. 1—Standard type of trussed rafter assembled with split ring connectors at joints.

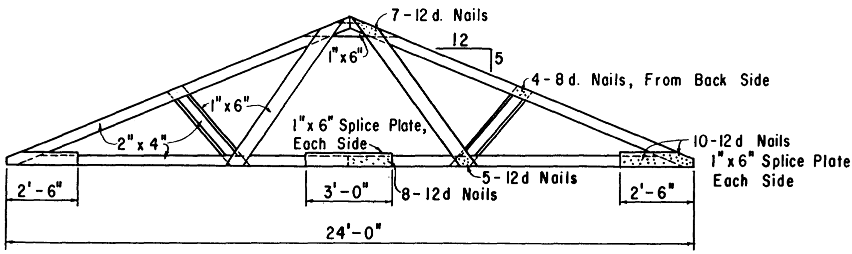


Fig. 2—Standard type of trussed rafter assembled with nailed-on splice plates.

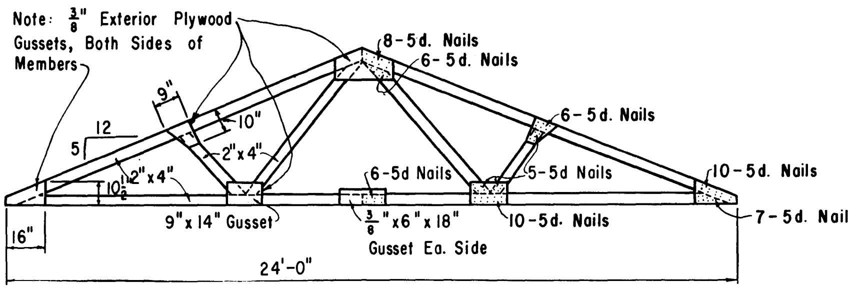
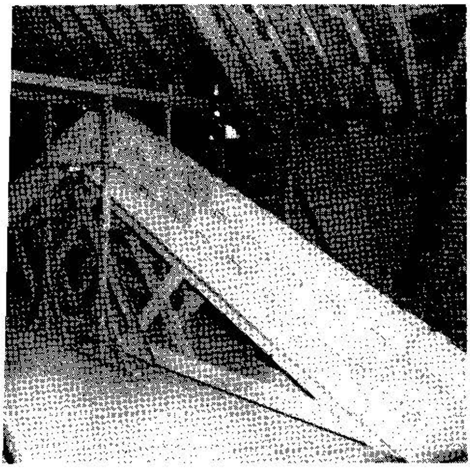


Fig. 3—Standard type of trussed rafter assembled with glue-nailed, fir plywood gusset plates.

ring connectors; (2) nailed-on 1x6-inch wooden splice plates at each side of the heel joint with nailed on diagonals, and (3) nail-glued, 3/8-inch Douglas Fir gusset plates. Further construction details are shown in Figures 1, 2, and 3.

Method of experiments—Three replications of each type were built and load-tested under long-term loads to simulate service loading.

All of the structural loading experiments were conducted in the Agricultural Engineering Department Structures Laboratory. A gravity loading system was used. Loads consisted of crushed rock in special containers hung from the trussed rafter top chord panel points. Loading procedure consisted in applying 100-pound weight increments at each of the three interior panel points at one-week intervals until a total load per trussed rafter of 1,500 pounds was obtained. Daily observations of strain and deflection were made. Upon completion of this loading sequence, the trussed rafters were unloaded. Next they were reloaded by applying 100-pound increments at each point as rapidly as readings could be obtained until failure occurred or a total load of 4,800 pounds was attained. This 4,800-pound load was carried by the trussed rafter until failure occurred. In one instance, failure had not occurred after nearly one year under the 4,800 pounds. The load was then increased until failure occurred.



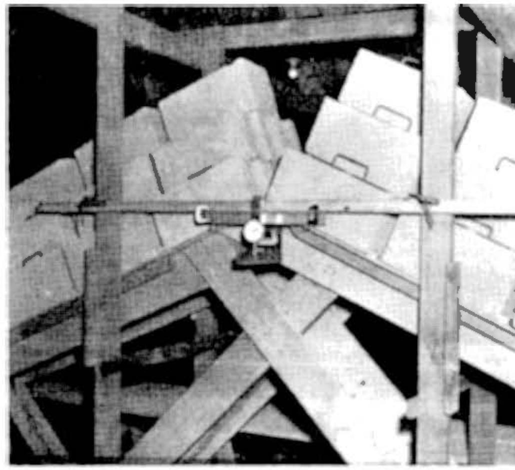


Fig. 4 (left). Typical loading system for trussed rafter tests. First experiments used crushed rock in containers hung from panel points. Fig. 5 (right). Micrometer dial installation for measurement of ridge deflection.

Figure 4 depicts a typical arrangement of the loading system. Figure 5 illustrates the Ames dial arrangement for ridge deflection observations. SR-4 strain gauges in conjunction with a standard switching unit and strain indicator were used to measure axial strain.

Results with conventional designs—Analyses of performance were based on data for ridge or peak joint vertical deflection, horizontal displacement of the heel joint, and wood fiber strain at selected points on the top chord. An analysis of linear regression of ridge deflection on time was applied to the data obtained during the 1-week increment-loading tests.

The results are presented in Table 1. Statistical analysis of variance of deflection rate, due to differences among joint connection methods, produced a variance ratio significant above the 99 percent confidence level. Effects on deflection rate due to size of load increment yielded a variance ratio of 0.783. The interpretation for these tests is that differences in deflection-time rate of trussed rafters under constant load were primarily due to differences in the kinds of joint connections. The deflection rate variance ratio, due to interaction of joint connections and size of load, was significant at the 92.5 percent confidence level. Inspection of the data in Table 1 revealed that for trussed rafters assembled with split-ring connectors and glued-on plywood gusset plates, respectively, the trend of the mean values is to increase with load; but this trend does not exist for the trussed rafters assembled with nailed-on

Table 1.—Deflection-time Rate At Ridge Of 24-Foot Span Trussed Rafters Of 2x4-Inch Dressed Lumber, Units In Inches Per 24 Hours.*

Joint Connection	Replication Number	CONSTANT LOAD INCREMENT, LBS. PER TRUSSED RAFTER				
		300	600	900	1200	1500
	1	2.29	1.70	2.55	4.99	5.16
Split-ring	2	3.67	3.20	3.69	9.36	7.20
Connectors	3	0.86	1.58	1.46	0.53	1.17
	MEAN	2.27	2.16	2.57	4.96	4.51
Nailed-on	1	0.80	2.55	2.70	0.58	1.75
Splice	2	5.33	3.66	2.63	3.94	3.40
Plates	3	1.79	0.80	1.44	3.36	2.86
	MEAN	2.64	2.34	2.26	2.63	2.67
Glued-on	1	0.40	1.85	1.93	0.26	0.28
Plywood	2	0.31	0.50	1.01	1.58	1.23
Gusset	3	0.57	0.49	0.46	1.18	0.12
Plates	MEAN	0.43	0.95	1.13	1.01	0.46

*Multiply tabulated values by 10^{-3} to obtain true values.

splice plates. The high confidence level for interaction seems consistent with this condition.

The mean deflection rate for trussed rafters assembled with split-ring connectors was 3.29×10^{-3} inches per 24 hours; for those assembled with nailed-on splice plates, 2.50×10^{-3} inches per 24 hours; and for those assembled with glued-on gusset plates, 0.80×10^{-3} inches per 24 hours. Compared to trussed rafters assembled with glued-on plywood gusset plates, the rate for those assembled with split-ring connectors was 4.11 times as great; and for those assembled with nailed-on splice plates, the rate was 3.13 times as great.

It should be noted that the deflection-time curve for a wooden frame or member under prolonged constant load will either become asymptotic to some ultimate value of deflection, or it will exhibit an inflection point at which failure will begin to occur. The elapsed time to the inflection point, if eventually reached, may require a long period of time, depending upon the magnitude of the load. If a trussed rafter continues to yield under a long-time loading test, therefore, the possibility of ultimate failure is indicated but may not occur within the time span of the experiments. Obviously, at the outset of a long-time loading experiment, it is not possible to predict with certainty whether or not failure will eventually occur. This is particularly so under loads only moderately less than those required to produce rather sudden and precipitous failure during a quick loading test.

Typical results from the strain measurements for one set of replications of the conventional trussed rafters are graphed in Figure 6. These data were obtained while loading the trussed rafters up to a maximum load of 4,800 pounds each as quickly as loads could be applied, and the observations of strain and deflection made. The data show that glued-on gusset plate joint assemblies produce more restraint against bending of the members than the split-ring joint

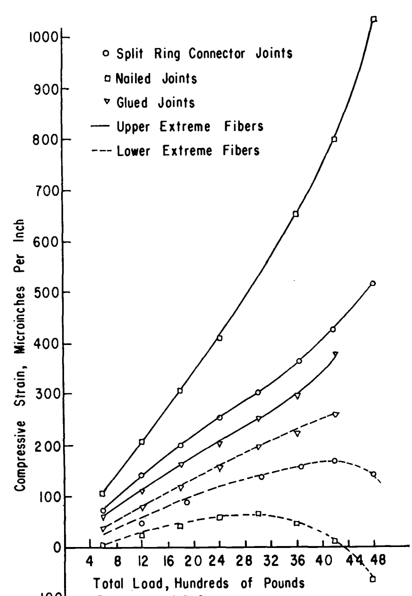


Fig. 6—Typical strain-load characteristics for standard types of trussed rafters.

assemblies, as evidenced by the smaller differences between upper and lower extreme fiber strain in the top chord. The trussed rafters with nailed-on splice plates were characterized by relatively high values of compressive strain in the upper extreme fibers. At a load of about 3,000 pounds, the joints apparently began to yield or slip excessively as evidenced by a change in the trend of the load-strain curve.

The results from loading the conventional trussed rafters to failure are tabulated in Table 2. Two of the trussed rafters failed due to lateral buckling of the top chord. This was before an appropriate stiffener against lateral buckling (to simulate action of a roof deck or spaced nailers) was developed. The failure loads (3,000 and 2,850 pounds) therefore, are not indicative of the ultimate strength of the joints. The stiffener used later consisted of steel angles separated approximately 1¾ inches by spacer plates, so that the stiffener rode freely on the top chord without offering restraint against bending in a vertical plane. In some cases, an observer was present when failure occurred, so that precise time values were obtained. In other instances, failure occurred when the installation was unattended. Elapsed time data for these were estimated.

Failure of the ring-connectored and glued-on splice plate assemblies occurred precipitously, with little advance warning other than minor "popping" noises. The nailed-on splice plate assemblies failed due to gradual yielding. If the trussed rafters had been in use in a structure, ample warning would have been given and emergency remedial measures could have been taken before the roof collapsed.

Initial Development of Lightweight Design

Need for improved design—The results with conventional trussed rafters indicated that joints assembled with glued-on gussets produced enough restraint to increase stiffness and reduce bending stresses in the members, as compared to ring-connectored or nailed assemblies. However, an improved design might eliminate the following fabrication requirements: extra cost of plywood, extra time needed to cut and install the gusset plates, necessity to turn the trussed rafter over to install gusset plates on two sides of certain joints, and need for some precision in cutting members to correct lengths.

Use of one-inch undressed lumber—After due consideration of possible improved designs and arrangements, the design shown in Figure 7 was evolved. It was assembled from one-inch undressed lumber. The joints were formed by overlapping the ends of the members so

Table 2.—Ultimate Loads For Trussed Rafters Assembled From 2x4-Inch Dressed Lumber, 24-Foot Span.

Type fastening at joints	Replication No.	Total load at failure lbs.	Elapsed time to failure, hrs.	Character of failure
2½ in. split ring connector	1	4800	3	Ring sheared out end of lower chord
	2	4600	1	Ring sheared out end of lower chord
	3	4800	Approx. 350	Ring sheared out end of lower chord
Nailed-on, 1 in. by 6 in. splice plates	1	4800	Approx. 40	Nailed joint failure under lateral load, diagonal web member.
	2	4800	Approx. 230	Nailed joint failure under lateral load, diagonal web member.
	3	3000	Approx. 15	Lateral buckling of top chord due to discontinuity in steel stiffner.
Glued-on, ⅜ in. plywood gussets	1	6900	8190	Shear failure, primarily in glue line between plywood gusset and top chord, with secondary shear failure in glue line in plywood, heel joint gusset.
	2	4800	Approx. 50	Glue starvation, lower chord splice plate.
	3	2850	24	Lateral buckling of top chord due to lack of stiffner.

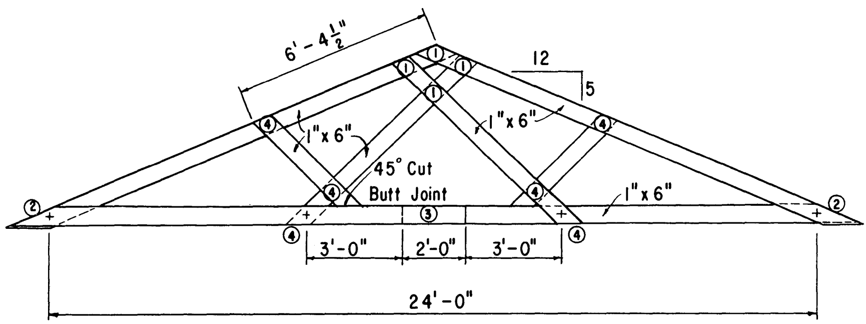


Fig. 7—Lightweight trussed rafter assembled from 1 in. undressed lumber. Refer to Table 4 for nailing schedule at each numbered joint.

that no splice plates or gussets were needed. This also eliminated any accurate pre-cutting of members to specified length or angles. After assembly the projecting ends of the members were trimmed off. The edges of the upper and lower chord members served to guide a hand-held portable electric saw when trimming the ends of the members.

The use of undressed one-inch lumber for trussed rafter construction has several inherent advantages compared to 2-inch dressed lumber. These include (1) a deeper section for the same cross sectional area, with a greater moment of inertia, a greater section modulus and therefore, more effective use of wood as a structural material; (2) greater overlap area at the intersection of two members, so that joints can be nailed or glue-nailed without resorting to splice or gusset plates; (3) easier assembly, since all members (except one end of each short diagonal) can be trimmed after assembly; and (4) greater compactness, since all members lie in only two planes with a total thickness of only 2 inches.

A one-inch member does not have stiffness against lateral buckling comparable to that of a 2-inch member when loaded in axial compression. Under usual gravity loads, however, only the top chord and the short diagonals of the "W" type arrangement are in compression. The short diagonal normally is not long enough so lateral buckling is critical. The top chord of trussed rafters is usually stayed against lateral buckling by the roof deck or spaced nailers.

Another consideration in the use of one-inch lumber for trussed rafter construction is the ability of workmen to nail into the edge of a one-inch member when applying the roof deck. If the roof covering is supported by spaced nailers, nailing presents few difficulties. Undressed, 1-inch lumber would be preferable to dressed lumber, since its thickness is approximately ⅓ greater. If undressed lumber could be effectively used for structural purposes, the wastage of structural material that occurs when lumber is dressed at the mill would be eliminated.

Strength of trussed rafter joints in single shear—It was anticipated that the rough surface texture of undressed lumber might require special adhesive bonding techniques to achieve joints with adequate strength. The joints for the lightweight trussed rafters would be loaded in single shear. The rough surface texture and dimensional irregularities in rough lumber could prevent adequate contact between the faces to be bonded.

These considerations led to a limited experimental program for testing the strength of small wooden lap joints in single shear to obtain information on the effects of surface roughness, of kind of adhesive used, and of nail-clamping treatment on ultimate strength of the joints.

A total of 36 specimen joints was made with 3 replications of 3 joint treatment effects including variations in adhesives, clamping pressure, and surface condition of the lumber. The adhesives used included regular casein glue and a modified epoxy resin formulated for masonry "welding" and patching. Extenders for the epoxy resin adhesive consisted of either one part by weight of normal portland cement or one part sugar sand to one part of resin. According to Thielsch (5) certain modified epoxy resins have properties for a suitable adhesive for bonding structurally-loaded joints in rough lumber. They have good wetting characteristics and require only contact pressure for bonding. Also, they possess good creep resistance, so that they are suitable for loads of long duration. At present, the cost is high. A suitable extender or filler would be desirable to reduce the adhesive cost.

The wood surface treatments included (1) ordinary dressed, one-inch Southern Yellow Pine boards and (2) rough or undressed 1-inch Southern Yellow Pine boards. The joint clamping pressure treatments included (1) contact pressure only, and (2) the pressure developed by four 6d galvanized nails in each joint. The average joint area was 4.354 square inches, resulting in a nail density of approximately 1.09 nails per square inch. Each test specimen included two joints formed by two pieces of lumber nominally 1¾ inches wide joined by a third overlapping piece 1¾ inches wide and 5 inches long. This arrangement produced two joints or single shear planes, each nominally 1¾ inches wide by 2½ inches long, either of which could fail under tensile load.

The lumber from which the test joint specimens were cut was Southern Yellow Pine purchased from a local lumber yard. The lumber had a computed specific gravity of 0.520 for the undressed material, and

0.487 for the dressed material. Moisture contents at time of fabrication of the joints were 10.2 percent for the undressed lumber and 8.3 percent for the dressed lumber.

The joints were load-tested to failure under tensile load in a hydraulic-type testing machine and a loading head movement rate of 0.05 inches per minute. Some joints failed in the wood due to the "peeling" effect of the eccentric load on a joint in single shear. Other joints failed largely in the plane of the adhesive.

Table 3.—Ultimate Strengths, Pounds Per Square Inch, Of Small Wooden Joints In Single Shear Under Tension Loading.

		Adhesive		
Clamping Pressure	Wood Surface Condition	Epoxy Resin With Sugar Sand Extender	Epoxy Resin With Portland Cement Extender	Casein Glue
Nails	Rough	558	525	472
	Planed	424	688	431
None	Rough	555	539	283
	Planed	650	491	508

The ultimate strengths of the joints are given in Table 3. The data listed are averages of three replications of each treatment. The data were subjected to statistical analysis of variance. The variance ratios for the main treatment effects (clamping pressure, kind of adhesive, and wood surface condition) indicated that: (1) the variation in ultimate strength due to the kind of adhesive used was significant above the 95 percent confidence level; (2) the variation in ultimate strength due to surface conditions was significant at the 72 percent confidence level; and (3) the variation due to differences in clamping pressure was non-significant (variance ratio less than one). The variance ratios due to interaction between clamping pressure and kind of adhesive used had an associated confidence level greater than 90 percent. For the interaction between clamping pressure and surface conditions, the associated confidence level was 75 percent. The variance ratio due to interaction of the effects of differences in adhesives and surface conditions was less than one.

It was concluded (1) that the kind of adhesive used had a significant effect on the joint strength; (2) the effect of clamping pressure developed by nails during hardening of the adhesive was conditioned by the kind of adhesive used and by the surface condition of the wood. Lack of clamping pressure did not appear to weaken the joints assembled with rough lumber and epoxy resin adhesives, but did appear to weaken seriously the joints assembled from rough lumber and casein glue. The mean ultimate strength in single shear developed by nail-glued joints assembled with rough lumber and casein glue plus nails for clamping pressure appeared adequate (472 pounds per square inch) for assembly of trussed rafters for farm service structures.

Trussed rafter loading experiments—A testing program was next conducted with the lightweight trussed rafter design in Figure 7. Six trussed rafters including two replications of each of the three joint assembly methods listed in Table 4 were built in the outdoor jig depicted in Figure 8. It consisted of crosspieces on small diameter fence posts set in the ground. The crosspieces were positioned to provide support for nailing under each joint, and to hold the pieces at a comfortable working height. The open spaces between the crosspieces were found to be desirable, since they allowed workmen to walk through the jig when removing a completed trussed rafter.

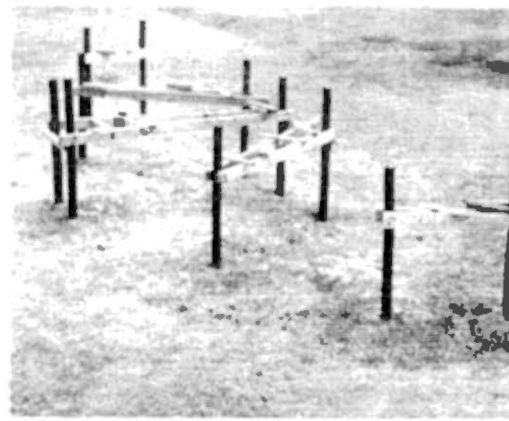


Fig. 8—Outdoor jig for assembly of lightweight trussed rafters.

The trussed rafters were load-tested in pairs in an upright position as depicted in Figure 4. The loading procedure consisted in applying loads in 500-pound increments per trussed rafter uniformly distributed over the top chords once each week. Observations were made daily of deflection at the ridge, of horizontal movement at the roller-supported heel joint, and of strain in the extreme fibers of the chords midway between the heel joint and first panel point. The total time under load for each trussed rafter was six weeks, with a maximum load of

Table 4.—Joint Treatments For Fabrication of Experimental Light-Weight Trussed Rafters. (Cf. Fig. 7)

Adhesive	Joint No. (see Figure 7)			
	1	2	3	4
	Number of nails in joint			
None	15	20	20	10
Casein Glue	10	10	15	10
Epoxy Resin Glue Plus Portland Cement	10	10	15	10

Note: 6d common nails used in joints without adhesive.
6d cement coated nails used in others.

3,000 pounds per trussed rafter in place during the last week of each loading experiment.

Loading experiments results—The deflection at the ridge and horizontal movements of the heel joint, respectively, are diagramed in Figures 9 and 10. The data for "loading" in these graphs are the values after the trussed rafters had been under constant load for one week. After the test loading period had been completed, the trussed rafters were quickly unloaded and the residual deflection observed. This is plotted as the deflection at zero load on the unloading line in Figures 9 and 10. It is apparent that with regard to ridge deflection the trussed

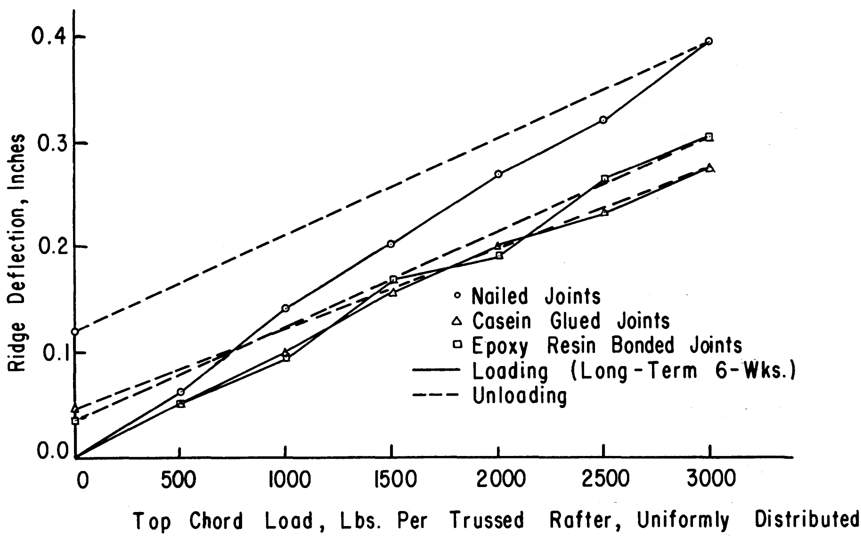


Fig. 9—Deflection-load characteristics for lightweight trussed rafters.

rafters assembled with joints bonded either with epoxy resin or with casein glue exhibited comparable performance, but those assembled with nails only in the joints behaved differently. The data on deflection during each of the one-week, constant load periods were subjected to statistical analysis of variance of deflection due to differences in size of load and type of joint (adhesive bonded versus nailed). The variance ratio due to effects of differences in joint treatment was significant above 95 percent confidence level. The variance ratio due to differences in size of load was significant slightly above the 70 percent confidence level.

The compressive strain in the extreme fibers of the lightweight trussed rafters had maximum values of 610 micro-inches per inch for

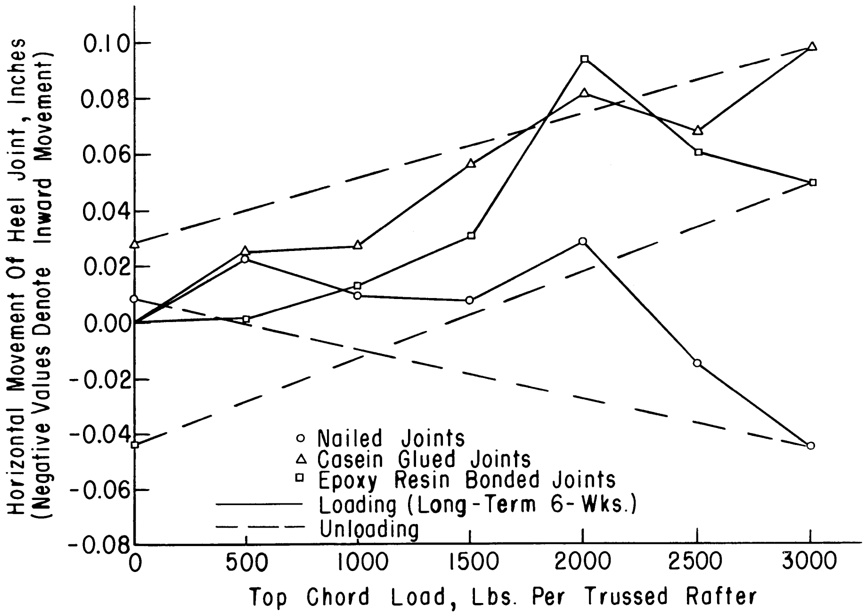


Fig. 10—Horizontal movement of heel joints, lightweight trussed rafters.

the ones assembled with nails only in the joints, 720 micro-inches per inch for those with casein glue bonded joints, and 900 micro-inches per inch for those with epoxy resin bonded joints. These values were obtained with a uniformly distributed top chord load of 3,000 pounds per rafter.

A comparative summary of the stiffness data for all trussed rafter loading experiments is given in Table 5.

Extension of Lightweight Design

Selections of spans and slopes—The foregoing studies led to an improved, lightweight, trussed rafter design for a 24 foot span and a 5 in 12 roof slope. Additional load-testing was subsequently conducted to ascertain if one-inch lumber members could be used for trussed rafters with spans wider than 24 feet and slopes flatter than 5 in 12. All of the additional load-testing was done with the lightweight design assembled wih one-inch undressed lumber as previously described. The range of spans in this additional load-testing included 20, 24, 30, and 36 feet. This range includes the widths of most farm buildings. The 20- and 24-foot span trussed rafters were constructed with a 3 in 12 slope. This is the minimum recommended slope for corrugated metal roofing and many types of shingles. The 30- and 36-foot span rafters were built with a 4 in 12 slope. These slopes were selected for both aesthetic and

Table 5.—Summary of Deflection Data For 24-Foot Span Trussed Rafters Under Gravity Loads of 5 Weeks' Duration. All Spans 24 Feet, Top Chord Slopes 5 In 12.

Type	Joint Connections	Replications	Maximum load	Ridge Deflection		Horizontal Movement of heel	
			lbs.	In./1000 Lb.	Percent	In./1000 Lb.	Percent
Conventional, assembled from 2"x4" dressed lumber	Nailed-on 1"x6" splice plates	3	1500	0.211	62	0.107	45
	2½" split ring connectors	3	1500	0.338	100	0.240	100
	Glued-on ⅜ in. plywood gussets	3	1500	0.105	31	0.003	1
Light-weight, assembled from 1"x6" undressed lumber	Epoxy resin-portland cement adhesive	2	2500	0.106	31	0.080	33
	Casein glue	2	2500	0.094	28	0.070	29
	Nails only	2	2500	0.128	39	0.085	35

structural reasons. The "low-setting" appearance they give is favored by many persons. A relatively flat slope for a given span and load, however, produces higher stresses in the members and greater loads on the joints than trussed rafters with steeper top chord slopes. If a trussed rafter with a comparatively flat top chord slope is structurally adequate, the members and fastenings used would be adequate for trussed rafters of the same span but with steeper slopes.

Testing method—Load-testing was conducted on two replications each of the additional designs. The loading method and general arrangement of the equipment was the same as used for the initial studies with lightweight trussed rafters of 24-foot span, 5 in 12 slope. Performance observations were limited to measurements of ridge deflection under uniformly distributed gravity loads applied to the top chord.

Since strength and deflection are dependent upon magnitude and duration of load, loads were left on the 20- and 36-foot span trussed rafters for one week to obtain data for effects of elapsed time under load. Additional detailed information on the testing and performance of each span follows.

20-foot span, 3 in 12 slope—The 20-foot span trussed rafters were designed with a 4-foot overhang of one eave. In some shelter buildings, wide roof overhang and relatively flat roof slope are desirable for additional shade on the south side, as in open-front shelters.

Results of tests for the 20-foot span, 3 in 12 slope trussed rafter are shown graphically in Figure 11. The two trussed rafters were loaded to a total load of 5,400 pounds, or 2,700 pounds per trussed rafter. The load was uniformly distributed over top chord and overhang. Final deflection of the overhang was slightly over ⅓ inch after elapsed time under load of one week.

24-foot span, 3 in 12 slope—Results of the 24-foot span, 3 in 12 slope trussed rafter tests are shown in Figure 12. The total final load per trussed rafter was 2,700 pounds uniformly distributed over the top chord. Deflection was well within the allowable limits. Elapsed time under load was one hour.

30-foot span, 4 in 12 slope—Results of tests for the 30-foot span trussed rafter are shown graphically in Figure 13. Twenty-foot lengths of undressed 1x6-inch lumber were required for the top chords. This was available locally only in No. 2 Southern Yellow Pine. As a result, some lumber defects occurred in critical stress areas.

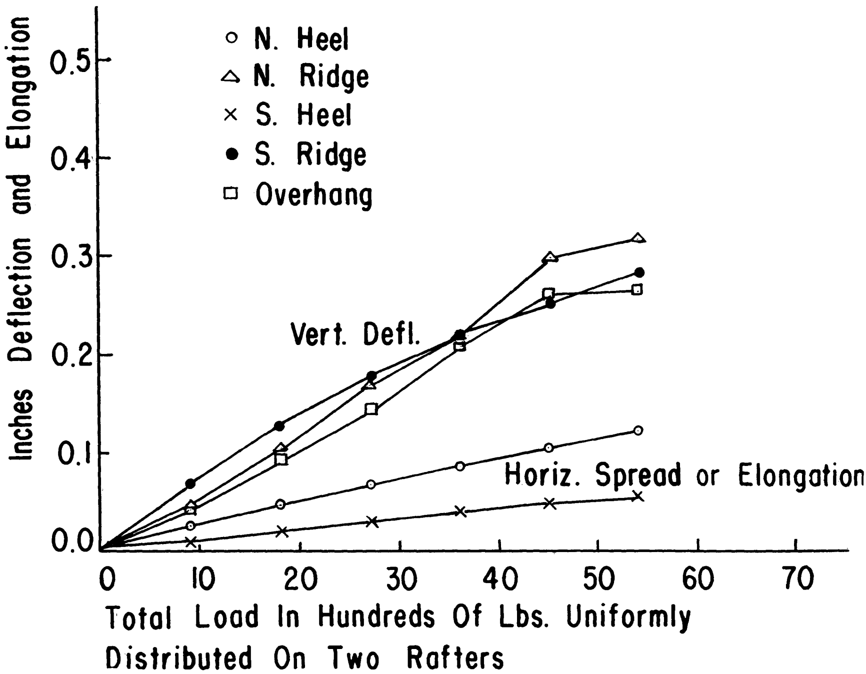


Fig. 11—Performance of trussed rafters, quick loading test, 20 ft. span, 3/12 slope.

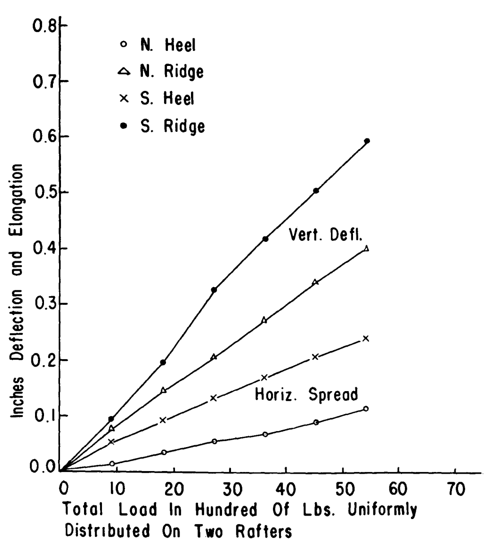


Fig. 12—Performance of trussed rafters, quick loading test, 24 ft. span, 3/12 slope.

One trussed rafter failed during loading at 2,700 pounds load per trussed rafter. The failure occurred in a large knot in the top chord just above the heel joint. This resulted in a buckling of the bottom chord and subsequent failure of both rafters. Damage to both trussed rafters was confined largely to one end of the pair.

The trussed rafters were repaired by nailing and gluing scab boards extending 18 inches from either side of the break. Joints that had been pulled loose were re-glued and nailed. The glue was allowed to set for approximately one week before the rafters were again tested.

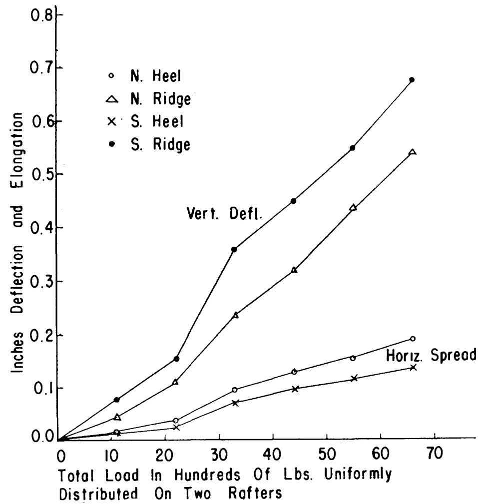


Fig. 13—Performance of trussed rafters, quick loading test, 30 ft. span, 4/12 slope.

The two rafters were then reloaded to 6,000 pounds total or 100 pounds per foot of span per trussed rafter. The load was allowed to remain on the trussed rafters for 1½ hours before it was removed. The deflection was well within allowable limits.

36-foot span, 4 in 12 slope—The 36-foot trussed rafters were assembled with undressed 1x8-inch lumber instead of 1x6-inch lumber as in the top chords for shorter spans. This resulted in a 77 percent increase in section modulus as compared to 1x6-inch members. This change also increased the joint area 33 percent for additional joint nailing and gluing area.

Since assembly of the 36-foot span trussed rafters would require members more than 20 feet in length if a single piece of lumber were

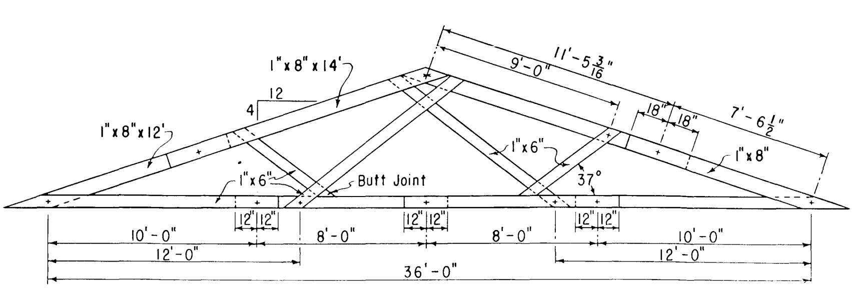


Fig. 14—Assembly details for 36 ft. span trussed rafter, 4/12 slope.

used for the top chord, the arrangement of the members was changed to utilize shorter lengths of lumber. This arrangement is shown in Figure 14. All members were included in only two planes. Fabrication was relatively simple. Four additional splices were required, which increased the amount of nails and glue needed and the assembly time.

Results of the tests for the 36-foot trussed rafter are shown in Figure 15. Total load on the two trussed rafters was 7,800 pounds. Ridge deflection was 1/570 of the span after an elapsed time under load of one week.

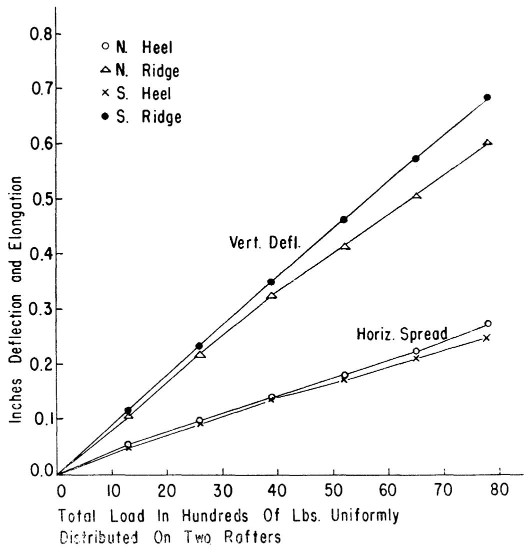


Fig. 15—Performance of trussed rafters, quick loading test, 36 ft. span, 4/12 slope.

Although the 36-foot trussed rafter was adequately rigid under gravity load when stayed against lateral buckling, it was difficult to lift into the jig and align properly because it lacked lateral stiffness. This condition might be remedied by fastening the trussed rafters together in pairs after fabrication. Spacing of these doubled rafters could then be increased. For example, two to three or more of these lightweight trussed rafters could be fastened together to form trusses for use at relatively wide spacings. Spacer blocks between the top chords should also be used at the quarter points.

If lifting equipment would be available, either of the above combinations could be utilized. Individual 36-foot trussed rafters weigh approximately 225 pounds, so any combination of two or more would require power lifting equipment.

Summary of Lightweight Design Tests

The results of the loading experiments are summarized in Table 6. The deflection, D, for all of the spans and slopes was considerably less than 1/270 of the span, L, under superimposed loads of 100 pounds or more per foot of span.

The maximum allowable deflection under design load is usually regarded as 1/270 of the span for farm shelter buildings. Design roof

Table 6.—Ridge Deflection Of Lightweight Trussed Rafters Measured Immediately After Loading.

L Span, Ft.	Top Chord Slope	P, Total Load, Lbs. per trussed rafter	P/L	D Average Ridge Deflection Inches	D/L
20	3/12	2700*	112*	0.303	1/793
24	3/12	2700	112	0.501	1/576
30	4/12	3000	100	0.606	1/594
36	4/12	3900	108	0.643	1/672

*Included weight carried by a 4 foot overhang, one end only.

live loads commonly used in design of farm shelter buildings in Oklahoma are from 12 to 15 pounds per square foot of horizontal projection.

Strength of Nailed Joints

Possible improvements—When glue-nailed joints cannot be used for fabricating the lightweight design trussed rafter, increased stiffness and ultimate strength might be obtained by an improved nailed joint compared to an ordinary nailed joint in single shear. It appeared possible that some improvement might be obtained by adding a 1-inch block to a 2-member rafter joint to receive the points of longer and heavier nails.

Joint types—An experimental investigation was conducted to evaluate the effect of two variations in nailed joint design on the stiffness and ultimate strength of the lightweight trussed rafter assembled with nailed joints but without an adhesive. The general design of the trussed rafters used in the experiments was similar to the lightweight design previously described. Span was 24 feet and roof slope was 5 in 12. Two nailed joint types were investigated. Type I consisted of six penny common wire nails in a simple two-member overlap joint. Type II consisted of ten penny common wire nails in a simple 2-member overlap joint with the addition of a 1-inch block to receive the points of the ten penny nails driven through the joint. It was thought that this block would provide some additional restraint against bending of the nail under lateral loads, some resistance to withdrawal that occurs when a nailed joint yields excessively, and some added restraint against lateral buckling of members that met at a joint or splice.

Two lightweight trussed rafter replications were built with Type I nailed joints throughout. These trussed rafters were designated Type A. Two replications, designated Type B, were built with Type II

Table 7.—Joint Nailing Schedule For Type A And Type B Trussed Rafters.

Joint Location	Joint Designation	Type A Trussed Rafter		Type B Trussed Rafter	
	(See Fig. 16)	Joint Type	No. Nails	Joint Type	No. Nails
Heel	1	I	4	II	3
Ridge	2	I	4	II	3
Ridge	3	I	3	I	3
Ridge	4	I	1	I	1
Top Chord	5	I	2	I	2
Lower Chord	6	I	2	I	2
Lower Chord	7	I	2	I	2
Lower Chord	8	I	2	I	2
Lower Chord Splice	9	I	3	II	2

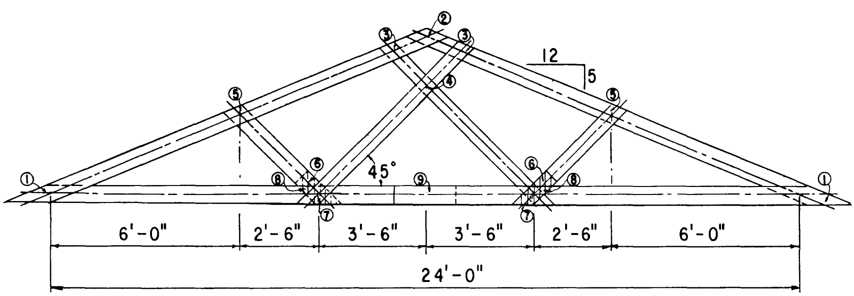


Fig. 16—Special lightweight trussed rafter design used in experiments on effect of joint nailing pattern. Numbers at joints refer to Table 7.

nailed joints at the ridge, the heel joints, and the lower chord splice respectively. The other joints in the Type B trussed rafters were Type I nailed joints. The arrangement of the members in these trussed rafters is shown in Figure 16. The nailing schedule is shown in Table 7.

Experiments—The trussed rafters were gravity load-tested in upright position in an auxiliary frame. A special loading platform was used so that load was applied only at the panel points. Fifty-pound concrete blocks were used for load. Restraint against lateral buckling was provided by wooden ties and metal stiffeners which were arranged to produce only negligible stiffness against deflection in a vertical plane.

The Type A trussed rafters were subjected to eight cycles of loading and seven unloading cycles. The Type B trussed rafters were subjected to three loading and two unloading cycles. Deflections of the ridges were observed with micrometer dials.

Results—The results are summarized in Table 8. The loads shown are superimposed loads. Additional dead load due to the weight of the

Table 8.—Ridge Deflection Of Type A And Type B Trussed Rafters.

Assembly Type	Loading Cycle	Maximum Load, Lbs. Per Trussed Rafter	Maximum Ridge Deflection, In., Total		Residual Deflection After Load Removed In.	
			North	South	North	South
A	1	350	0.0871	0.0942	0.0034	0.0022
	2	350	0.0378	0.0955	0.0090	0.0032
	3	375	0.0980	0.1040	0.0091	0.0050
	4	475	0.1492	0.1494	0.0239	0.0131
	5	500	0.1793	0.1662	0.0642	0.0509
	6	600	0.2804	0.2825	0.0911	0.0815
	7	675	0.3715	0.3759	0.1640	0.1875
	8	875	0.5887	1.9190	-----	-----
B	1	175	0.0521	0.0388	0.0179	0.0157
	2	500	0.2115	0.2153	0.0831	0.1147
	3	625	0.2610	0.3328	-----	-----
		750	0.3492	0.4610	-----	-----
		875	0.4555	0.5888	-----	-----
		1000	0.6350	0.8310	-----	-----
		1125	0.7015	1.1180	-----	-----
		1250	1.1890	1.6510	-----	-----
		1375	1.7010	2.4700	-----	-----
		1500	2.4715	3.1290	-----	-----

trussed rafter and loading platform was approximately 300 pounds per trussed rafter.

Evidences of failure were produced for trussed rafter Type A at superimposed loads of 875 pounds, and for trussed rafter Type B at superimposed loads of 1,500 pounds per trussed rafter. One of the Type A trussed rafters failed by total separation of the joint at midspan of the lower chord, accompanied by considerable bending and eventual pull-out of the nails. Type B trussed rafters ultimately failed due to a combination of twisting and lateral movement of the heel joint, which produced separation of the lower from the upper chord. Secondary failure was noted in lateral separation at the joint between the long diagonals in the Type B trussed rafters, where the diagonals crossed under the ridge. It was noted that failure of the Type I nailed joints with six penny nails was characterized by separation of the members; but, the Type II joints failed primarily by parallel-to-grain shearing of the nails in the wood.

The results are plotted in Figure 17. As shown therein, the failure loads were 875 pounds of superimposed load per Type A trussed rafter, and 1,500 pounds per Type B trussed rafter. This increase in ultimate strength by a factor of approximately 1.7 was obtained by a modification of the main joints in the trussed rafter.

The ultimate strengths per nail in lateral loading on the joints were, for the Type I joints, 215 pounds per six penny nail, and for the

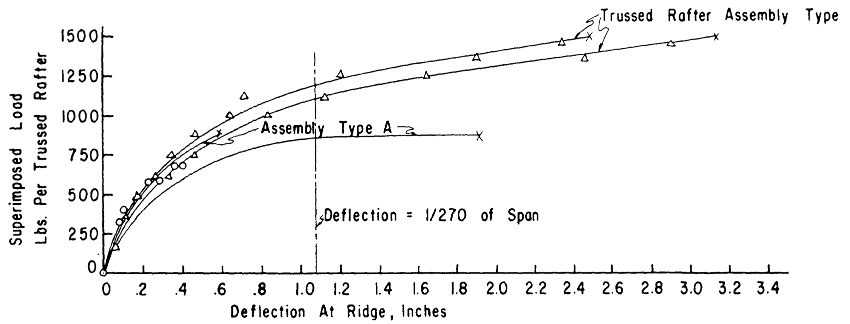


Fig. 17—Deflection of special lightweight trussed rafters as affected by nailed joint design. Refer to Table 7 and Fig. 16 for joint details.

Type II joints, 540 pounds per ten penny nail. These were based upon a stress analysis for the loads on two joints which failed, namely a lower chord splice in the Type A trussed rafter and a heel joint in the Type B trussed rafter. The duration of the ultimate load until failure was 24 hours for the Type I joint and 90 hours for the Type II joint.

The increased joint strength of the Type II joint was accompanied by some inconvenience when positioning the third member or block under the joints to receive the points of the ten penny nails. Additional material cost was negligible, since scrap pieces were used for the block.

Observations / Assembly and Use

Assembly method—The lightweight trussed rafters were assembled by laying the proper lengths of lumber in position in the jig (page 15) against the guide blocks. Assembly of the lightweight trussed rafters was found to be quite simple since all members were included in only two planes and all joints were simple lap joints. Only the two short diagonals needed to be precut to a 45 degree angle on one end before assembly. All other members were trimmed to the outline of the trussed rafter after assembly. This eliminated precision cutting to measured length of members. Little waste was encountered that would not occur in conventional trussed rafters built with dressed 2-inch material.

Glue was applied to the overlap areas. Adequate nailing after gluing was essential to provide clamping pressure until the glue hardened. It was found that immediately after assembly the trussed rafters could be removed from the jig and carefully stacked on level blocks or on a level floor until the glue hardened. Structural casein glue proved satisfactory if the trussed rafters are not to be subjected to prolonged or repeated wetting or moisture during use. After the trussed rafter had been assembled and the glue hardened, the projecting ends were trimmed off.

Assembly time—Assembly time for the lightweight trussed rafters varied with the size of the rafter and the speed and efficiency of the crew. Larger trussed rafters required heavier, longer members and more nails. Assembly and handling time was greater compared to smaller, lighter rafters. The 24-foot span trussed rafters required a two-man crew approximately 18 minutes to assemble, or 0.60 man-hours per trussed rafter. The 30-foot rafters were assembled by a 3-man crew at the rate of four per hour or 0.75 man-hours per trussed rafter. This time did not include trimming off the projecting ends of the members. These assembly rates were obtained with semi-skilled, inexperienced workers. Faster assembly doubtless would result if experienced carpenters were used. Careful stacking of the lumber conveniently located near the jig increased assembly rate.

Erection experience—Lightweight trussed rafters were used on three buildings erected on University farms. These included a turkey shelter and two hay shelters. All structures were erected with farm workers or student labor inexperienced in carpentry. The use of trussed rafters was a completely new concept to them.

24-foot span turkey shelter — Trussed rafters were used to span a 24-foot wide center bay of a 48 by 48-foot turkey shelter on a University poultry farm. The trussed rafters were spaced 3' 0" o.c. with 2x4-inch purlins nailed flat to support metal roof covering. A companion structure of the same dimensions but erected with trusses 6' 0" o.c. and 2x4-inch purlins on edge, was constructed at the same time. Comparative erection data were kept on the two structures. Both were erected by the same work crew.

Fig. 18—Erection method for lightweight trussed rafters of moderate spans. Projecting board at ridge was used to secure rafter temporarily after it was swung upright.

Erection time for both structures

was the same except for the roof framing and roof application. The lightweight trussed rafters required less total time to fabricate than the heavier trusses, even though only half as many trusses were needed. The light weight and simplicity of fabrication made this possible. Erection of the roof frame was faster when trussed rafters were employed, since two men could easily handle them. Two men on the ground lifted them up to the girders in an inverted position. Then they were rotated into place as illustrated in Figure 18. The application of the purlins was also easier since they were applied flat and were nailed directly to the trussed rafter top chords. Purlins for the other building, with trusses 6' 0" o.c. were placed on edge, toe-nailed to the truss, and then anchored with steel straps. This extra fastening, plus the hazard to the workmen due to the wide spacing of the trusses, slowed erection compared to the lightweight trussed rafters.

Workmen found that they could more readily walk on and work from the flat purlins used on the trussed rafters when applying the roof covering. Therefore, roof application time was less for the shelter with trussed rafters as compared to the shelter with the trusses. The workers also voiced a strong preference for working on the shelter with the trussed rafters.

30-foot span hay shelters—Two hay shelters were erected on the University dairy farm using 30-foot span lightweight trussed rafters for the roof framing. Attempts were made to erect the trussed rafters in the same manner as for the turkey shelter, but because of the greater length, the trussed rafters were too flexible to rotate up into position. They could be placed in an inverted position on the girder from the bed of a truck but would sag and slip off the girder when attempts were made to turn them upright. A saddle and hoist were then erected on the roof as illustrated in Figure 19. After three trussed rafters were manhandled into place to provide support for the hoist, the trussed rafters were easily hoisted into place. A different erection method was used for the second hay shelter. A tractor with a front-end loader was placed on the bed of a truck to provide extra lift height. The trussed rafters were then placed in the bucket of the loader and raised onto the girders. Men on either girder steered the ends of the trussed rafters onto the girder and into position.

Table 9 lists the man hours required to construct the first 30x120-foot hay shelter and the number of men in the work crew for each job. All were inexperienced workers. Most of the crew worked only part-

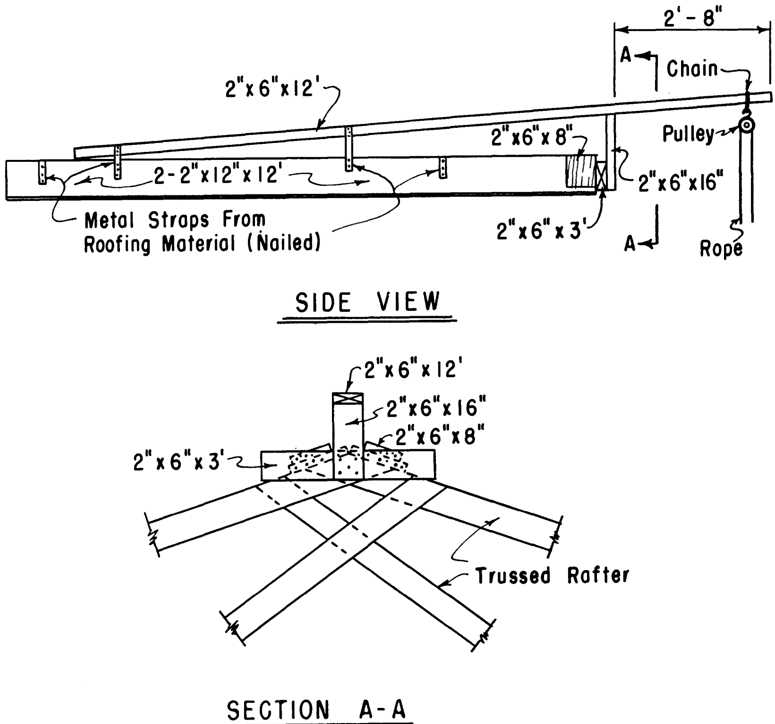


Fig. 19—Ridge mounted saddle hoist used for lifting 30-foot trussed rafters for hay shelter.

time, as between classes. Experienced or full-time workers should result in higher efficiency.

A severe wind storm, with gusts up to 70 mph, struck Stillwater during construction of the first hay barn. Approximately ⅓ of the

Table 9.—Man-Hour Requirements For Hay Shelter Construction With Lightweight Trussed Rafters (Shelter Size 30 Ft. by 120 Ft.)

Task	No. Men Required	Man-hours Required
Construction of Jig	2	16
Fabrication of Rafter	3	41
Layout of Building	2	6
Setting and Tamping Poles	3	36
Notching and Sawing off Poles	2	24
Installation of Plates	3	24
Trimming Rafters	2	10
Placing Rafters on Plates	5	75
Roofing and Braces Installation	4	120
Clean-up	2	8
TOTAL Man-hours		360
Man-hours/sq. ft of Shelter Area		1/10 man-hr./sq. ft.

trussed rafters were in place at the time but were not permanently stayed. As a result, all trussed rafters were blown down and many were broken. Although the rafters had been guyed in place with heavy ropes, the force of the wind was too great and the ropes parted. Since buildings at this stage of completion are especially vulnerable to storms, precautions should be exercised.

Summary

A design has been developed for a lightweight trussed rafter for farm building erection. The design appears to possess advantages that include more convenient and rapid assembly and greater efficiency in use of wood as a structural material, compared to other designs that have been commonly used.

The present lightweight trussed rafter design calls for 1-inch undressed lumber, of No. 1 grade Southern Yellow Pine, or equivalent in other species. All of the joints are assembled by overlapping the ends, nail-gluing the overlapped areas, then trimming the ends to conform to the outline of the trussed rafter.

This design performed as well as or better than conventional designs assembled with 2x4-inch dressed lumber during structural loading experiments. The lightweight design was load-tested in slopes and spans varying from 20 to 36 feet in span and 3 in 12 to 5 in 12 in slope of the top chord. Structural performance under load was satisfactory for all of these variations tested.

Erection and use of observations of lightweight design trussed rafters as used in construction of three typical shelter buildings revealed that it was well suited to the needs and capabilities of farm building construction crews.

Conclusions

1. A trussed rafter design that is easy to assemble by farm building constructors and that is structurally efficient in use of wood can be obtained by use of high quality, undressed 1-inch lumber.

2. The use of 1-inch undressed lumber for fabricating farm building trussed rafters simplifies joint assembly and produces greater structural efficiency in use of wood, compared to 2-inch dressed lumber.

3. Structurally adequate, lightweight trussed rafters can be built

with 1x6-inch undressed lumber in spans up to and including 30 feet and 1x8-inch undressed lumber in spans of 32 to 36 feet.

4. Short and long term loads on lightweight trussed rafters in spans of 20 to 36 feet and top chord slopes of 3 in 12 to 5 in 12 produced ridge deflections of 1/450 of the span or less under superimposed gravity loads of 100 pounds or more per foot of span, uniformly distributed over the top chord.

5. Casein glue-nailed joints in undressed 1-inch lumber subjected to single shear produced by an eccentric tensile load had an average ultimate strength of 472 psi, which appeared adequate for fabricating the overlapping joints in lightweight trussed rafters assembled from 1-inch undressed lumber.

6. The ultimate strength of the joints in a lightweight trussed rafter can be increased by a factor of approximately 1.7 if ten instead of six penny common wire nails are used. A third short member or nailing block 1-inch thick must be applied at each joint to receive the points of the ten penny nails.

7. No. 1 Southern Yellow Pine kiln dried lumber or structurally equivalent grade in other species should be used for fabrication of trussed rafters with 1-inch undressed lumber. The use of undressed lumber does not imply that structurally inferior or ungraded material is acceptable for trussed rafter construction.

8. The 24-foot span lightweight trussed rafters were assembled at a rate of 0.6 man hours per trussed rafter by a crew of two semi-skilled men. The 30-foot span lightweight trussed rafters were assembled at the rate of 0.75 man-hours per trussed rafter by a 3-man semi-skilled crew.

9. Erection of a 24-foot span farm shelter roof proceeded more rapidly and with less hazard to workmen when lightweight trussed rafters were used compared to heavier trusses assembled from 2-inch dressed lumber 6' 0" on centers.

10. When lightweight trussed rafters of 30- and 36-foot spans are handled, as during erection, they tend to bend excessively in a lateral direction. Erection procedures should be used that overcome this behaviour. After the trussed rafters have been installed in place and stayed by the roof deck or spaced nailers, lateral stability is adequate.

11. Trussed rafters assembled with casein glue should be stockpiled under cover until used. Otherwise, moisture damage to the joints can occur.

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