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BY

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LOADING TESTS ON FULL-SCALE HOUSE ROOFS

By H. J. Thorburn[1] and W. R. Schriever[1]

Synopsis

Earlier loading tests on single roof frames had shown that many conventional rafter-and-joist frames had failure loads well below the design snow loads specified in Canada. This suggested that either actual snow loads were lower than the design values or that the strength of individual roof frames do not indicate full strength of the complete roof. Consequently, a number of full-scale house roofs were load tested to failure in the laboratory to determine what additional strength is derived from the roof sheathing providing the roof with "folded plate action." The results indicate that on the whole most roofs do not derive much extra strength from the sheathing.

House structures as they are known today have developed largely on the basis of tradition and experience. Unlike larger buildings and other structures, they do not generally lend themselves to the normal methods of structural design. As a result, adequate strength of the structures had to be obtained initially by a "cut and try" process and subsequently by patterning the designs after those which had given satisfactory performance. Some components of the structures could be analyzed. For many years these have been designed on the basis of certain minimum design loads, maximum stresses, and acceptable performance. For many components, however, such criteria have not been generally established, and the design and acceptance must be based primarily on experience. Consequently, whenever a change in the traditional methods of construction is considered, the structural effect and merit of the change cannot always be easily and quickly evaluated.

Such a problem of a new design arose when the Division of Building Research of the National Research Council of Canada became concerned with the evaluation of light wooden W-trusses for house roofs. Although W-trusses can be analyzed readily and therefore designed and evaluated according to normal engineering methods, it was found that trusses so designed were, in general, much stronger than conventional roof frames. As both trusses and conventional roof frames have to support the same loads, there is obviously an inconsistency in the strength requirements of the two systems. Since well-built conventional joist and rafter roofs have, generally, a record of satisfactory performance, there would seem to be no need for trusses to be stronger than the conventional systems they would replace. It was therefore decided that trusses would be designed and evaluated on the basis that they would provide

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performance equivalent to that of the better types of conventional construction.

Since only limited information was available on the performance of conventional systems (1,2),[2] the Division of Building Research, in cooperation with the Forest Products Laboratories of Canada, undertook a program of loading tests on several types of conventional roof frames. These tests, which were carried out on pairs of frames loaded by means of hydraulic jacks, indicated that roof frames in common use in Canada had failure loads varying all the way from 20 to 140 lb per sq ft, with those of the better types of construction in the 100 lb per sq ft range. On the basis of this information, it was decided that W-trusses would be required to carry at least 100 lb per sq ft before failure. This load-carrying capacity of 100 lb per sq ft was considered satisfactory for areas with design snow loads up to 50 lb per sq ft. Thus, with trusses required to carry at least 100 lb per sq ft, a minimum load factor of 2 has been implicitly established with regard to the present design snow loads. It will be recognized that this represents a significant departure from the load factors of 3 or 4 normally found in timber construction. Although the important question of load factors, particularly those used in house design, deserves much discussion, it is a matter outside the scope of this paper.

Of immediate concern are the low capacities of the weaker conventional frames. If these types of construction are used extensively, and several field investigations have indicated that they are, then a significant question is raised. Since some types of roof frames have failure loads in the range of 20 to 50 lb per sq ft and the design snow loads specified in the National Building Code of Canada[3] range from 30 to 50 lb per sq ft in the heavily populated areas (and higher in some other areas), why have there not been more numerous house roof failures in Canada?

There seem to be two, or a combination of two, possible answers to this question. First, it may be that the snow loads that actually occur on roofs are substantially less than the design values specified in the Building Code, or second, it may be that loading tests carried out on conventional frames do not indicate the true strength of a complete roof. Possibly the sheathing which covers the frames provides additional strength by acting as a "deep beam" on each slope or by folded-plate action and perhaps the gables also contribute significantly to the strength.

Both of these factors are being investigated. It is hoped that useful information on snow loads will be gained from a survey of these loads on roofs all across Canada that the Division has been conducting since 1956 (3). This survey, which is being carried out primarily to provide a more rational basis for design snow loads in the National Building Code of Canada, now comprises observations of actual snow loads on more than 100 roofs in Canada. Additional information is also being gained from studies of a number of roof failures from snow loads (3). Although the survey is in its fifth winter, final quantitative conclusions cannot yet be drawn because of the variable nature of snow loads.

Investigation of loading tests of roof components promises to bring more immediate results, since this lends itself more readily to analysis and experiment. One obvious part of such an investigation involves the load testing of full-

[2] The boldface numbers in parentheses refer to the list of references appended to this paper.

[3] National Building Code of Canada, 1953, Associate Committee on the National Building Code, National Research Council, Ottawa, Canada (1953).

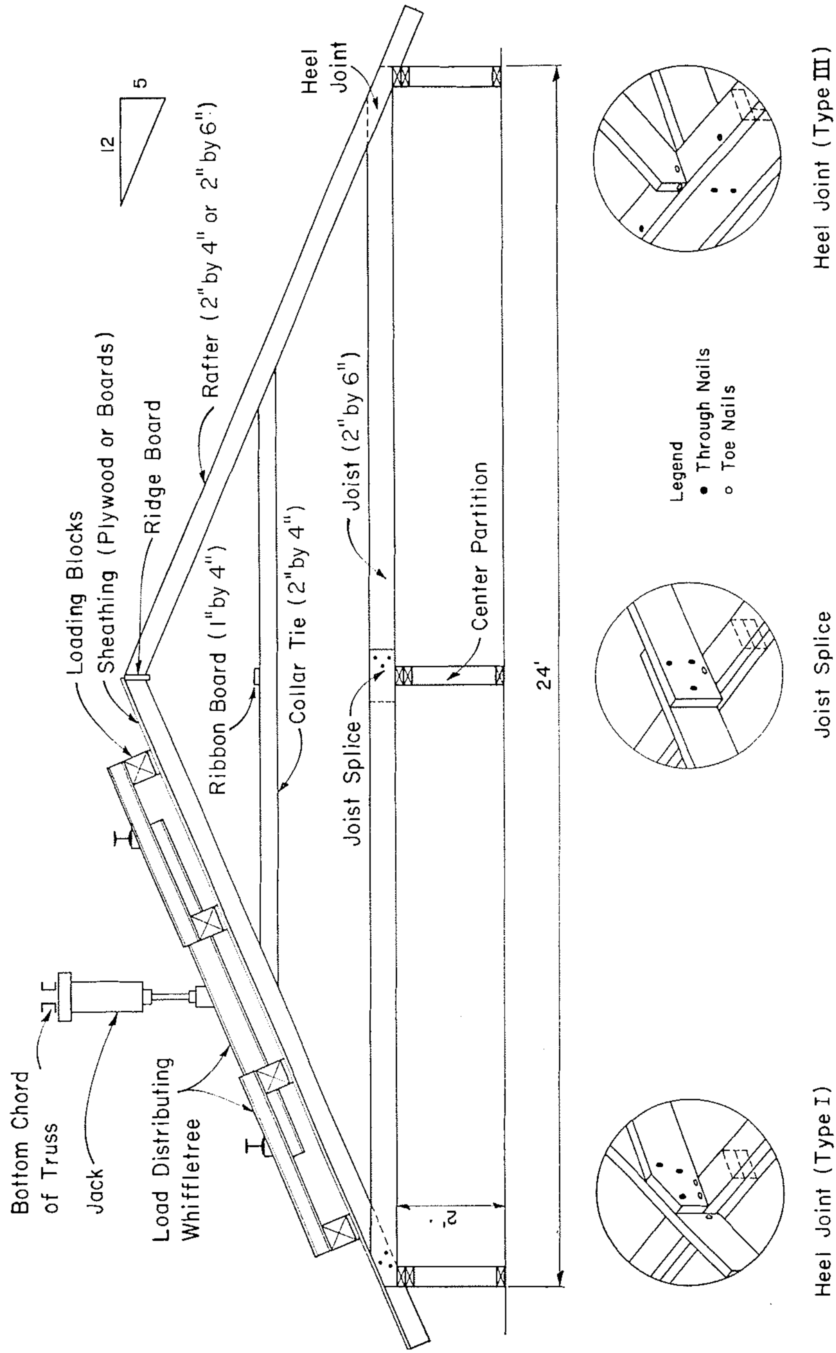

FIG. 1.—Cross-Section of Typical Roof with Details of Construction and Loading.

scale house roofs, which this paper describes.

TEST STRUCTURES

The type and size of the eight full-scale roof structures tested in the laboratory were governed by two main factors. First, to provide information on the effects of the sheathing and gables, it was essential that the construction used in the complete roofs be the same as that used in the earlier tests on single frames (2). Secondly, it was desirable that the complete roof be as representative of full-scale roofs as conditions would allow in order to make the results as valid as possible. On these bases, the eight test roofs were constructed as follows.

The test structures were simple gable roofs each of the same span, length, and slope. The frames of all roofs thus had the same over-all size and also had the same arrangement of members. Each frame had a span of 24 ft and a slope of 5 in 12, and consisted of a pair of rafters, a pair of joists, and a rafter or collar tie (Figs. 1 and 2). The rafters were joined at their upper ends through a ridge board and were supported at their lower ends on exterior side walls. The joists, which were spliced at the mid-point over a simulated center partition, tied the lower ends of the rafters together. Similarly, the collar ties connected the midspans of the rafters together. All members were No. 1 (Construction) Eastern spruce lumber, 2 by 4's and 2 by 6's being used for rafters, 2 by 6's for joists, 2 by 4's for collar ties, and 1-in. material for ridge boards. In each roof, the frames were placed 16 in. on centers and had a continuous 1 by 4-in. ribbon strip connecting the centers of all collar ties. The

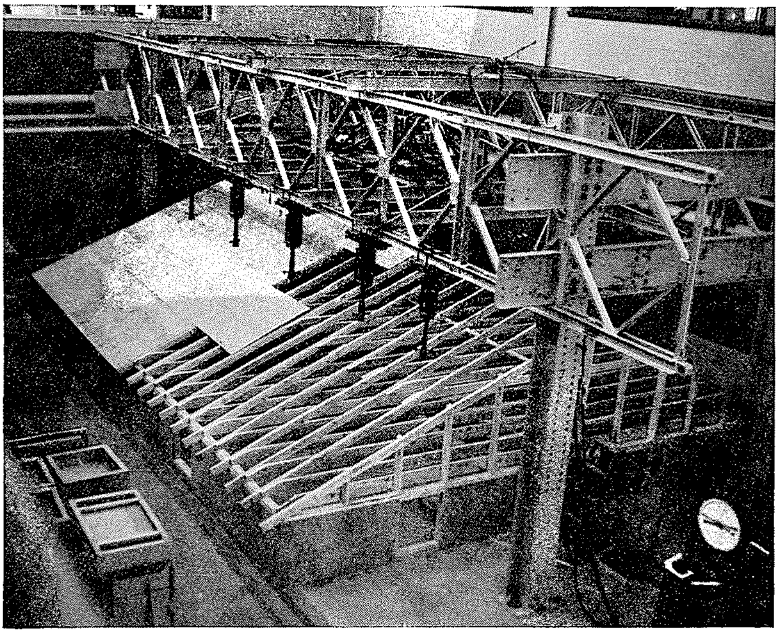

FIG. 2.—Plywood-Sheathed Roof Under Construction Showing Details of Framing and Sheathing.

ribbon strip was necessary because, in spite of their name, collar ties used as intermediate rafter supports usually act in compression when the frames are loaded and thus tend to buckle. This tendency is aggravated by the eccentric connections of the collars to the rafters.

The length of the complete roof was not governed by the previous single frame tests, except that the length was not to be less than the span. An upper limit on the length was imposed by the available laboratory space and loading capacity. In view of these limits and the requirement that the test structures be as representative of full-scale roofs as possible, the length was set at 30 ft.

The support conditions provided for the roof at the side walls were selected on the following basis. In the tests on single frames, the two extreme conditions were used: some frames were supported on rollers which gave complete freedom and others were completely fixed. The situation existing in a house, however, lies between these extremes, the actual condition being determined by the type of construction and the locations of interior partitions which meet the exterior side walls. Since there are no apparent average or typical conditions, it was decided to support the test structures on low walls, which were fixed at their ends and free at their centers, only to the extent that their own stiffness would allow.

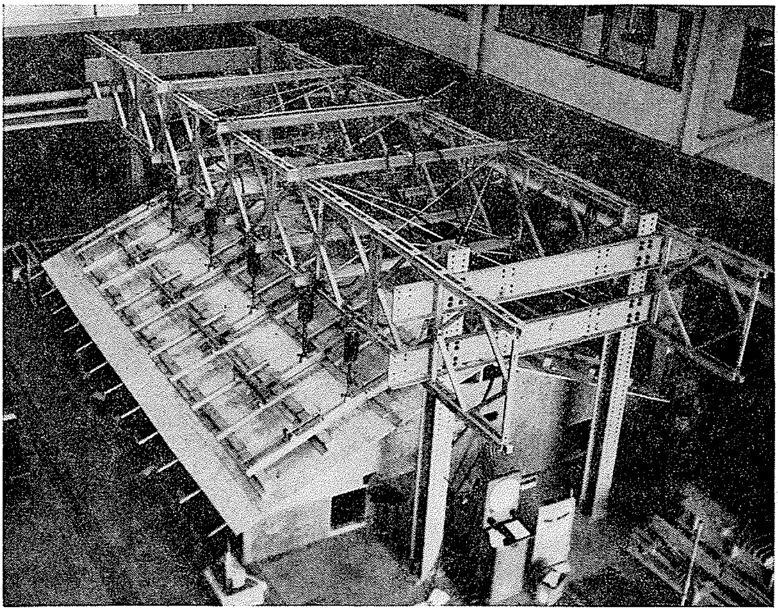

FIG. 3.—Board-Sheathed Roof Ready for Testing.

The center partition was similarly fixed at the ends. The height of all walls was arbitrarily set at 2 ft on the assumption that any variations caused by different heights would be of little importance.

Within the limits allowed by the single frame tests, several features of the eight test structures were treated as variables. The size of the rafters was one of these, 2 by 4's being used in six roofs and 2 by 6's in the other two. Another variable was the through nailing at the joist splice and the heel joint using $3\frac{1}{2}$-in.

(16 d) common nails. Three nails, as required by the National Building Code (1953)[3] were used at these joints for four roofs; four nails, as required in the 1960 revision of the Code,[4] were used in two roofs; and no nails and six nails were used to compare flexible and stiff roofs. The toe nailing at these joints was kept constant. The only other variable, and one which was not governed by the previous tests, was the sheathing applied to the rafters. It was either 4 by 8-ft sheets of $\frac{3}{8}$-in. plywood nailed at 6 and 12 in. intervals at edge and interior supports, respectively, or $\frac{3}{4}$ by 6-in. square-edge boards nailed with two nails per board at each support. In both cases 2-in. common nails were used.

In the construction of the eight test structures, average materials and workmanship were used in an attempt to obtain roofs built to "average" standards, and, equally important, an attempt was made to be consistent in these standards.

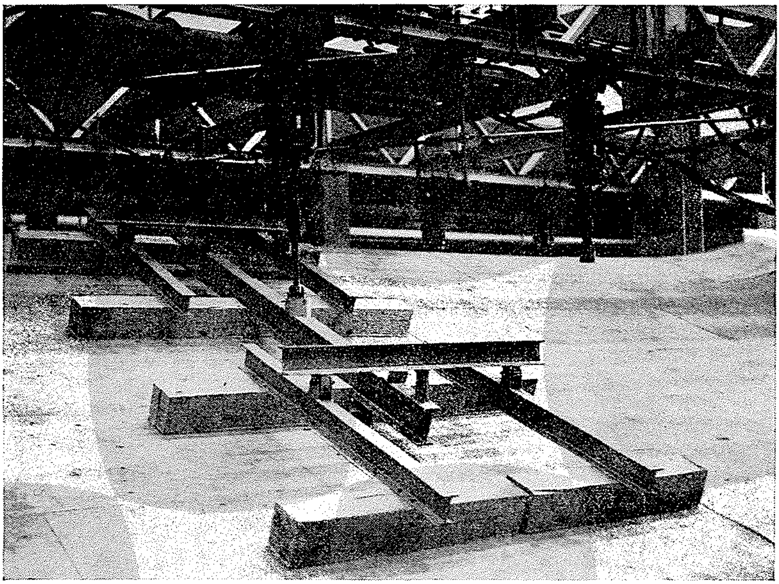

FIG. 4.—Hydraulic Jack Loading Divided into Four Equal Line Loads by Whiffletrees.

TEST ARRANGEMENT

Loading conditions were the same as those in the tests on single frames: eight concentrated loads applied to the rafters at the center of each eighth of the span (Fig. 1). Expanded to cover the complete roof, this arrangement consisted of eight equally spaced line loads parallel to the ridge.

The loading system consisted of a reaction framework (Fig. 3) (4), hydraulic jacks, and load-distributing whiffletrees (Fig. 4). The reaction framework was made of a pair of columns at each end of the roof and a pair of trusses supported by the columns. The trusses, which were Bailey bridge trusses, spanned over the roof between the pairs of columns and ran parallel to the ridge in positions directly over the quarter points of the

[4] National Building Code of Canada, 1960, Associate Committee on the National Building Code, National Research Council, Ottawa, Canada (1960).

roof span. Six hydraulic jacks, which provided the actual loading force, were suspended from the lower chord of each of these trusses, each jack being positioned along the chord over the center of an area of roof proportional to the jack capacity. From this position over each slope, the load from each jack was divided by a whiffletree into four equal line loads. The application of the load to the roof was made through felt-covered blocks, each 3 ft long. The twelve jacks mounted on both trusses were operated by a common hydraulic system. Each jack was fed oil by a central distributor which in turn was fed by a pump. The oil pressure delivered to the jacks was measured by a pendulum dynamometer which indicated the load applied by each jack.

The deformations of the roofs under load were measured at a number of locations. The deflection of the ridge was measured by a system of thin wires and pulleys which transmitted the movements to an indicator board. The deflections of the mid-spans of the rafters of every second frame were measured by suspending a scale from the rafter and sighting on the scale with a level. The outward movements of the rafters at the side walls and the movements of the walls were also measured, the first by scales read relative to a tight wire and the second by scales and dial gages. The movements at the joints of the frames were observed by means of lines drawn across the joints before loading.

TEST PROCEDURE

Because of the importance of comparative evaluation of the results, the test procedure for the full-scale roofs was similar to that used in the single-frame tests. Loads were applied on a short-term basis with the rate of loading 10 lb per sq ft per min, and loads were held at each major increment for 10 min. Loading was divided into three steps which were based on an assumed design load of 50 lb per sq ft. The roofs were first subjected to a "bedding-in" load of half the design load (25 lb per sq ft) and the load was then removed. In the second step, the load was increased to the full design load (50 lb per sq ft) and

TABLE I.—LOADING CAPACITIES OF SINGLE ROOF FRAMES AND COMPLETE ROOFS.

Frame			Location of Failure	Failure Load, lb per sq ft		
Type	Nails	Rafter		Single Frame	Plywood-Sheathed Roof[a]	Board-Sheathed Roof[a]
Type III	0	2 by 4	Heel	18	25 (+39)	...
Type I	3	2 by 4	Splice Heel	48 63	72 (+50) 80 (+27)	45 (−6) 60 (−5)
Type I	3	2 by 6	Splice Heel	60 67	65 (+8) 85 (+27)	50 (−17) 72 (+7)
Type I	4	2 by 4	Splice Heel	56 71	80 (+43) 85 (+20)	51 (−9) 65 (−8)
Type I	6	2 by 4	Collar Heel	79 90	85 (+8) 100 (+11)	... ...

[a] Figure in bracket indicates per cent difference between strength of complete roof and corresponding single frames.

then removed again. Finally, the load was increased until the roof failed. Some of the roofs failed during the first or second steps. Loads were applied in increments of 10 lb per sq ft (sometimes 5), and after each increment deflections were read.

The initial failure of the roof usually occurred at the joist splice and did not cause much distortion at other points. This separation could be readily repaired, allowing a second test on the same roof. In this repair work, the failed joints were made stronger than before so that on reloading, the second weakest joint or member would fail. For these second loadings, only one step was used —from zero load to failure. Deflections were measured at intervals to obtain an indication of the rate and mode of failure.

TEST RESULTS

Sheathing:

On the basis of a comparison of the strength of the complete roofs and the single roof frames, the results fall into two definite groups.

Without exception, the failure loads of the plywood sheathed roofs were greater than those calculated from the test loads on the corresponding single frames, the differences ranging from approximately 8 to 50 per cent (Table I). For example, frames with 2 by 4 rafters with three through nails at the heel joints and the joist splices failed at 65 lb per sq ft in the complete roof, whereas when tested singly they failed at 48 lb per sq ft. A similarly large difference was observed for the same frames with four nails at the mentioned joints, 80 and 56 lb per sq ft being the corresponding failure loads. Frames of stiffer construction, on the other hand, such as those with six nails at the joints or with 2 by 6 rafters showed smaller increases in strength; for example, the frames with 2 by 6 rafters increased from 60 to only 65 lb per sq ft.

For roofs with board sheathing, the situation was completely different. They showed little or no increase in strength over that of the single frames; indeed, most of the roofs with board sheathing were weaker than the single frames. The observed difference in strength suggests that perhaps some systematic experimental variation was present, perhaps due to the test method. In spite of this, however, the results for the board-sheathed roofs are considered significant. A typical case is the board-sheathed roof with frames of 2 by 4 rafters with three through nails at the joints. It failed at 45 lb per sq ft compared with failure loads of 48 lb per sq ft for the single frames.

The difference between plywood sheathing and board sheathing indicated by the failure loads was also evident in the deflection measurements. For example, the deflections for the board-sheathed roofs at a load of 40 lb per sq ft were, on the average, 50 per cent greater than those for the corresponding plywood-sheathed roofs. Those of the plywood-sheathed roofs did not show any significant difference compared with the deflections of the single frames. Deflections of the board-sheathed roofs were, however, greater than those for the single frames, probably for the same reason that the failure loads are not in accord with those for the single frames.

Gables:

The contribution of gables to the strengths of the complete roofs was demonstrated in two forms. First, the fact that the board-sheathed roofs had strengths not significantly different from the single frames suggests that the direct contribution of the gables was negligible. Secondly, the deflection measurements made only a short distance along the roof from the gables were comparable to those at the mid-length of the roof, thus indicating that the strengthening effect of the gables did not extend very far into the roof (Fig. 5). These two points lead to the conclusion that the *direct* contribution of the gables was negligible. *Indirectly*, however, the contribution of the gables was considerable in that they provided the supports for the sheathing acting as "deep beams."

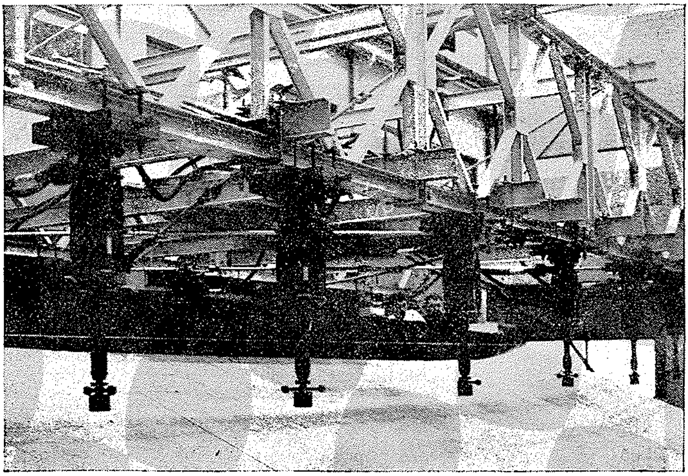

FIG. 5.—Small Effect of the Gables Shown by Deflections of the Ridge. (Note string stretched from gable peak.)

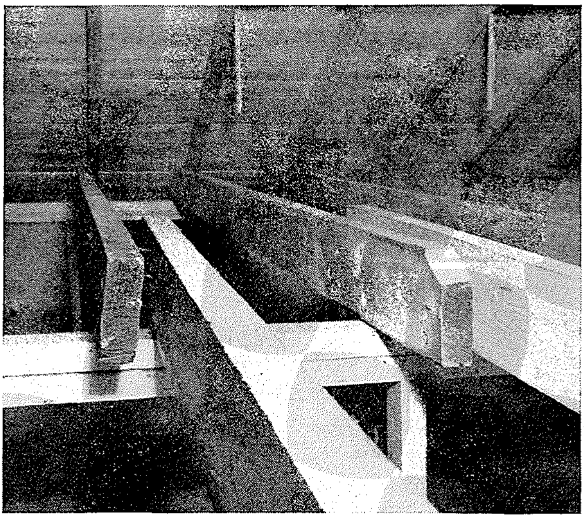

FIG. 6.—Failure at the Joist Splice.

Joist Splice Nailing:

Another finding was the relation between the through nailing at the heel joint and that of the joist splice. Several building codes, including that of the Federal Housing Administration[5] and the National Building Code of Canada,[3] specify the same number of nails in the joist splice as in the heel joint. This requirement was met by six of the eight roofs tested, and in every case the joist splice failed before the heel joint (Figs. 6 and 7). This suggests that the nailing at the joist splice should be greater than that at the heel joint. Perhaps two or more additional nails are required at the splice, although it might be expected that the sheathing action of the ceiling would tend to reduce the force on the joist splices.

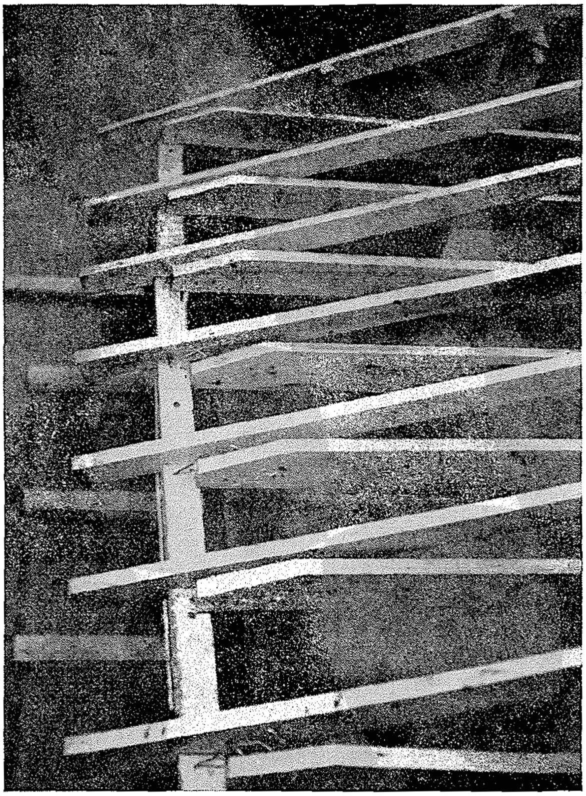

FIG. 7.—Failure at the Heel Joint.

[5] Minimum Property Standards for One and Two Living Units, Federal Housing Administration (FHA No. 300), Washington, D. C. (1958).

CONCLUSIONS

In drawing conclusions from the results of these loading tests, it must be remembered that since only one of each of the eight different roof constructions was tested, the results may not be quantitatively accurate. There are, however, a number of qualitative conclusions that can be drawn for roofs of the type tested:

1. The contribution of plywood sheathing to the strength of a complete roof can be substantial, particularly when the roof frames are relatively flexible.

2. The contribution of board sheathing to the strength of a complete roof is negligible.

3. The direct contribution of gables to the strength of a complete roof is small.

4. The nailing at the joist splice of a roof frame should be greater than that at the heel joint for balanced strength in roof design.

Since the strengths determined from the single frames appear to be representative of many complete board-sheathed roofs and since it can be assumed that many roofs in Canada have board sheathing, it may be concluded that the snow loads they experience are often less than the design snow loads because of wind action, melting due to heat loss, or snow removal by the owner. This conclusion serves to reemphasize the importance that is already attached to the survey by the Division of Building Research of actual snow loads on roofs, the results of which will be published as soon as sufficient statistically satisfactory information has been assembled and assessed.

Acknowledgments:

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REFERENCES

(1) Symposium on Full-Scale Tests on House Structures, *ASTM STP No. 210*, Am. Soc. Testing Mats. (1957).

(2) A. T. Hansen, "Lightweight Trusses Bear Up Better Than Conventional Roofs," *National Builder*, Vol. VIII, No. 11, Nov., 1959, pp. 38–40, 51.

(3) H. J. Thorburn and W. R. Schriever, "Recent Failures Point Out Importance of Snow Loads on Roofs," *National Builder*, Vol. VIII, No. 5, May, 1959, p. 18.

(4) W. R. Schriever and W. G. Plewes, "A New Canadian Structural Test Installation," *Engineering Journal*, Vol. 44, No. 1, Jan., 1961, pp. 35–41.