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Structural Development and Evaluation of a Modular House

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The Virginia Agricultural and Mechanical College came into being in 1872 upon acceptance by the Commonwealth of the provisions of the Morrill Act of 1862 "to promote the liberal and practical education of the industrial classes in the several pursuits and professions of life." Research and investigations were first authorized at Virginia's land-grant college when the Virginia Agricultural Experiment Station was established by the Virginia General Assembly in 1886.

The Virginia Agricultural Experiment Station received its first allotment upon passage of the Hatch Act by the United States Congress in 1887. Other related Acts followed, and all were consolidated in 1955 under the Amended Hatch Act which states "It shall be the object and duty of the State agricultural experiment stations . . . to conduct original and other researches, investigations and experiments bearing directly on and contributing to the establishment and maintenance of a permanent and effective agricultural industry of the United States, including the researches basic to the problems of agriculture and its broadest aspects and such investigations as have for their purpose the development and improvement of the rural home and rural life and the maximum contributions by agriculture to the welfare of the consumer . . . ."

In 1962, Congress passed the McIntire-Stennis Cooperative Forestry Research Act to encourage and assist the states in carrying on a program of forestry research, including reforestation, land management, watershed management, rangeland management, wildlife habitat improvement, outdoor recreation, harvesting and marketing of forest products, and "such other studies as may be necessary to obtain the fullest and most effective use of forest resources."

In 1966, the Virginia General Assembly "established within the Virginia Polytechnic Institute a division to be known as the Research Division . . . which shall encompass the now existing Virginia Agricultural Experiment Station . . . ."

STRUCTURAL DEVELOPMENT AND EVALUATION OF A MODULAR HOUSE

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Cover: Recent photograph of the test house, Martinsville, Virginia, where it is owned and rented by Nationwide Homes.

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ABSTRACT

A 12' x 44' house module utilizing less than half as much framing lumber as usual was built by Nationwide Homes and delivered to Virginia Tech for structural evaluation. It was subjected to the following combinations of simulated loading: (a) wind load on the front wall and roof, (b) snow load on the roof, and (c) live load on the floor.

The module was very resistant to wind load and distorted very little with forces of 26.0 psf on the front wall and under the overhang while 20.2 psf uplift was applied to the roof. The above loads did fail the foundation and turned up the overhang.

The roof structure failed when 93.6 psf of simulated snow load were applied but it successfully withstood 83.2 psf. For one month loading this reduces to approximately 58 psf or nearly three times the minimum FHA allowable load.

The continuous and composite floor system failed at 202.8 psf of load, which is approximately five times design live load. Much of the carrying capacity of the floor was attributable to composite action by exterior walls and partitions (4).

INTRODUCTION AND PURPOSE

The executive personnel of Nationwide Homes have a long and distinguished record in the business of providing housing for low and moderate income families. For many years the firm has operated in a field of competition which has put many out of the housing business. Ralph Lester, former Chairman of the Board, and James Severt, President of Nationwide Homes, represent the second generation of home builders. Many others of the firm also have the necessary knowledge in the complex field of housing production, marketing, and financing to be successful. They are constantly seeking ways and means to reduce housing costs while maintaining and/or improving housing quality.

An example of cost-cutting pertinent to this study that Nationwide Homes' personnel initiated nearly twenty years ago is the substitution of one-inch S2S, sized two sides, wall and roof framing for some conventionally financed houses. Apparently those houses have served equally as well as others built with two-inch lumber (about twice as much total lumber per house).

Interest continues to increase in reducing housing costs through the conservation of materials, which also conserves energy. Evidence of such interest was indicated in 1975 by the American Association of Housing Educators and the Building Officials and Code Administrators International, Inc. (1,2).

Over twenty-two years ago, some of Virginia Tech's housing research efforts were concentrated on continuous floor framing systems, utilizing one-inch S2S lumber. The author's home, built in 1961, utilizes a continuous floor framing system of S2S 1 x 10 joists (3). The home has served satisfactorily from the beginning even though it has only 43 percent as much framing material in the floor as would have been used in a conventional system.

With this kind of experience behind the executives of Nationwide Homes and representatives of the Virginia Tech Housing Research Team, it was naturally decided to construct the experimental modular house frame with all one-inch lumber. The purpose of this study was to combine the economy housing experience of personnel from Nationwide Homes and Virginia Tech in developing and structurally evaluating a prototype module which will meet use and regulatory requirements at minimum production costs.

Scope

This study should be considered primarily exploratory since it was limited to a single full-scale module as illustrated in Figures 3 and 4. However, all of the structural members and components were replicated with three floor joists, 21 trusses, and several dozen studs. The specimen was subjected to three major tests: (a) simulated wind load on the front wall and roof; (b) simulated snow load on the roof; and (c) simulated live load on the floor. Ultimate or failing loads were applied in all three cases. Structural performance was measured by recording building movement, displacement, or distortion when predetermined loads were being applied.

It should be noted that even with a single full-scale module there were many opportunities for evaluating repetitive members and components. For example, there were 21 roof trusses of the type shown in Figure 7. Also with the floor system shown in Figure 2 supported on the foundation shown in Figure 1, joist spans were repeated six times and the center joist spans were repeated three times. However, none of the components can be considered true replicates because each occupied a different location with respect to the foundation, side walls, and partitions (4).

MATERIALS AND METHODS

Module Description

The test specimen is the front half of a Nationwide Homes three bedroom house, the Dover, as illustrated in Figures 3, 4, and 8. In outward appearance it is the same as the standard Dover (7) at that stage of construction even though it required less than half as much framing. The 528 ft^2 test module is framed with one-inch S2S, sized two sides, No. 2 Southern Pine. The continuous and composite flooring system consists of strip hardwood flooring glue-nailed to the one-inch pine board subfloor which was glue-nailed perpendicular to the 1 x 10 joists spaced 3 feet apart. Walls, partitions, and roof structures were framed with 1 x 4's instead of 2 x 4's. The exterior wall sheathing is 3/8 inch plywood glue-stapled to the 1 x 4's spaced 16 inches apart. Half-inch plywood roof sheathing was stapled to trusses of 1 x 4's which were spaced 2 feet apart. The interior finish is half-inch gypsum board glue-nailed to the 1 x 4 framing.

Test Procedures

Simulated Wind Load

The module, which had been built in the Nationwide Homes' Martinsville, Virginia, plant, was delivered to the Virginia Tech structures laboratory near Blacksburg, Virginia, where it was anchored to the foundation shown in Figure 1. The first test was the simulation of wind-load on the front wall, hinged overhang, and roof. Load was applied to the front wall and hinged overhang by inflating an air bag (6) between the surfaces to be loaded and a reaction wall constructed a few inches in front as shown in Figures 3 and 5. Uplift wind-load pressure on the 3-in-12 slope roof was simulated with hydraulic cylinders rigged as shown in Figures 5 and 6.

Wind-load pressures for the front wall and roof were computed by standards recommended by the American Society of Agricultural Engineers, the American Society of Civil Engineers, the American Metal Buildings Association, and the U.S. Department of Defense. The average inward pressure on the front wall when the wind is blowing perpendicular to and toward it is approximately 29 percent more than the uplift pressure on the roof for a 3-in-12 slope. Wind-load pressure at this ratio of 29 percent more on the wall than roof was applied at several load levels.

The primary objective of the wind-load test was to structurally evaluate the module. An accepted measure of how well buildings resist wind-load is often expressed in racking or horizontal drifting movement of the structure at any particular elevation with respect to another elevation. In this case, the horizontal movement at the top plate in relation to the bottom plate was measured by hanging a plumb bob from a point on the exterior wall at the top plate level at each end of the module. (Movement at the top plate was indicated as it moved along a horizontal scale mounted at the bottom plate level.) Racking movement at each end of the module was read from the scale at each load level.

Simulated Gravity Load on Roof

The original plan was to also use hydraulic cylinders for simulating snow-load on the roof, as shown in Figure 6, except in a downward direction. However, the procedure was changed to the air-bag loading method in order to impose a more uniformly distributed load perpendicular to the roof. In order to compensate for the horizontal component of the air-bag force, a pipe roller was rigidly supported horizontally, but free to move vertically, between the house and the laboratory frame. The roller was located opposite the top plate.

An air bag was again inflated between the roof and a reaction platform a few inches above. Air pressure in the bag was controlled and applied in 10.4 psf increments.

Each increment of loading was maintained at least five minutes. The 10.4 psf is equal to 2 inches of water, which was conveniently measured with the manometer shown in Figures 11 and 12.

Two trusses over each room were selected for instrumenting with continuous deflection recorders. The selected trusses--3, 4, 11, 12, 19 and 21--were well removed from partitions and end walls, all of which tend to give additional support. These trusses were considered to be the most critical because of their locations, from 3 feet to more than 7 feet 6 inches from partitions.

Simulated Gravity Load on Floor

In order to rig and instrument the module for floor testing, it was necessary to elevate it from normal foundation height (Fig. 3) to that height shown in Figure 11. Each joist was instrumented with a continuous deflection recorder at all supports and at or near midspan where deflection was expected to be greatest. Corrected net deflection of each span was obtained by subtracting support settlement from the total recorded deflection.

The air-bag method was used for loading the floor of all three rooms. Hydraulic cylinders were used in tension under the closet areas. To assure equalization of air pressure, all three bags were (a) interconnected with one-inch hoses and (b) each simultaneously inflated by individual 1/4 inch hoses which were connected to a pressure manifold by a hand valve on the compressor. Pressures were observed to be the same in all three bags as measured by individual manometers for each bag. The air-bag reaction platforms were held in place by steel straps going through the floor in the corners of all three rooms and connecting to either soil anchors or special reaction beams under the wood foundation panels.

The final load-test was conducted as a public demonstration in order to immediately inform many housing decision makers of the results. In addition to selected personnel of Nationwide Homes and Virginia Tech, national and state representatives of building codes and government finance agencies were invited. Other researchers, builders, the press, and the local general public were also invited, and many were present. On the first day of the demonstration, all observers were invited to thoroughly inspect the test module. The inspection included walking and jumping on the living room floor as well as observing the floor structure from below while others were walking and jumping on it. After the inspection, the loading apparatus was reinstalled and the final test was conducted on the second day of the demonstration.

RESULTS AND DISCUSSION

Simulated Wind Load

Wind load racking resistance of the module was excellent. It withstood 20.8 psf on the front wall simultaneous with 15.9 psf uplift on the roof for more than an hour, resulting in a net horizontal movement of 0.19 inch at each end. One end completely recovered when the load was removed, and the other had only 0.03 inch of set 15 minutes after the load was removed. The foundations did not resist horizontal movement so well at the above load. At one end, the module moved 0.37 inches and did not recover any of that movement when the load was removed.

The front wall was finally loaded to 26.0 psf with roof uplift of 20.2 psf. The foundation (Figure 10) failed and permitted an additional movement of 1.06 inches or a total movement of 1.43 inches at one end. The front overhang turned up when subjected to the above loads. Racking movements at the ends were 0.63 inch and 0.34 inch, which recovered to 0.13 inch and 0.09 inch, respectively, when the load was removed.

Except for the foundation and front overhang, the module appeared to be very resistant to wind load. The roof sheathing, to which the uplift forces were applied, showed no indication of failure or separation from the rough 1 x 4 roof trusses. The trusses and their attachments to the module all performed well at the highest loads applied, which were 26.0 psf on the front wall and under the overhang and 20.2 psf uplift on the roof.

Simulated Gravity Load on Roof

An examination of Figures 14, 15, and 16 does not reveal that any of these trusses were influenced by the nearness of partitions or end walls; however, all seven failures did occur over the living room, where distances were greatest from partitions.

The ultimate or failing load for the living room trusses was 93.6 psf, and the last loading increment which was sustained for seven minutes was 83.2 psf. On the basis of duration of maximum load data published by the National Forest Products Association (8), the 83.2 psf should be reduced to approximately 58 psf for one month loading and 54 psf for one year loading. If one month of loading is sufficient, even the weakest trusses of the test module had a carrying capacity of almost three times the FHA minimum design load for this roof structure.

The initial truss failure in every case resulted from buckling of the 1 x 4 diagonal web member. Failure of the web members caused the upper rafters to fail from bending stresses, as shown in Figures 17 and 18. The whole roof structure could be strengthened substantially by laterally supporting the diagonal web members at the center with a 1 x 4 stringer running the full length of the house.

Simulated Gravity Load on Floor

Deflection data for the floor-load tests up to 145.6 psf are presented in Table 1. Graphical presentations of the floor performance are shown in Figures 8 and 9. Spans No. 1 and No. 3 are the same, and the loading was distributed as nearly uniformly as possible with air bags in all rooms and hydraulic cylinders under the closet area. Span No. 1 was obviously much more rigid than span No. 3. The difference in rigidity is attributable to composite action between the floor structure, and such elements as exterior walls of 3/8 inch plywood staple-glued to 1 x 4 studs with 1/2 inch gypsum board glue-nailed. These elements were very effective in stiffening the floor below. This is well illustrated in Figure 9 in that joist No. 1 deflected only about 10 percent as much as in span No. 3. Also, the exterior wall over joist No. 1 of span No. 1 has a double window over the center of the span and a door almost over the interior support (Fig. 8). The door opening probably weakens the wall most because it is so near the support. These open-

Table 1. Floor Load-Test Results

Live Load PSF	Joist No.	Deflection, In. Span 1	Deflection, In. Span 2	Deflection, In. Span 3	Live Load PSF	Joist No.	Deflection, In. Span 1	Deflection, In. Span 2	Deflection, In. Span 3
10.4	1	0.00	0.01	0.00	83.2	1	0.03	0.08	0.29
	2	0.05	0.03	0.07		2	0.40	0.20	0.79
	3	0.05	0.02	0.10		3	0.49	0.16	0.73
	4	0.04	0.02	0.07		4	0.38	0.18	0.57
	5	--	--	0.00		5	--	--	0.02
20.8	1	0.01	0.01	0.02	104.0	1	0.04	0.11	0.39
	2	0.10	0.04	0.14		2	0.49	0.26	0.97
	3	0.11	0.03	0.21		3	0.63	0.21	0.89
	4	0.09	0.03	0.16		4	0.47	0.23	0.69
	5	--	--	0.00		5	--	--	0.03
41.6	1	0.02	0.03	0.12	124.8	1	0.05	0.15	0.49
	2	0.20	0.09	0.28		2	0.59	0.32	1.16
	3	0.23	0.09	0.40		3	0.79	0.26	1.07
	4	0.04	0.02	0.07		4	0.38	0.18	0.85
	5	--	--	0.01		5	--	--	0.04
62.4	1	0.03	0.06	0.20	145.6	1	0.06	0.18	0.58
	2	0.30	0.14	0.60		2	0.70	0.40	1.31
	3	0.35	0.11	0.56		3	0.94	0.31	1.23
	4	0.28	0.13	0.42		4	0.71	0.35	0.97
	5	--	--	0.02		5	--	--	0.05

ings in the exterior wall greatly reduce its capacity for strengthening the floor below. The exterior wall over joist No. 1 in span No. 1 has only one small window in it.

Span No. 2 is about 18 percent longer than either of the other two but was considerably stiffer, as shown in Figures 8 and 9. It was greatly strengthened by the closet partitions which tend to act as overhead supports for the floor. Because the partitions were interconnected to the rather rigid exterior walls, they acted as supports with the floor systems suspended below.

When the original foundation or support system was designed, computer analysis showed that the end supports should be set in about two feet. If the end spans were decreased by 2 feet, providing a cantilever at both ends, the 16-foot 4-inch center span would be stressed more than the end spans. However, stress in the center span would still be less than in the end spans as the module was finally designed, built and tested. Structural analysis showed that the flooring system as finally built would more than meet design requirements even with the exterior supports at the ends. Test results showing that the exterior supports can be located anywhere within 2 feet of the ends confirmed the analysis. If the supports are located at the ends, the adjacent spans should be decreased to 13 feet 4 inches for best performance.

CONCLUSIONS

The following statements are based on computations, laboratory tests of the full-scale module, and many years of research and field experience with this kind of structural situation.

1. The basic module as constructed with less than half the framing lumber as conventionally used is many times stronger than required by FHA and other construction standards.
2. The foundation used in this study, consisting of concrete block supports, was the weakest part tested. It is recommended that (a) the foundation be reinforced or strengthened, (b) special attention be given to anchorage of module to plate as well as plate to foundation, and (c) the hinged overhang be shortened to decrease the upper and lower surfaces, both of which are exposed to severe wind loading.
3. On the basis of these tests, the roof trusses should be analyzed and the web members relocated if necessary to get more load-carrying capacity without increasing their cost. The diagonal web should definitely be laterally braced to prevent buckling.
4. The foundation supports should be located to take advantage of the continuous and composite action of the flooring system in combination with exterior walls and partitions.
5. The load carrying capacity of the walls and partitions with 1 x 4 studs 16" O.C. should be analyzed to determine stackability of modules with this framing system.
6. This experimental flooring system, which is very resistant to deflections, should also be tested for vibrational resistance (5).

ACKNOWLEDGMENT

The author gratefully acknowledges the encouragement and support of Ralph Lester, former Chairman of the Board of Nationwide Homes, Inc. In addition to substantial financial support, his firm provided the test module and cooperated fully with the university research personnel.

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8. National Forest Products Association, "Wood Structural Design Data," 1970.

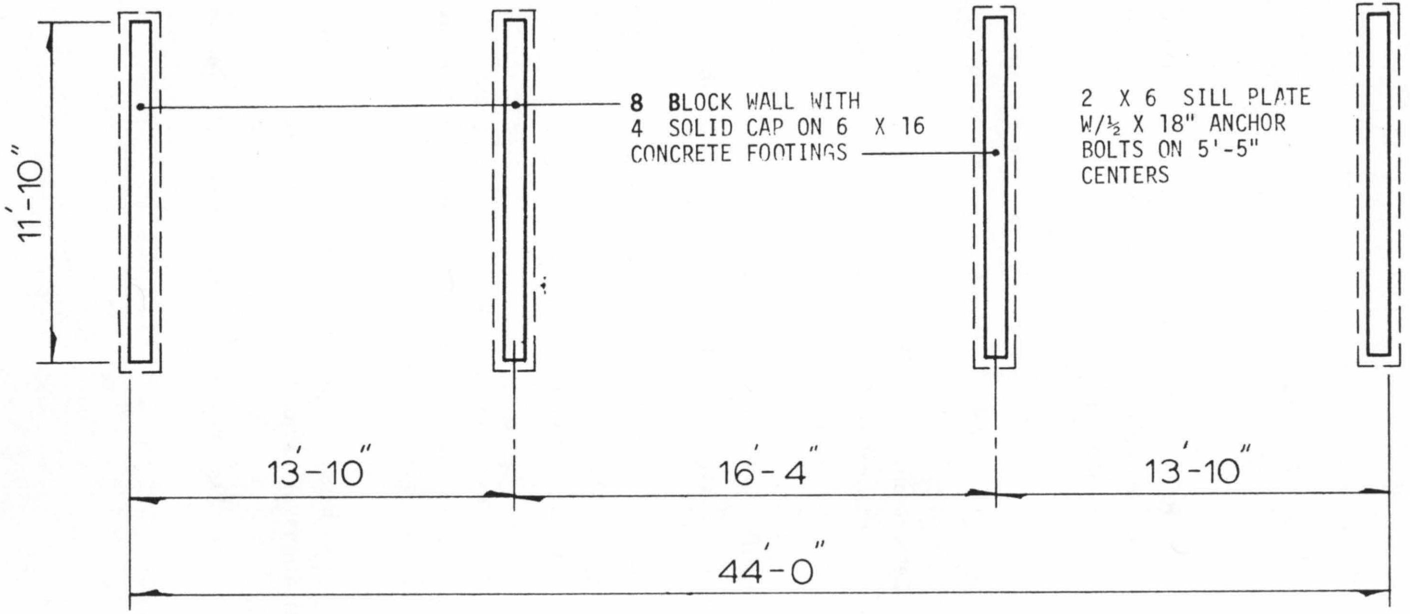
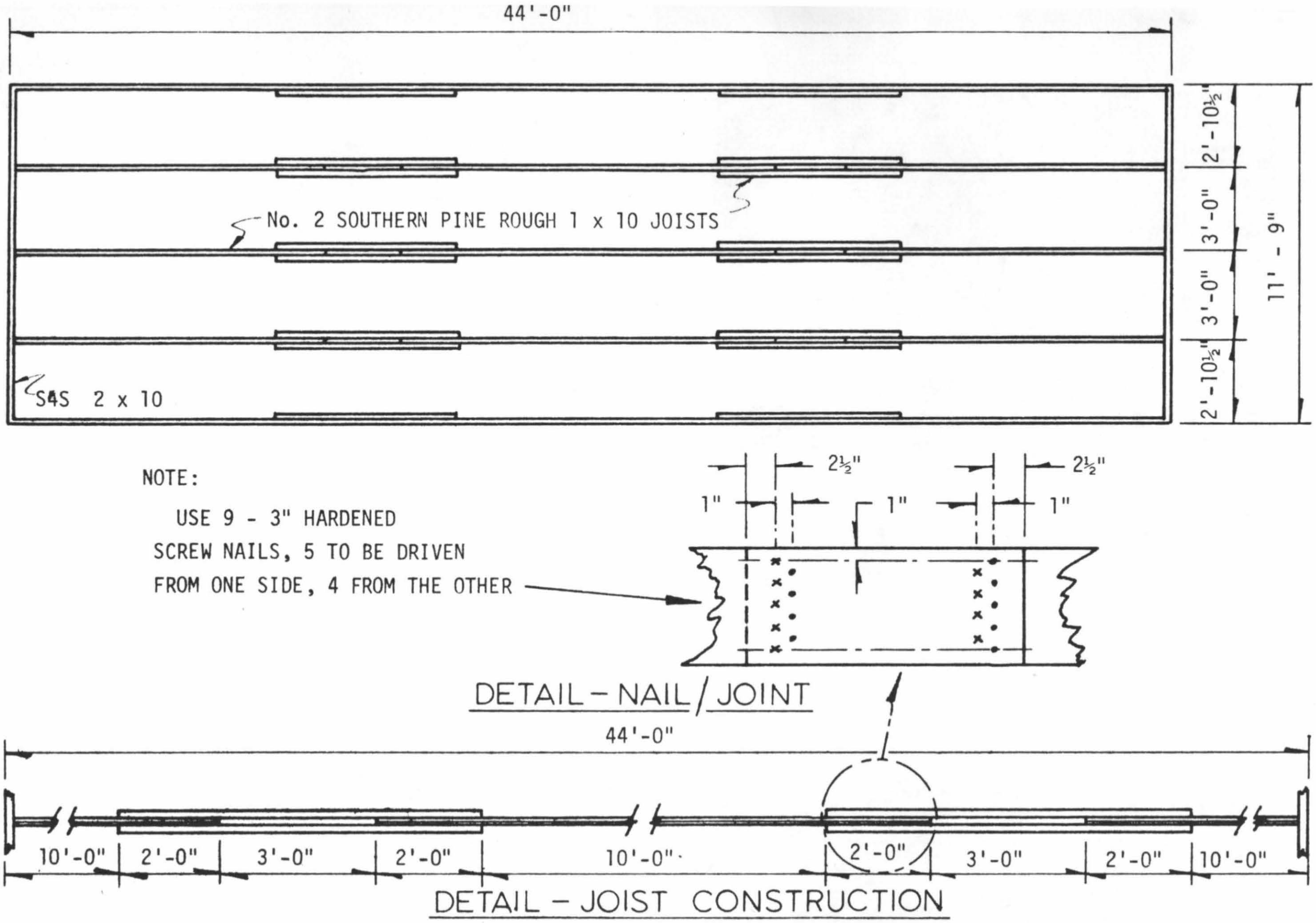


Fig. 1. FOUNDATION PLAN FOR MODULE



NOTE:

USE 9 - 3" HARDENED SCREW NAILS, 5 TO BE DRIVEN FROM ONE SIDE, 4 FROM THE OTHER

Fig. 2. FLOOR FRAMING PLAN FOR TEST MODULE

Fig. 3. THE MODULE

This 12' x 44' test specimen is framed entirely with one-inch S2S, sized two sides, No. 2 Southern Pine lumber. It is being rigged for simulated wind-load testing by (a) inflating an air bag between the front wall and a "reactor" wall which is under construction, and (b) up-lift forces on the roof by hydraulic cylinders (See Figures 5 and 6).

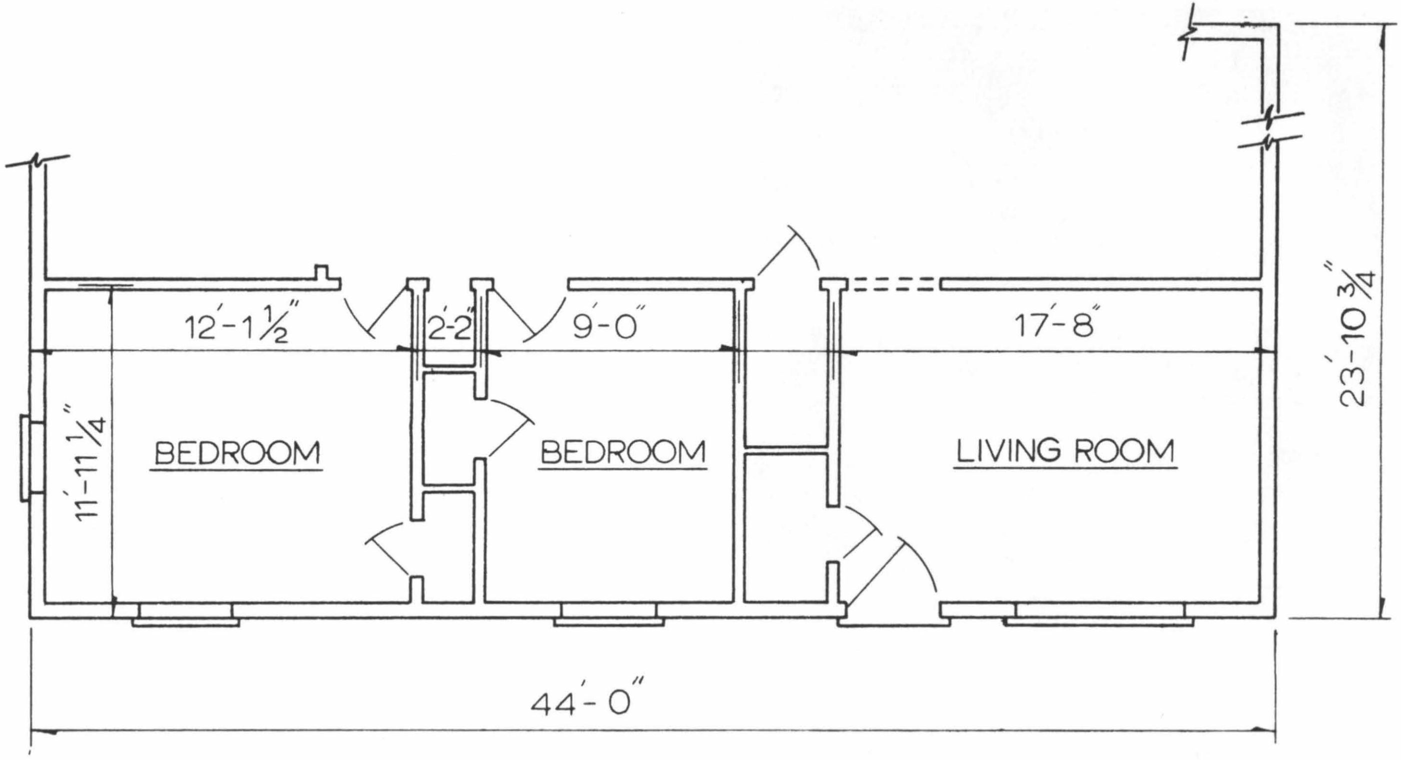


Fig. 4. FLOOR PLAN

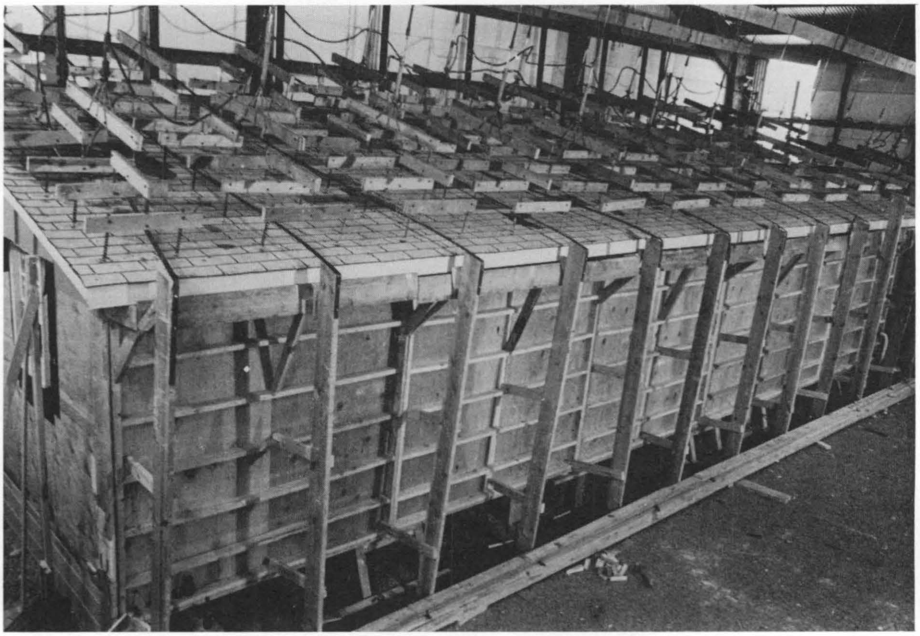


Fig. 5. THE MODULE RIGGED FOR SIMULATING WIND-LOAD TESTING (See Figures 3 and 6).

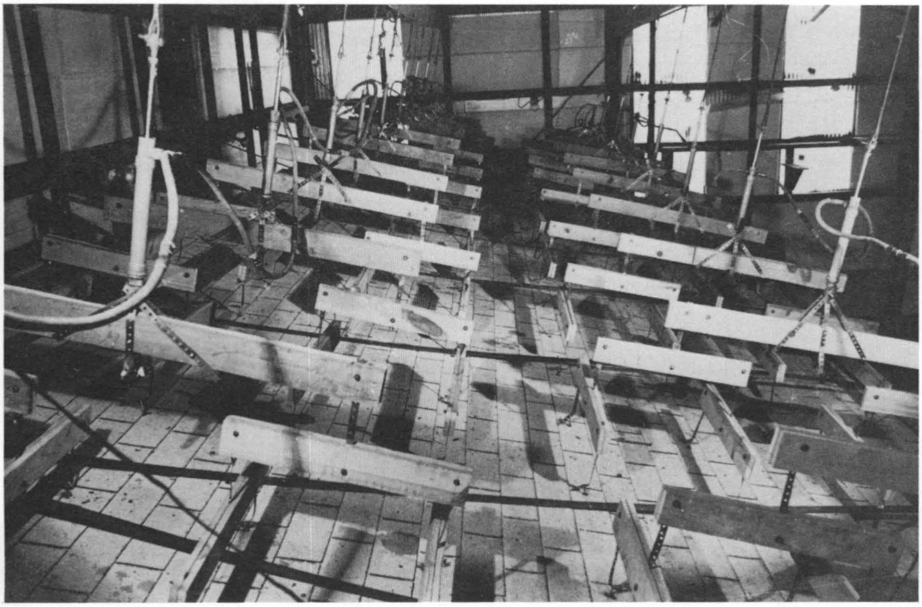


Fig. 6. RIGGED FOR SIMULATING WIND-LOAD UPLIFT FORCES BY HYDRAULIC CYLINDER (See Figure 5)

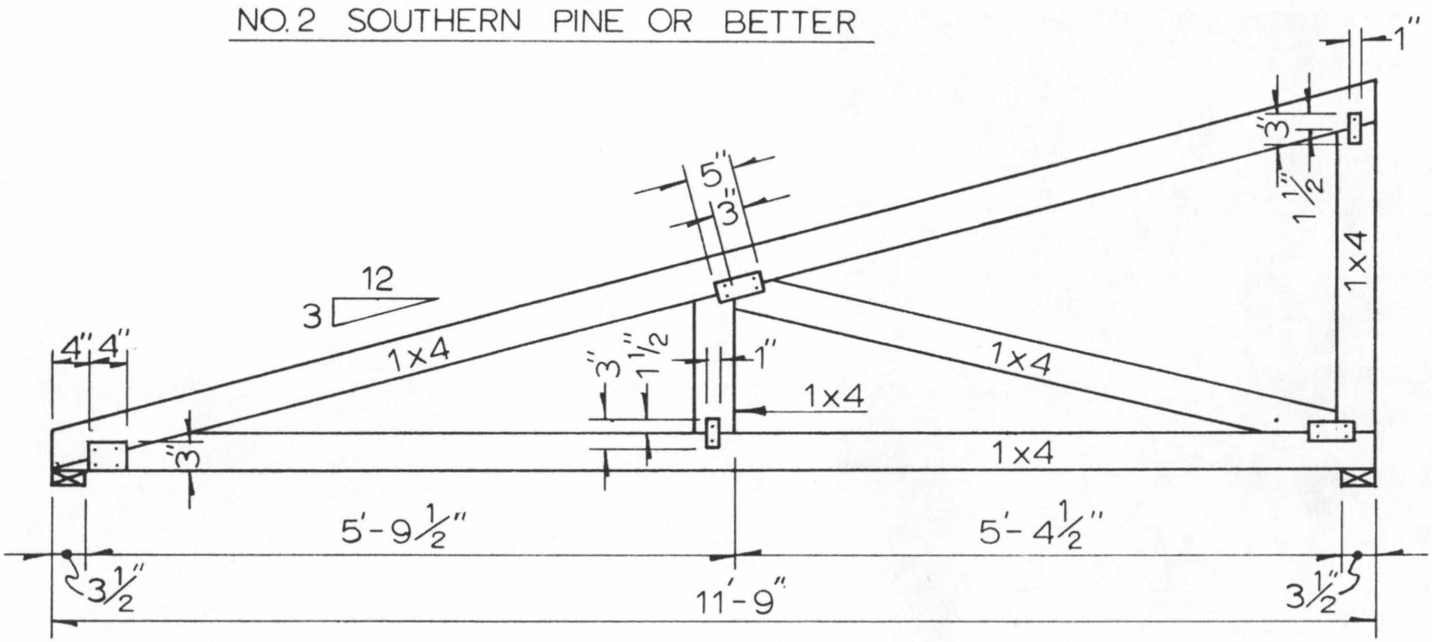


Fig. 7 MODULE TRUSS, SPACED 2 O.C.

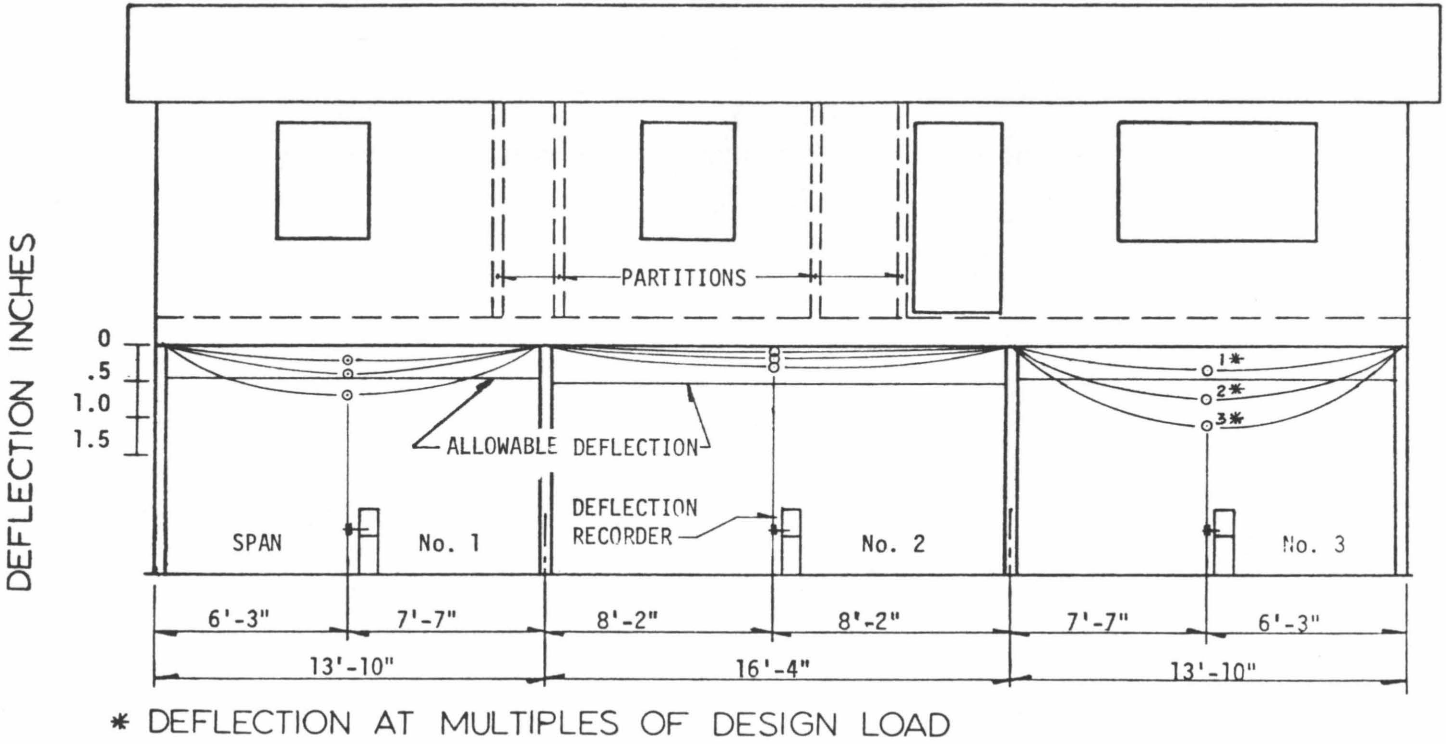
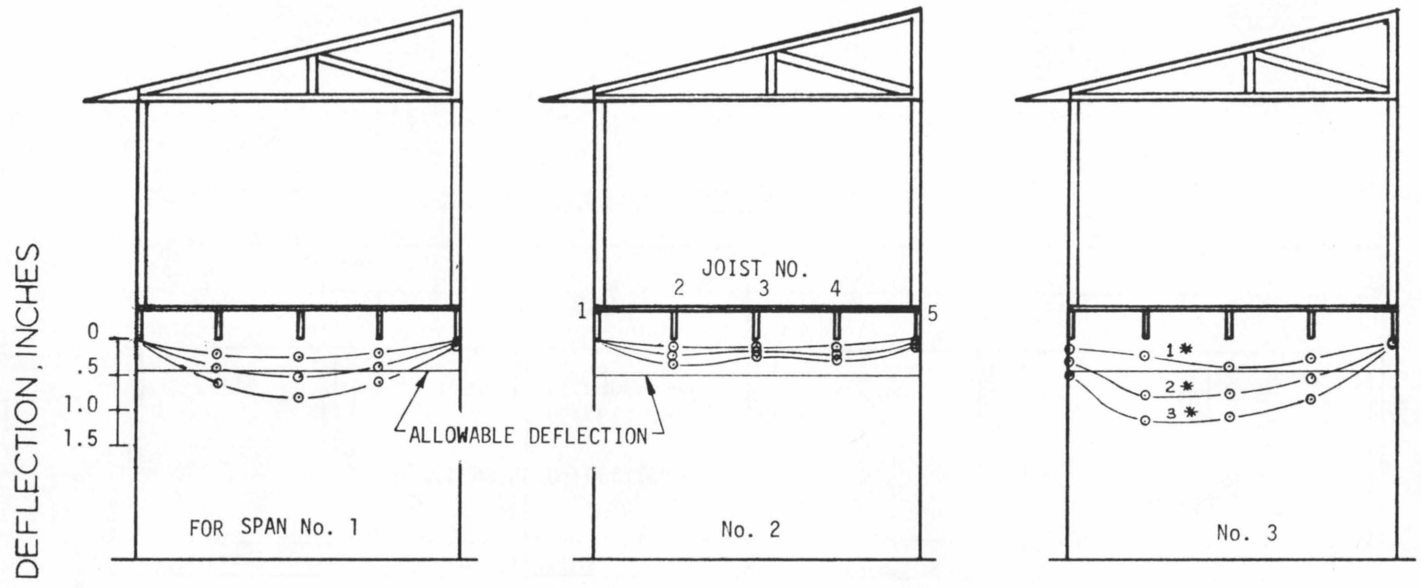


Fig. 8. FLOOR SYSTEM DEFLECTIONS FOR THE AVERAGE OF 3 INTERIOR JOISTS



* DEFLECTION AT MULTIPLES OF DESIGN LOAD
(SEE FIGURE 8)

Fig. 9. FLOOR SYSTEM DEFLECTIONS FOR INDIVIDUAL JOISTS OF EACH SPAN

Fig. 10. FOUNDATION FAILURE

This failure resulted from appying (a) 26.0 psf to front wall and lower surface of overhang and (b) 20.2 psf uplift perpendicular to roof surface.

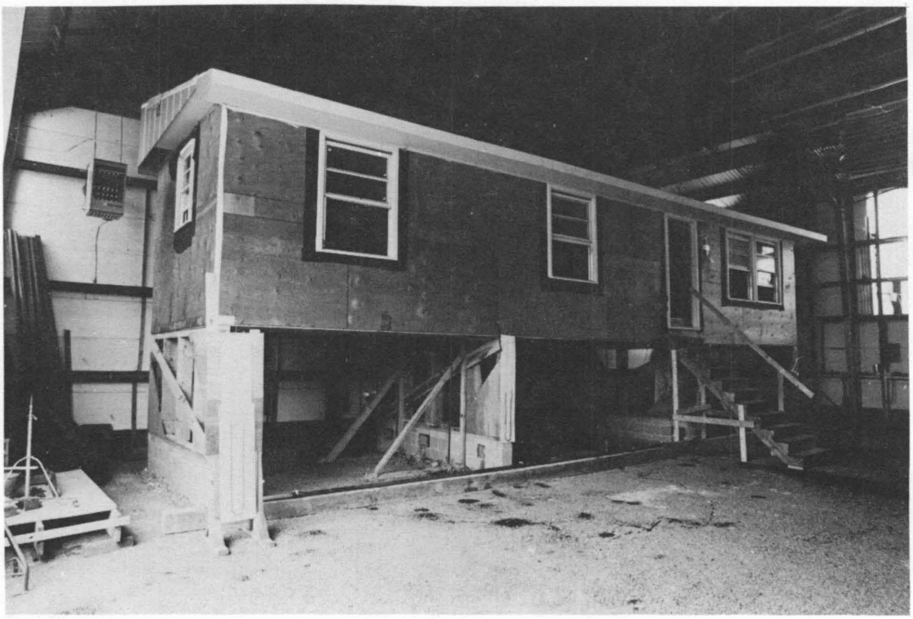


Fig. 11. MODULE ELEVATED FOR FLOOR LOAD-TESTING

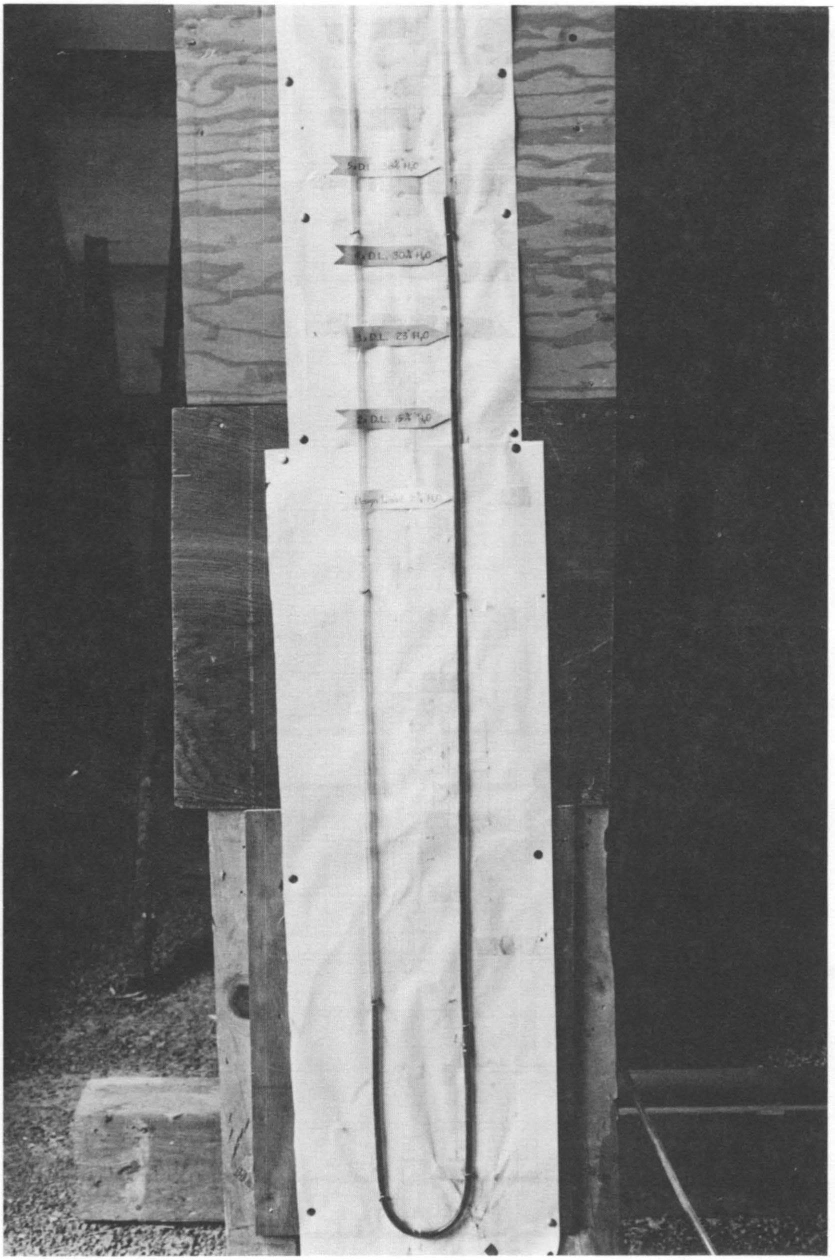


Fig. 12. THE MONOMETER USED FOR MEASURING SIMULATED LOADING BY SENSING PRESSURES INSIDE AIR BAGS

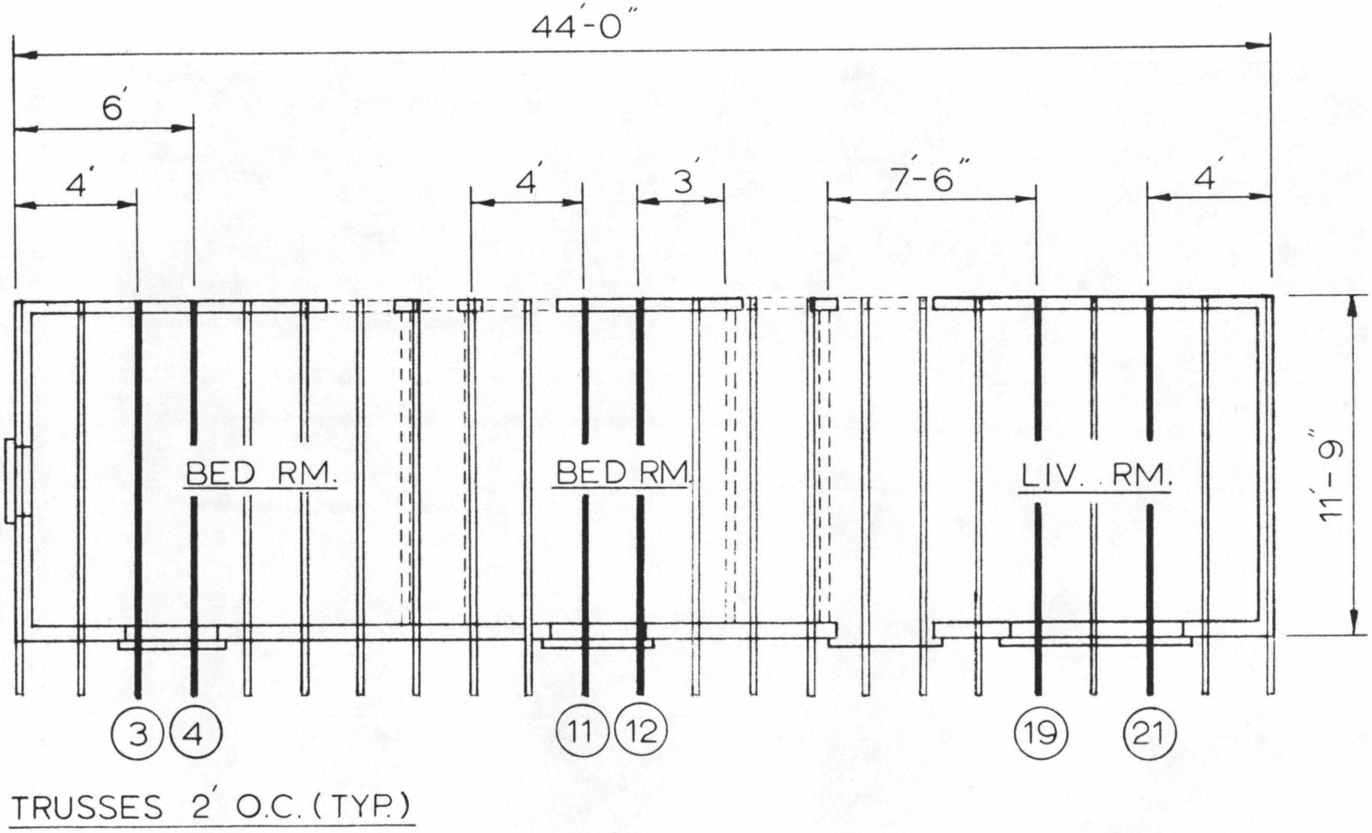


Fig. 13. ROOF TRUSS LOCATIONS

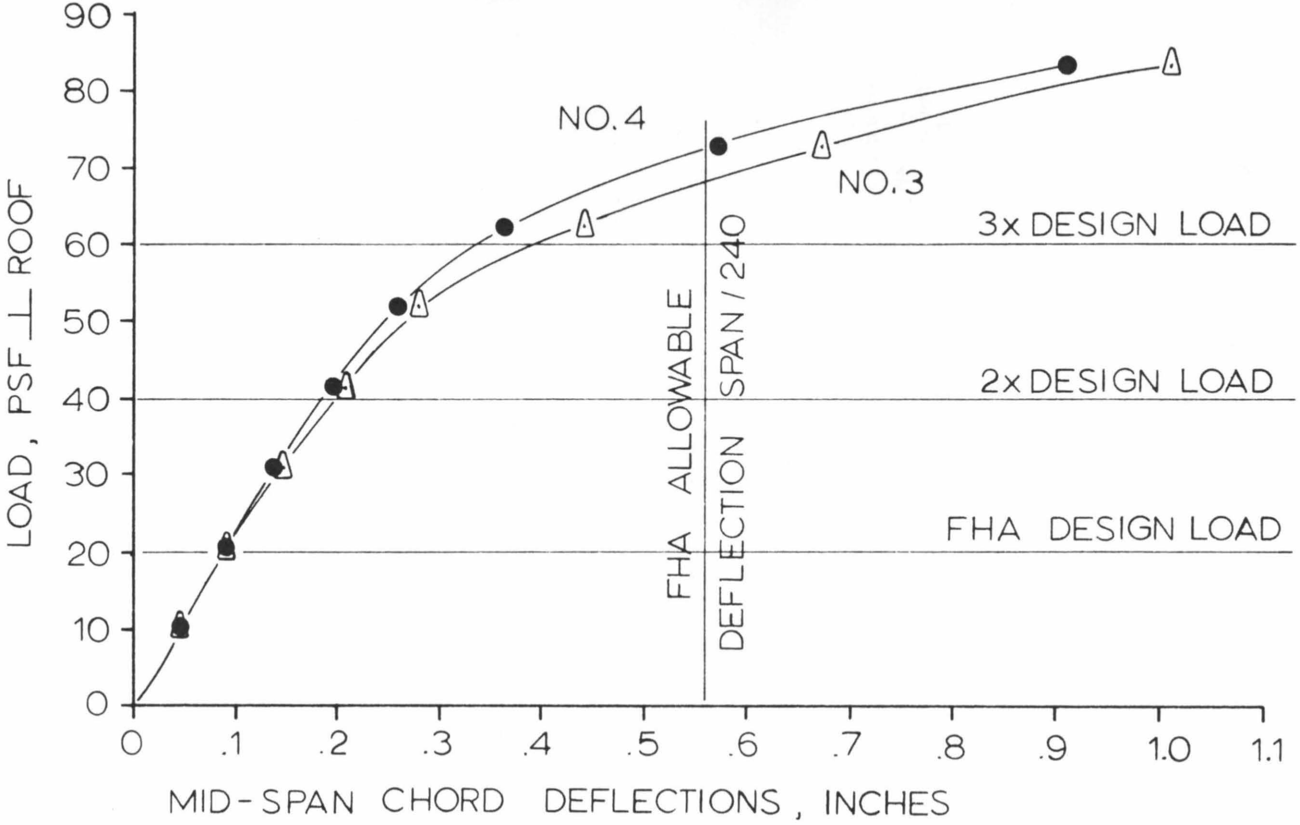


Fig. 14. TRUSS PERFORMANCE OVER END BEDROOM

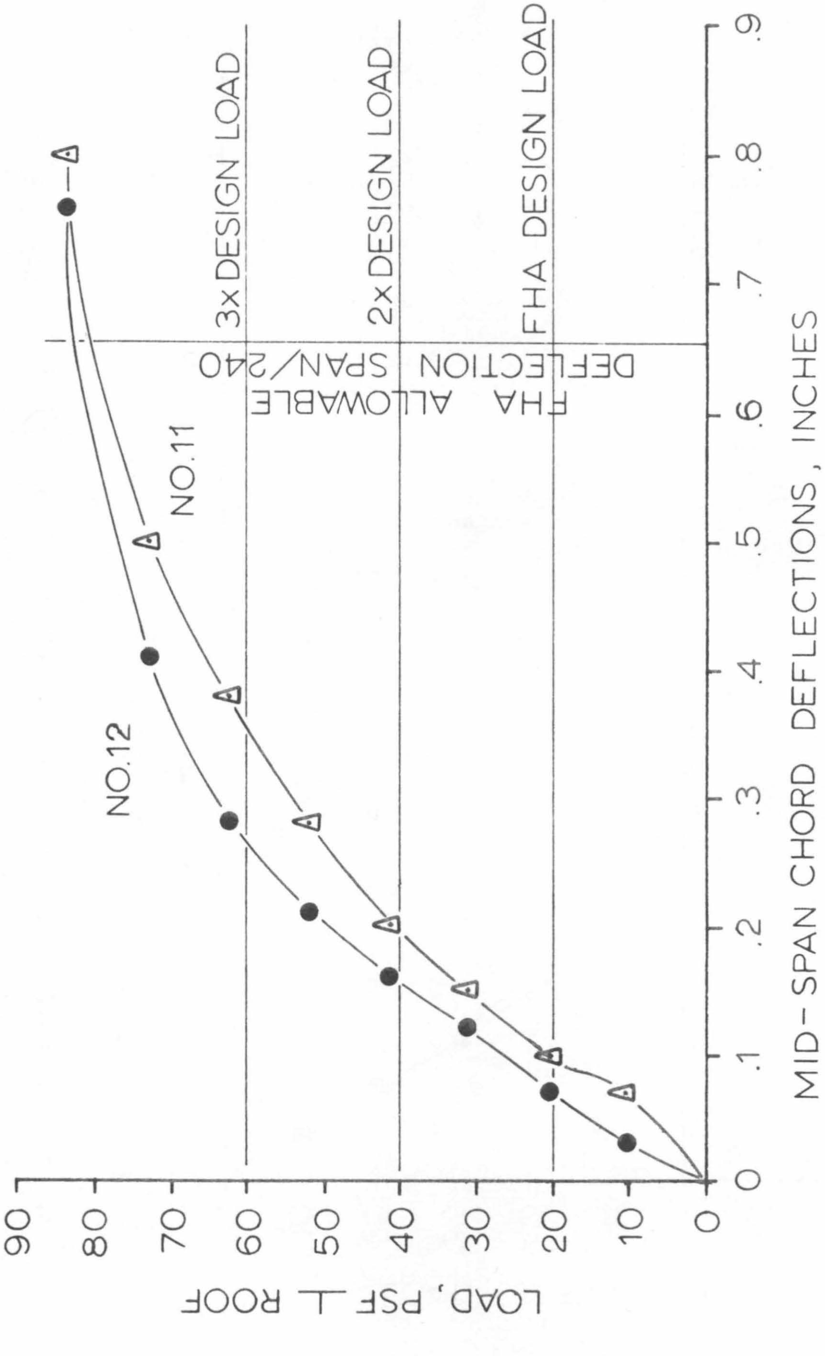


Fig. 15. TRUSS PERFORMANCE OVER CENTER BEDROOM

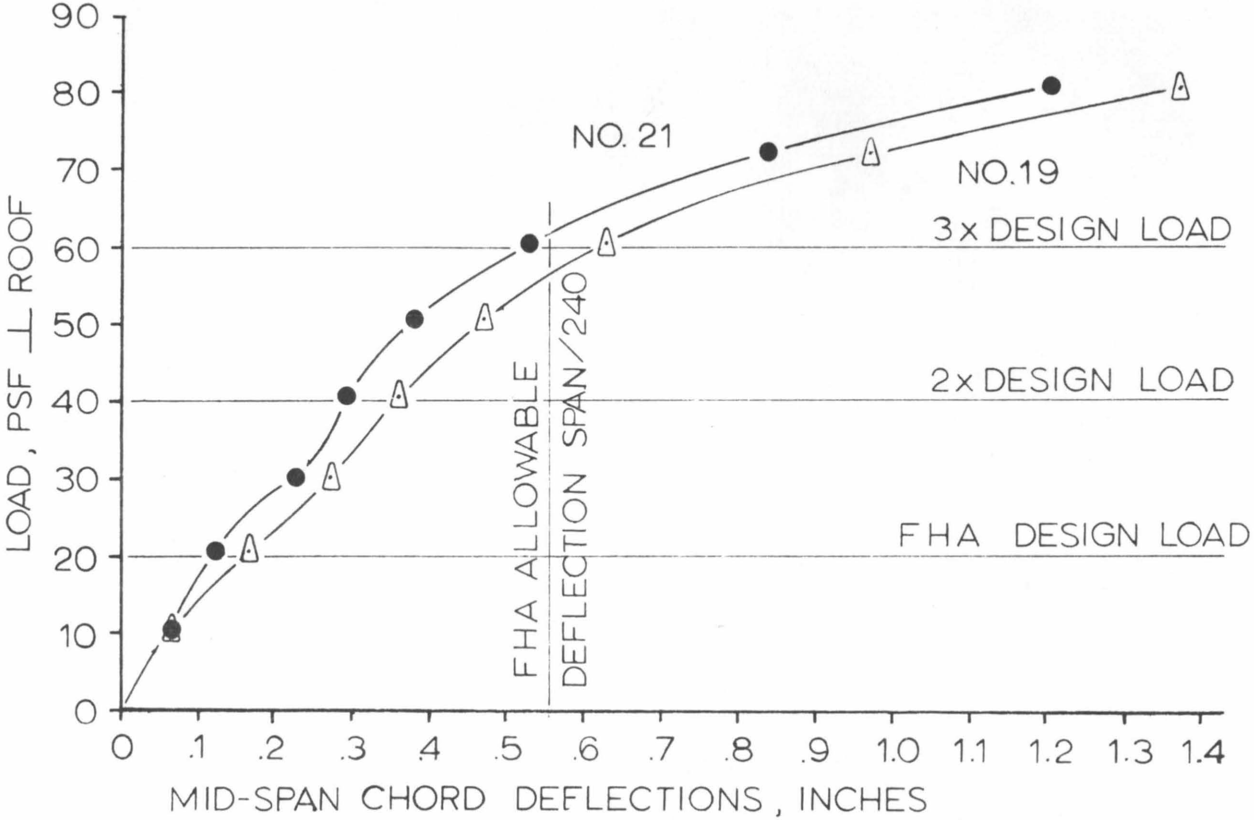


Fig. 16. TRUSS PERFORMANCE OVER LIVING ROOM

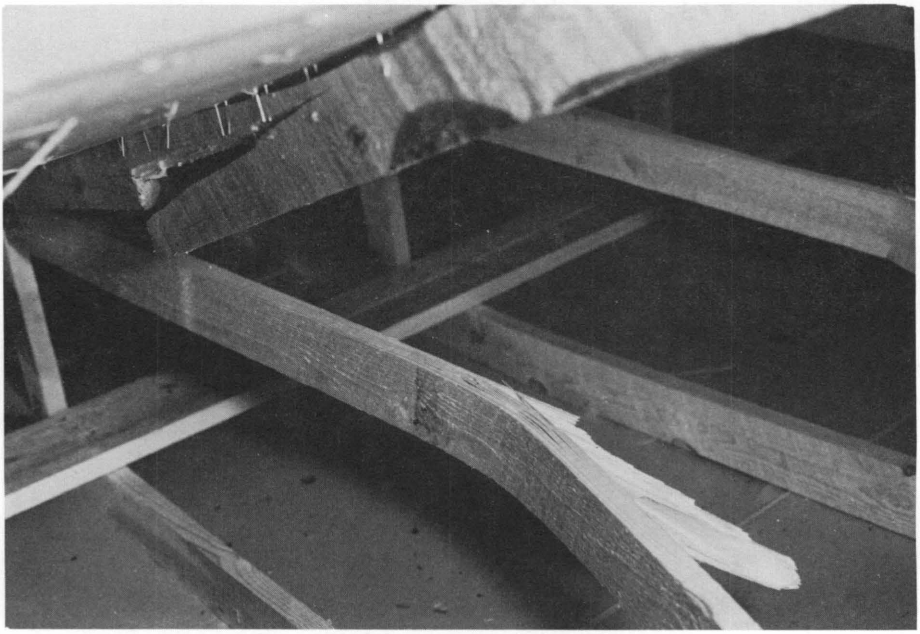


Fig. 17. ROOF TRUSS FAILURE

This typical failure resulted from the application of 93.6 psf applied perpendicular to the roof. The original failure was buckling of the diagonal web (lower right) which caused the rafter to fail in bending (upper left).

Fig. 18. A TYPICAL ROOF TRUSS FAILURE

This truss failure and six others occurred under the same loading conditions as the one in Figure 17.

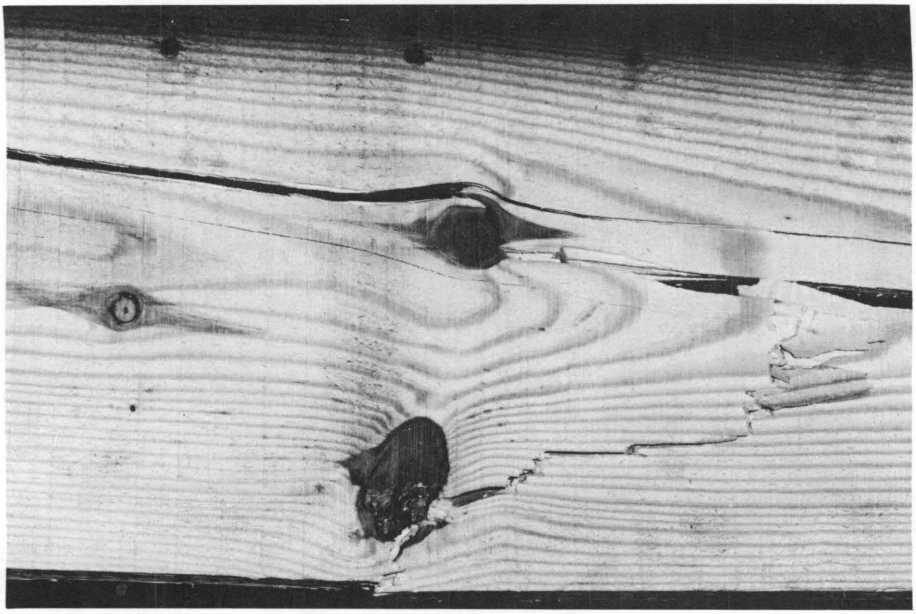


Fig. 19. JOIST 3 OF SPAN 3, EAST SIDE

Structural failure occurred within one minute after 202.8 psf were applied.

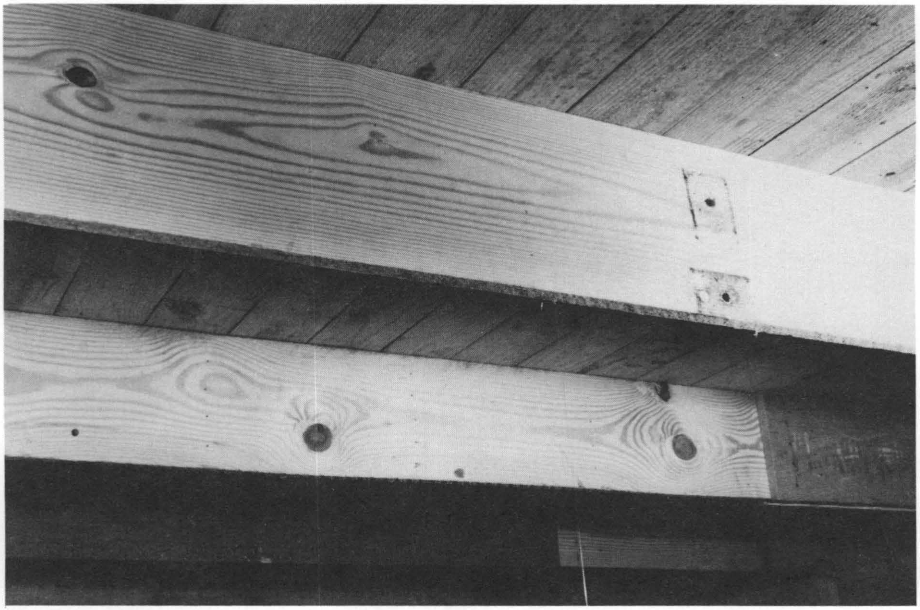


Fig. 20. (FRONT TO BACK) JOISTS 2 AND 3 OF SPAN 1

The bolt holes in joist 2 were necessary for attaching the transporting carriage. Joist 3 was changed before the final floor load-test because it was substandard. Before changing joists a load of 135 psf was applied which did not completely fail the substandard joist shown.

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