1933

I. Wind damage to Iowa farm buildings, II. The design of the bent rafter to resist wind loads

Elmer F. Clark
Iowa State College

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I WIND DAMAGE TO IOWA FARM BUILDINGS
II THE DESIGN OF THE BENT RAFTER TO
RESIST WIND LOADS

by

Elmer F. Clark

A Thesis Submitted to the Graduate Faculty
for the Degree
MASTER OF SCIENCE
Major Subject Agricultural Engineering
(Farm Structures)

Approved:

Henry Giese (Signed)
In charge of Major Work

J. B. Davidson (Signed)
Head of Major Department

R. E. Buchanan (Signed)
Dean of Graduate College

Iowa State College
1933
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WIND DAMAGE TO IOWA FARM BUILDINGS

PART I
INTRODUCTION

The amount of farm property which is damaged directly or indirectly by wind is almost incredible. The Iowa Mutual Tornado Insurance Association has paid an average of nearly $214,000.00 per year, for the last three years, on claims resulting from this hazard. This is a great economic waste to the farms of Iowa, and also such destruction may cause the loss of life.

Inspection of damaged buildings shows that the losses in many cases are due to improper construction and the failure of the building to follow building specifications. It is believed that a big percent of the losses might be prevented by proper construction and by repairing and bracing of buildings now in use.

The purpose of this study is to analyze the wind damage to Iowa Farm Buildings, from the records of claims paid by the Iowa Mutual Insurance Association of Des Moines, Iowa, in an attempt to formulate practical and economical building construction standards which will reduce the losses due to this hazard.

The work reported herein is the second report of "Wind Damage to Iowa Farm Buildings", which is part of the general project "An Investigation of Wind and Fire Losses to Iowa Buildings in Iowa". The first report covered the losses for 1930, while this report covers the losses for the years of 1930-31-32.
Wind damage to farm buildings has received very little attention as a problem until recently even though different authorities consider that it is a problem for investigation. Henry Oiese (3) in his bulletin on Research in Farm Structures states the following:

"The losses due to fire and wind are truly economic. While the individual may be partly protected by insurance, the loss must be paid ultimately by the agricultural industry............"

"Studies should be made as to the reasons of these losses and as to improved construction methods for reducing future losses."

The Associated Factory Mutual Fire Insurance Companies (4) state the following in summarizing a study of wind damage to buildings and stationary structures:

"Monolithic reinforced concrete construction is most resistant to windstorms.

"Effectively braced, steel-frame buildings will generally resist the most severe storms except that light-weight siding or roofing, glass, and poor masonry may be damaged.

"Heavy timber construction with strong anchored roofs and substantial walls and floors will withstand gales, hurricanes or minor tornadoes, but may be severely damaged or even wrecked by a major tornado.

"Flimsy or large, poorly braced, wooden structures, ineffectively braced steel frames, inferior masonry and weak or poorly secured building parts are frequently severely damaged by moderate storms."

A few of the recommended precautions are stated as follows:

"Wooden frames require liberal bracing throughout; otherwise they may loosen at the joints under ordinary usage and collapse under a heavy wind. Effective bracing is also needed for roof trusses............."

"Wooden roofs require fastening to masonry walls with adequate anchor straps............."
"Roof coverings and flashings are especially vulnerable. They must be well secured and maintained. Periodic inspections should be made. Non-corrodible nailing strips are advised for fastening seams of prepared roofings. Non-corrodible metal flashings are much better than felt.

"Masonry requires good workmanship with good bonding of units and at corners and intersecting walls. Brick units permit better bonding than hollow blocks. Portland cement mortar should be used and should fill all joints. Tying of masonry to interior framing and to the roof is important.

"Plain glass windows or weak, poorly fastened sash is likely to be broken out by wind, debris or hail.

"All light-weight roof and siding sheets, such as corrugated iron and asbestos require extensive fastening. Corrugated iron is best secured to steel frames with straps bent around the members and riveted to the corrugated sheets. Corrugated asbestos is best fastened with bolts and special clips. Long nails or drive screws are used for wooden frames. Even where properly fastened, corrugated iron will be ripped away by the most violent storms and asbestos will be broken by the wind or flying debris.

"Skylight frames should be strongly secured. Wire glass should be used and securely held with clips and putty. As further protection against breakage by wind-blown debris, skylights should be covered with substantial wire screens."

In a study of Farm Building Losses in Iowa for 1930, M. F. Schweers (5) drew the following conclusions:

1. Field observations are essential in a study of this type in order that intelligent research may be carried on.

2. Many losses are apparently due to improper design and construction.

3. Many causes for losses can be ascribed to the failure of the plate joint on the leeward side of the building.

4. A great amount of research and study is necessary to determine (a) wind stresses on farm buildings, and (b) best methods of construction."

In a circular on The Prevention of Wind and Fire Losses to Farm Buildings, Henry Giese (2) 1931 discusses the following as important preventive measures against wind damage:
"1. Rigid wall bracing.
2. Brace to tie rafter to plate.
3. Collar beam to tie rafters together.
4. Sheathing should not all be spliced on one rafter.
5. Wind brace under the mow floor.
6. Sufficient anchorage to foundation."

Mr. O. Betts and Wallace Ashby (1) 1932 list the following as chief safeguards against wind damage:

2. Anchorage between building and foundation.
3. Rigid bracing of walls.
4. Ties between inner and outer walls and between walls, roofs and floors.
5. Roof bracing.
6. Anchorage of roof structure to side walls."
INVESTIGATION

Scope and Method

The statistical data presented in this report were taken from the records of the Iowa Mutual Tornado Insurance Association, Des Moines, Iowa. Personal investigation of some damaged buildings, upon which claims were paid by the association, modifies or verifies the conclusions drawn from the correlations.

The Association requires that a loss report be turned in to the secretary not later than 60 days after the loss and that the loss must amount to $5.00 or more. A proof sheet is then sent to the claimee or taken by an adjuster who must verify the loss in all cases. The proof sheet contains a description of each item of loss and the amount paid on the claims. The data used in this analysis were taken from the proofs which are filed in the office of the Association. Some of the proofs were poorly written, and lack of a system for descriptions and itemizing different items made the recording of data extremely difficult. In many cases the divisions into items depended upon the recorder. For instance, a hail damage might be reported, glass, screens, paint, and shingles as a certain sum, and as each item was to be recorded the amount to apportion to each item was left to the recorder.

Since the claims for each year amount to several thousand, and because of the amount of information to be recorded on each claim, the tabulations were all made by machine. A special card was printed so that the data could be taken from the proofs and recorded directly on the card by means of a code. This method of handling data reduces greatly the chance for error as well as speeding up the work. After being tabulated the data were recorded in the various table forms which appear in this report. The tables include the losses with an average for 1930-31-32 and the manuscript and charts present the material as an average for the three years unless otherwise noted.

The Association does not carry all of the wind and tornado risks in the state, however, it does carry the greater part except in the southern and southeastern counties where another Association operates. Risks are carried in all counties in Iowa and some in South Dakota.

Loss by Counties

The average loss of the state by counties was investigated to determine where the greatest losses were paid and
also find low areas of loss which may exist.

The distribution in Fig. IV indicates the areas which have the greatest loss providing other factors are equal. However, several factors may influence the distribution. The distribution of investment in buildings and character of buildings differs with the several types of farming in the states. Also, distribution is affected by the fact that the one association does not write all of the insurance in the state as can be seen by comparing the average insurance in force, Fig. III, with the farm building investment, Fig. II. The amount of insurance carried may also depend on the area of the county, farm building investment in the county, and how active the agent is in writing insurance.

The types of farming which influence building investment vary with different sections of the state, Fig. I. The Milk Producing Area in the northeast section requires a large investment in buildings.

The Cash Grain Area has a lower building investment because the common practice is to market the grain immediately after harvest and no large storage buildings are required.

The Meat Production Areas in western and eastern Iowa require a large investment in buildings. The feeding of hogs and beef cattle, as practiced in this area, calls for relatively large investment on shelters for livestock and storage for feed.

The southern part of the state has an area defined as the Southern Pasture Area where the grazing of cattle is the main enterprise and requires a small building investment.

Considering the above facts, it is seen that the loss by counties does not give a true idea of the distribution of wind damage to farm buildings in the state.

**Dollars Paid per $1000 Insurance in Force**

The ratio of losses paid on insurance in force, Table I, was investigated in an endeavor to obtain a true picture of the losses in the state; first, as to where the heavy losses occur in an attempt to determine if possible a storm area; second, the relation of the losses to the building investment and whether or not the types of buildings suitable to the different types of farming had any influence on the damage.

The losses for 1930, Fig. V, show the heaviest losses in the northwest section of the state with large losses in the south central and in the eastern counties.
Fig. I Types of Farming in Iowa

Fig. II Farm Building Investment in Iowa Counties (1930 Census)
Fig. III Insurance in Force in Iowa Counties
Average 1930-31-32
Fig. IV Wind Loss In Iowa Counties Average 1930-31-32
The map on which the losses for 1931 are shown, Fig. VI, indicates that Davis County received the heaviest loss of $6.30 per $1000 insurance in force. This is much above that of any other county as the next highest during the three years was Chickasaw having a loss of $2.69. Not considering Davis County, the north central counties show the greatest wind damage with considerable damage in the eastern part of the state.

The losses for 1932 show that the only section suffering heavy losses was in the northwest corner of the state. Some counties along the northern part of the state and some along the eastern side had smaller losses.

Figure 8, which shows the average dollars paid per 1000 dollars insurance in force for the three years, indicates that in 79 of the 99 counties less than 50 cents was paid per $1000 insurance in force. Nineteen counties had claims for less than a dollar, and one county (Davis) had an average claim of $2.65 due to the heavy tornado and hail losses in 1931.

Analysis of the maps suggests that the location of losses is very spotted. Some years it occurred in one section of the state and some years in another. For this reason a three year analysis does not include a long enough period to determine a storm area.

As to a correlation between the losses paid per $1000 insurance in force and the farm building investment, the first thing very noticeable is the fact that Davis County suffered the highest loss and has a comparatively low farm building investment. Lucas, Wayne, and Jefferson counties, with low building investment, are shaded the same as the rest of the counties which have a higher investment. This could mean one of two things; either the storms are more severe in that section of the state; or due to the type of farming, as in a pasture area, less buildings are used per farm and they are poorly constructed so that in a severe storm the losses would be greater than in other parts of the state where buildings are better constructed. The latter seems to be the more logical conclusion.

Distribution of Magnitude of Losses

The distribution by magnitude of losses was investigated to determine the number and amount of losses according to the size as graphically represented in Fig. IX, and taken from data in Table II.

The interesting and surprising fact shown by the chart
Fig. V  Loss per $1000 Insurance in Force 1930
Fig. VI  Loss per $1000 Insurance in Force 1931
Fig. VII  Loss per $1000 Insurance in Force 1932
Fig. VIII  Loss per $1000 Insurance in Force
Average 1930-31-32
Table I. Farm Building Investment, Wind Damage and Loss per $1000 Insurance in Iowa Counties

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<td>County D</td>
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Note: Data represents estimated losses due to wind damage.
is that 93% of the number of total losses are less than 100 dollars each and also that the amount paid in dollars for losses which are less than 100 dollars each, is 45% of the total amount of claims paid. The losses between 100 and 200 dollars are less than 4% of the total numbers and a little over 11% of the entire amount of loss. The number of losses over 1000 dollars is very small being less than \( \frac{1}{2} \) of 1%, and the amount paid for claims is the second largest, or 14\( \frac{1}{2} \) of the total.

The large number of losses amounting to less than 100 dollars each may be given the following interpretation: This group includes some of nearly every item of damage except buildings which are completely demolished. For instance, if a building is out of plumb, has the roof partly blown off, or any of the other small damages, it may be repaired for less than 100 dollars, and it is in this group where the losses might be materially lowered.

Such losses in many cases are due to carelessness, lack of proper maintenance and repair, insufficient bracing, and lack of anchorage to the foundation.

**Losses by Months**

The occurrence of losses by months, Fig. X and Table III, shows that during the months of May, June, July, August, and September the losses are the heaviest. These in general are caused by cyclonic winds of high velocity which come with thunder storms. Thunderstorms are often accompanied in part by hail which causes much loss by breakage of glass and the puncturing of roof coverings.

The highest loss for 1930 and 1931 occurred in June, while in 1932 it took place in July. The heavy loss in 1932 which occurred in July was a result of a big hail storm on July 6 in Plymouth County. A tornado on July 9 along the state line in Lyon County lifted and continued across the northern part of the state as a heavy wind storm with some hail at various places. The losses for 1932 were considerably less than for the two preceding years.

The curve for 1931 shows a high loss in August and September unlike the years of 1930 and 1932. However, 1930 does show a small increase in losses during September.

The average curve indicates that May, June, July, August, and September are the months in which to expect the heaviest losses due to wind. October is low with a small increase in November and the rest of the months very low.
Table II Magnitude of Losses

![Image of Table II Magnitude of Losses]

Legend

No. Of Losses

Amt. Of Losses in Dollars

Fig. IX Magnitude of Losses
Fig. X Month of Occurrence

Fig. XI Causes of Damage
### Table III Month of Occurrence

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### Table IV Property Damaged

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Property Damaged

Iowa ranks first among the states in farm building investment with a total slightly in excess of 1 billion dollars according to 1930 census report. The value of farm dwellings is about 475 million dollars, or nearly one-half the total, on which the wind damage amounts to only 3% of the total. Ninety-seven percent of the losses are distributed over the remaining investment.

Nearly $214,000.00 was the average total loss paid in 1930, 1931, and 1932 comprising 5906 items of loss which are listed under 22 heads, Table IV. These data were taken from the proofs and in many instances several items were included on one proof. In some cases the items were not listed but included in one total which left the proportioning of the amount of loss to each item to the discretion of the recorder. For this reason there might be a slight error as to the amount listed for each item. However, a close estimate could be made.

A graphical summary of losses as shown by Fig. XII ranks the items of loss as to amount giving the percentage and the percentage of number of losses. The items of loss included are all self-explanatory except unspecified buildings and miscellaneous losses. Unspecified building losses include buildings with no specific report and those which were damaged by debris or trees, silos, chute, and windmills. The miscellaneous losses have reference to the damage of tanks, automobiles, veterinarian bills, etc.

Wind damage to barns is the major item of loss which accounts for 38% of the total claims paid. The next highest item is roofing materials which is slightly above 8%. Corn crib and granary ranks third, with glass and screens nearly equal to the farm machinery, and implements for fourth and fifth places respectively.

As to number of items, damaged glass and screens rank first, very close to 20% of the total; roofing materials second with 15.3%; machinery and implements third; barn fourth and doors fifth.

The remaining items are all less than 5% both as to amount and number.

Causes of Damage

The wind is directly or indirectly the cause of all damage to buildings upon which claims are paid by the Association and reported herein. It seems desirable to investigate
Fig. XII Property Damaged
these causes to determine the major causes and also the
relative importance of the smaller causes.

The data in Table V as graphically represented in Fig.
XI, indicate that wind is the direct cause of nearly 85% of
the losses, and hail, a direct cause, is less than 10%. The
remaining losses are caused by other agents but indirectly
by the wind and amount to less than 10% of the total loss.
Wind as the major and direct cause of damage is considered
and studied under a later section while the rest of the causes
will be considered here.

The damage due to trees falling could be eliminated to
some extent by trimming out the old dead limbs and dead trees
each year. They are frequently too close to a building and
may cause a loss by being blown over on the roof or breaking
down the cornice. The common practice of using the grove as
a machine shed accounts for the most of these losses. Old
dead trees blow over on the machinery and a claim is made on
the association.

Building debris is responsible for many losses. Boards
become loose and blow off the building breaking glass,
splitting siding or puncturing roofs on another structure.
It is important that all buildings be repaired and properly
maintained.

Rain blows into a house or other buildings through
broken windows or after the roof has been partly blown off
and causes considerable loss to the contents.

A strawstack falling quite often kills some livestock
since it is used as a means of protection in time of storm.
A strawstack which has been eaten away until one side stands
vertical should be pushed over to help eliminate this loss.

A silo close to a building is a dangerous hazard unless
properly built or supported by guy wires, as it will cause
considerable damage if it should fall.

Windmills close to a building frequently are blown over
and the building partly demolished. They should be securely
braced and guyed.

Construction damage to Buildings

In order to give a true picture of the constructional
damage to buildings which was due directly to wind, it was
necessary that the data be tabulated for causes of damage;
Table V Wind Damage by Causes

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</tbody>
</table>

Note: The table continues with similar entries for other years and categories.
then the damage due directly to wind was tabulated and recorded in Table VI. Again, there is a possible chance for error due to the fact that the insurance adjuster in filling out the proof had the general tendency to put down the cause of the loss as wind, even though it might be some other indirect agent. However, in most cases explanation which was written on the proof gave the real cause of the loss.

Analyzing these data as shown graphically in Figs. XIII, XIV, and XV, brings out clearly where the greatest constructive loss occurs, and analyzing the major losses will help to determine where research should be directed in order to help eliminate losses and where a careful inspection should be made by the insurance companies.

The constructional losses due directly to wind, Fig. XIII, show that about 53% of the total claims are paid on barns. Unspecified buildings (defined under property damaged) are second with nearly 15%. Corn crib and granary is third with less than 10% of the total. The dwelling, as a rule the most stable structure on the farmstead, received the least amount of damage.

The items of constructional damage as reproduced in Fig. XIV indicate that the major losses are paid on buildings which were demolished, amounting to about 53% of the total. Buildings out of plumb are second and those off foundation are third. However, in ranking the items as to number of losses, buildings out of plumb is the greatest and nearly 17% of the total, with doors damaged as second, buildings off foundation third, and demolished, which was first in amount, is sixth in total number of losses.

In a few cases the demolition was caused by a tornado. A tornado is so drastic in its actions and force and occurs so infrequently that it is considered uneconomical to build to withstand such storms. However, very few of these losses were caused by a tornado but rather by a wind of cyclonic nature. Pictures taken of building failures indicate that some member in the building was weak and due to the weakness other members were overstressed and finally failed, allowing the building to collapse. The first place of failure, as is very apparent in most cases, was on the leeward side.

A great many claims were paid for buildings which were out of plumb. The photos in Figs. XVI and XVII are excellent examples of this item of constructional damage. The cross sectional views below show the reasons for these failures which are the entire lack of bracing in the case of the shed
roof barn and not sufficient bracing in the case of the barn with the curved arch roof. If the wind had been a little stronger the shed roof barn would have been completely demolished.

The carpenter, lumber, and labor bills paid to put the barn with the curved roof back in line totaled $250.00 which proves that a few extra dollars invested in the building in the way of proper bracing is well spent. Another thing, a building once pushed out of line is not as good as a building as it was in the first place. The nails in all the joints have pulled loose and boards split making repair an expensive operation, and even though it is repaired, the building is more liable to be damaged in another storm. If they are properly braced when constructed the joints are not as liable to work loose under usage and finally completely collapse even though the storm is not severe.

Nearly $10,000 was paid on claims where buildings were off foundations. The constructional damage occurs when the sill lacks sufficient anchorage to the foundation or the building was not anchored at all, which is the cause in many cases. Some buildings do not have a foundation as in the case where posts which have been set in the ground rot out in a few years leaving the building with no anchorage, and may be easily turned over by the wind.

A little more than 5% of windstorm loss is paid for roofs blown off. This is directly attributable to the omission of proper anchorage and wind bracing in the roof. The loss is not only to the roof, for rain causes damage to contents in the building, and roof debris carried by the wind can cause damage to adjoining roof structures as well as glass and other parts of buildings. The wind damage to doors, which ranks fifth, is in many cases caused by the lack of proper fastenings and catches to hold them back when they are left open. Shingles are in many cases blown off by the wind especially after they are old and begin to curl up so that the wind can get beneath. The nails also rust off, which gives the wind a better chance to blow off the shingles. The nails and anchorage of cupolas rust and rot out allowing them to be blown off, injuring the roof when they fall, and occasionally even killing stock. Roofing includes everything in the way of roof coverings except wooden shingles. Additions are damaged by wind because of lack of anchorage to the main building. Wind damage to chimneys is caused by chimneys being built too high without being guyed. They are sometimes laid up in lime mortar which does not have sufficient bond.

Constructional damage by items to barns, Fig. XV, shows
that according to the amount, the items are ranked about the same as in total of all buildings. However, the number of losses paid on barns out of plumb amounts to 35% of the total and additions damaged accounts for 28% of the total. Barns off foundation rank third with a slight excess of 15%.

If these particular losses can be decreased by improved construction, it is believed that the total of barns demolished will be decreased. The other items of damage are places of weakness which might have caused the building to be demolished had the storm been more severe, or which might fail in a later storm. These items are not discussed in detail, as the same items were discussed rather fully in the preceding section and will apply to the windstorm damage for barns.
Fig. XIII  Buildings Damaged Directly by Wind

Fig. XIV  Items of Constructional Damage to Buildings

Fig. XV  Items of Constructional Damage to Barns
## Table VI
Construtional Damage Due Directly to Wind

<table>
<thead>
<tr>
<th>Item of Loss</th>
<th>Barn</th>
<th>Crib &amp; Granary</th>
<th>Dwelling</th>
<th>Hog Houses</th>
<th>Machine Shed</th>
<th>Faulty House</th>
<th>Unspecified</th>
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**Note:** The table includes constructional damage due directly to wind, categorized by item of loss and type of building affected.
Fig. XVI
Shed Roof Barn Out of Plumb

Fig. XVII
Curved Arch Roof Barn Out of Plumb
DISCUSSION OF RESULTS

Probable Storm Areas

After locating the areas in the state which have the heaviest loss, it is apparent that they are so spotted that no storm area can be located.

Prevention of Losses to Existing Buildings

A well constructed building will resist severe wind storms. The addition of bracing to many of the existing buildings and thorough maintenance are the best protections against windstorm damage.

Bracing of buildings

1. Diagonal bracing of walls.
2. Brace to tie rafter to plate.
3. Knee braces at the mow floor.
4. Knee braces from supporting members to purlins.
5. Additional bracing to a wall which has large openings as the hay door in the barn.
6. Collar brace to tie rafters together.

Maintenance of buildings

1. Repair roofing which may be loose or damaged.
2. Inspect and repair flashings.
3. Securely fasten doors.
4. Repair broken or loose boards.
5. Securely fasten all windows.

Suitable Wind Resistant Construction

Since the above statements apply to this section, they will not be restated. A few more details which affect the ability of a building to withstand windstorm damage, and can be incorporated when buildings are constructed, are as follows:

2. Anchoring sill to foundation.
3. Use Portland Cement Mortar for all masonry work.
4. Anchoring roof to masonry walls.
5. Tleting masonry to interior framing.
6. Non-corrodible nailing strips to fasten prepared roofings.
7. Use galvanized nails to nail shingles.
8. Use long nails or drive screws to fasten corrugated sheets.
9. Cover all windows and skylights with hardware cloth.
CONCLUSIONS

1. The windstorm was less for 1932 than for 1930 or 1931.

2. No storm area was determined in the state.

3. The greatest damage was to barns and equaled slightly over 38% of the total.

4. Nearly 75% of the claims were paid for constructional damage due directly to wind.

5. The greatest losses occurred during the months of May, June, July, August, and September.

6. Considering the losses paid per 1000 dollars insurance in force, the heaviest loss occurred in Davis County with smaller losses in surrounding counties and in the northern part of the state.

7. Eighty-five percent of the damage was caused directly by wind while other damage was indirectly caused by the same agent.

8. Eighty-five percent of the number of claims paid amounts to less than 100 dollars each and the amount paid is nearly 45% of the total.

9. Windstorm damage is best averted by suitable construction and thorough maintenance.

10. A regular and thorough inspection should be made of all insured buildings by the companies to reduce losses and improve risks.

11. Research is necessary to improve methods of construction which will reduce windstorm damage to farm buildings.
LITERATURE CITED


THE DESIGN OF THE BENT RAFTER TO RESIST WIND LOADS

PART II
INTRODUCTION

The pleasing appearance and unobstructed storage space for hay characterise the curved arch roof which makes it popular among builders. The best rafter used in barn construction came into prominence as a result of the wastefulness of materials and labor experienced in building the sawed rafter.

It has been observed that a large number of barns using the bent rafter sag at the ridge. Investigation of this failure indicates that the cause in many cases is due to the slighting of materials in the construction and that present designs do not entirely fulfill the loading requirements placed on the rafter.

The purpose of this experiment is to study the design of the bent rafter and to determine as nearly as possible the loads that may be placed upon each rafter; to analyze the present types of construction; and to promote simplified practice through design of a rafter which will meet the load requirements as well as be economical in labor and materials.
HISTORICAL
Review of Literature

In his bulletin, "Research in Farm Structures", Henry Giese (7), former Senior Agricultural Engineer, U. S. D. A., considers wind and fire losses to farm buildings a problem of utmost importance. He has listed as a special problem for investigation the following:

"A Study of Farm Building Framing with Reference to Resistance to Wind Pressure."

R. W. Trullinger (9) in a report, "Research in Agricultural Engineering", conducted by the Research Committee of the American Society of Agricultural Engineers, states, after summarizing the studies at the Michigan Station on barn roof construction, the following:

"These and other investigations seem to indicate that some basic studies of barn roof design are necessary before such structures can be made satisfactory as well as economical. Apparently the requirements which barn roofs must meet are more or less well known. However, it does not seem to be fully established that the present designs of barn roofs meet these requirements economically. It seems likely that this is due, in some cases at least, to the fact that roofs used are practically indeterminate structures."

In a study of bent rafters used for barns in Michigan, F. E. Fogle (6) considers that the rafters of this type have adequate strength for barns up to 36 feet in width and that failures are due to gross errors in the design or construction.

A. W. Clyde (3), in testing some rafters for curved arch roofs, found that the sawed rafter will take a greater bending moment than laminated rafters. Also, there is much less deflection in the case of the former than the latter.

"Tests of Laminated Bent Rafters" by Giese and Anderson (8) shows that the application of glue to laminated beams increases the comparative stiffness approximately four times over similar beams which were not glued. The glued beams were approximately comparable in stiffness to solid beams of the same dimensions.

Further studies of laminated rafters at this station show that moisture has little effect on the water-resistant glue after the duration of one year. The rafters had been stored
in a damp shed.

The horizontal shearing strength was found to compare favorably to glueing specifications, even though it was applied rapidly as might be done in rafter construction. A strip of glue was applied to little more than one-half the width of the board and without the use of clamps the laminations were nailed.

Conclusions

1. There is a problem in the design of the bent rafter to resist wind loads.
2. The use of water-resistant glue in the design of the bent rafter should help to prevent a barn, which uses the bent rafter for roof construction, from sagging at the ridge.
3. The glue seems to be resistant to moisture.
4. The glue has sufficient horizontal shearing strength if applied as the boards are nailed together.
ANALYSIS OF THE PROBLEM

Standardization of Requirements

The roof dimensions to be used in the design are dependent upon certain standard requirements for a barn which affect the dimensions of the roof. There are two things which influence the roof dimensions; (1) the barn width, and (2) the mow area required for the storage of hay.

Barn Width

The barn width depends upon the spacing and dimension requirements set up for the interior of the barn, which is a big study in itself. The 36-foot and 34-foot barn widths have been standard for the dairy and general purpose barns with a tendency of going to the 32 foot because of the less space required to be heated by the animals and less waste room in litter and feed alleys. The 34-foot width was chosen for these tests as it is more nearly an average width used for dairy and general purpose barns.

Mow Area

The mow area required for a barn depends on (1) the present and possible future practices of hay storage; (2) appearance; (3) stability; and (4) feed requirements.

The present and possible future practices of hay storage present an interesting problem. If the area required is based on loose storage it will have to be twice as great as if it were based on chopped hay or baled hay. Also, the drying of hay allows for it to be stored in a smaller area than loose hay. However, the design herein will be such that it will accommodate the storage of loose hay according to the feed requirements of animals.

The curved roof seems to have a certain element of appeal and appearance is based on the proportion and shape of the roof. There are a great many different shapes and proportions depending upon the idea of each individual builder as to how it should look and be built. Some roofs come to a sharp peak at the ridge and others vary from that shape to a semi-circle. However, in the latter case the roof is too flat on top making it difficult to have a water-tight roof.

It is evident that in the design of a bent rafter the radius used in making the arc for the rafter should be as long as possible so that the boards will not have to be bent
to too small a radius when being nailed together and still maintain the proper shape and appearance of the roof.

The matter of stability seems to be in favor of a well constructed curved arch roof. This is due to the fact that there are no joints between the plate and the ridge. In the case of the gambrel roof barn from field observations, the purlin joint quite often is the first point of failure. There is also the added advantage that in a roof shaped nearly like that of an inverted catenary, the resultant of the dead loads falls within the line of the rafter itself, which, however is not so important in a wood structure.

In Fig. XVII of Part I the curved arch barn on the Fry Farm at Sibley, Iowa was blown out of plumb 18 inches by a severe wind storm. Two gambrel roof barns in the vicinity were entirely demolished by this storm. A personal investigation showed that the plate on the leeward side had nearly been torn loose but due to 2"x6" knee braces which had been placed every 6', the plate was not completely pulled off the studwall which probably saved the barn from destruction. The roof was built out of sawed rafters every 6' with laminated rafter of 2 - 1"x4"s placed on 2"x4" girts. The roof received no apparent injury from the storm. The stability of a structure is increased by a design which used as few joints as possible and sufficient bracing.

The mow area based on feed requirements of animals will determine the cross section area of the mow. In a study of the feed requirement for animals Schweers (10) states that the mow area should be approximately 500 square feet in cross section. This cross sectional area will be used in determining the length of rafter and height of the roof.

Present Types of Bent Rafter Design

Each individual has his own idea as to shape and method of construction in designing a bent rafter. For this reason there is a great variance in types of rafters now in use.

The most common bent rafter is cut off at the plate with a joint as in ordinary rafter construction. The roof may be made up entirely of bent rafters or a sawed rafter placed 6 to 8 feet on centers to stiffen the roof.

The Louden Machinery Company has a design for a bent rafter which is continuous from one foundation to the foundation on the opposite side. Every so often in the length of the building a rafter has laminations separated and blocks
placed between to give them additional strength at points where high stresses occur. Others have employed the same idea in designing a bent rafter.

The present bent rafter design varies considerably as to specifications for building the rafters. Some designs specify 4 nails per linear foot in nailing, while others specify 8 nails per linear foot. The size and spacing of the bolts vary in different designs. The spacing of end joints, which is an important consideration in the strength of the rafter, is not entirely agreed upon.

After a careful analysis of various specifications for bent rafters and results obtained by Giese and Anderson (4) on "Tests of Laminated Bent Rafters", the following specifications were made for bent rafter construction.

Specifications for Rafters

1. To be to a scale 6" - 1'-0".
2. The rafter for a barn 34' in width.
3. The rafter to be an arc of a circle with center 3/4 the width of the barn and 3' below plate line.
4. Rafter specimens to be made with 5 - 1"x4"s and 6 - 1"x3"s glued and unglued.
5. Lumber - Grade No. 1 common Fir dimension.
7. Application of glue - A strip of glue one-half the width of the board applied on each lamination before nailing.
8. Joints - No end joints to be closer than 3 ft except rafters with 6 laminations where they will be 2'-8" apart in order to use 16' lumber.
9. Nailing of laminations -
   Second nailed to first with 4d common 1 nail per ft.
   Third " second " 6d " 2 nails " "
   Fourth " third " 8d " 2 " "
   Fifth " fourth " " " 2 " "
   Sixth " fifth " " " 6 " "
   First " second " " " 6 " "

The above was used for the rafters which were not glued. Specifications for the glued rafters vary only in nailing of the two outside laminations where four nails per linear foot were used instead of six nails per linear foot as in the unglued specimens.

10. Bolts -
   3/8" x 4 1/2" bolts placed 40 C. for 5 - 1"x4"s.
   3/8" x 5 1/2" " " 6 - 1"x3"s.
The important part in analyzing this problem is to make the proper wind load assumptions on the barn roof. Since wind loads make up the largest excentric forces on the structure, they should approximate as closely as possible the actual conditions. Then the design of the structure should be such that it will resist these loads. The remaining loads to consider other than from the roof itself, such as those from snow and the hay fork, were neglected in assumption. The wind forces act in opposition to those caused by snow and the hay fork; also, due to the shape of the roof, there will be no snow on the roof at times when the wind is of high velocity. The hay fork would not be used during such a storm.

Review of Wind Pressure Investigations

To determine the actual wind loads on a structure requires that the pressures on a model of the proposed structure be measured in a wind tunnel. However, this would be a very large problem in itself, so the wind loads used in this work are assumptions taken from several wind pressure investigations to determine as nearly as possible the magnitude and distribution of wind loads under actual conditions.

Captain O. Costanzi (4) performed experiments on models of an airship hangar 1912. The general cross sectional shape was that of the apex of a Gothic church window or ogival point. The results, Fig. A3, show that the phenomenon of suction, or outward pressure, was experienced on the leeward side and nearly one-fourth the distance to the ground line on the windward side. The position of the resultant shows the lifting effect of the wind pressures.

Professor Smith (11), at Purdue University, conducted in 1913 a series of tests in natural wind on a model of a building with a roof semi-circular in section. An average of results is shown graphically in Fig. A1. Negative pressure or "suction" constitutes the largest part of the total force acting, being a lifting force in effect.

Similar results, Fig. A2, were obtained by Carl Arnstein's (1) wind tunnel experiments on the model of the large airship hangar at Akron, Ohio. The positive or impact pressure constituted a very small part of the total wind load. The results were very similar to those obtained by Costanzi.

Dryden and Hill (5), in their tests on cylinders and circular chimneys, found that the larger pressures were directed outwardly. Similar results were found in their tests
on a model mill building. In many instances the loads on appreciable areas of a face were often as great as twice the average over the entire face.

The most important phenomenon observed by H. M. Sylvester (12) in his wind tunnel tests on model airship hangars was that of the large negative pressures. He quotes the following: "The extensive areas over which these pressures are exerted is surprising, but the extent to which their consideration has been neglected is even more surprising."

The Building Research Board (3), of London, England, in their attempt to determine how results obtained from small scale models may be applied to full sized buildings, found that the pressure on the leeward side of the full-sized building is greater, on the whole, by about 50 percent.

Experiments on serofoils in aerodynamics have shown that 60 to 70 percent of the total lifting force is due to a negative pressure.

The results of these and many other investigations show that negative pressure constitutes a large part of the total force acting and that the wind pressure distribution for a structure varies considerably with its shape, and must in many cases be determined experimentally. These results further show that formulas cannot be comprehensive enough to account for variation of pressure distribution and form variation in buildings. Therefore, an attempt is made here to make wind load assumptions on the basis of the results of the above investigations, which permit perhaps a more close approximation of wind load conditions than could be obtained by any one of several formulas.

Wind Load Assumptions

To determine the distribution and the magnitude of wind pressures for a given wind velocity involves the consideration and evaluation of the following: (1) maximum wind velocity, (2) relation of the normal pressure to a given velocity, and (3) the effect of the shape of the building.

The maximum wind velocity recorded at the various weather stations in the State of Iowa is 68 miles per hour which, when corrected to a true velocity, is 65.2 miles per hour. This value unquestionably is exceeded for short intervals of time, since the anemometer records the average velocity for five minute periods. It is needless to mention that the maximum velocity of gusts in high winds should be considered.
However, since there is no precedent upon which to base an assumption to take into account the effect of gustiness, the maximum wind velocity was established at 70 miles per hour to determine the wind load assumptions on the barn roof.

That the pressure due to wind varies as the square of its velocity is generally known and may be expressed as $P = K A V^2$, where $K$ is a constant depending upon the density of air. The value of $K$ is equivalent to 0.00256 when the density of air is taken at standard conditions and the variables, $P$, $A$, and $V$ are expressed in pounds per square foot, square feet, and miles per hour, respectively. Results of a number of experiments on planes normal to the wind have shown $K$ to be nearly equal to the calculated value, although considerable variation was found in some experiments.

For sake of convenience, the pressures are frequently expressed in ratios or coefficients of the "velocity pressure", which is a term used for the expression $P = K A V^2$. These so-called "resistance coefficients" are the same for different wind velocities, and once these have been determined for various points on a structure the pressures for different wind velocities may be determined conveniently.

Fig. A4 shows the wind pressure diagram for the barn roof under consideration, which has been determined on the basis of the results of the above and similar experiments. The resistance coefficients for a wind velocity of 70 miles per hour are indicated on the diagram for various parts of the roof.
Fig. A Wind Pressure Distribution Diagrams

Pressure Diagram - Smith

Wind Velocity: 10 miles per hr.

DISTRIBUTION OF WIND PRESSURE COEFFICIENTS ON CURVED ARCH ROOF

DISTRIBUTION OF WIND PRESSURE ON AN AIRSHIP HANGAR - COSTANZI
EXPERIMENTAL

The heading "Experimental," as used in this report includes the procedure followed in building rafters as to the specifications in the analysis of the problem and testing the specimens to determine any weakness which may exist in the design in order that such weaknesses may be corrected.

Selection of a Scale for Models

The ideal method of procedure would be to build specimens to a full scale to test. Such a course, however, would require a considerable expenditure of money for apparatus and equipment to test specimens of this size. For this reason, and because of the apparatus already available, a scale of 6" = 1'-0" was selected for constructing the models to be tested.

The lumber used for building the specimens was No. 1 common 2"x6" fir dimension which was picked from the pile in order to secure lumber with a fine grain and free from large knots. This was sawed to 1/2 scale for a 1"x4" and a 1"x3" which would be 25/64" x 1 7/8" and 25/64" x 1 3/8" respectively, considering that the 1"x3" would be ripped from a 1"x6".

The nails and bolts used were to 1/2 scale of those in the specifications and were as follows:

<table>
<thead>
<tr>
<th>Nail</th>
<th>Diameter</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full size 8d</td>
<td>.131 in.</td>
<td>2 1/2 in.</td>
</tr>
<tr>
<td>Scale size 16 gauge</td>
<td>.0625 in.</td>
<td>1 1/2 in.</td>
</tr>
<tr>
<td>Full size 6d</td>
<td>.113 in.</td>
<td>2 in.</td>
</tr>
<tr>
<td>Scale size 17 gauge</td>
<td>.0540 in.</td>
<td>1 in.</td>
</tr>
<tr>
<td>Full size 4d</td>
<td>.0985 in.</td>
<td>1 1/2 in.</td>
</tr>
<tr>
<td>Scale size 18 gauge</td>
<td>.0475 in.</td>
<td>3/4 in.</td>
</tr>
</tbody>
</table>

Where 3/8" and 1/2" bolts were used in the specifications, 3/16" and 1/4" bolts respectively were required.

Determination of Loads on the Rafter

Determination of the Wind Loads

The logical way to design a building is to make air tunnel tests on the particular type of building one is designing before it is built. To do this would be an experiment in itself, so the next approach to the problem is to analyze various tests which have been made by different individuals and arrive at a conclusion as to what the pressures and distribution of
pressures may be on a curved arch roof such as is used on a barn. This was done in a preceding section and applied in this section of discussions.

The wind load on a rafter has the effect of an increasing or decreasing uniform load, so in order to assimilate actual condition in a test would require the application of an infinite number of concentrated loads which would as nearly as possible give a loading with the same distribution as that caused by the wind. Since this is not impossible to do, but as a reasonable number of loadings will approach very nearly that of uniform loading, it was decided to apply 6 loads to each half of the rafter or to load at the 1/7 pts.

To determine the wind loads the coefficients were taken from the diagram in Fig. A4 and substituted in the formula \( P = K A V^2 c \). As the values for \( K, A, \) and \( V \) were shown "c" was found by scaling on the diagram, drawn to a large scale, the length of small increments over each one-third of the rafter and the average length was determined. Thus, the average pressure coefficient for each one-third of the rafter was determined.

The resultant was located by the principles of mechanics and the total uniform load over the one-third section was applied at two points equal distant from the line of the resultant. Thus, six loads were applied to one rafter by the use of three loading systems.

**Determination of Hay and Snow Loads**

As stated in the section on wind load on the roof, the hay and snow loads are not considered to affect the design of this rafter.

**Determination of Dead Loads**

The dead loads considered for a roof include the weight of all the members in the structure, or that portion of structure taken for design purposes. In this case the shingles, sheathing, and rafter make up the members in the roof structure. Since the weight of the rafter takes care of itself, the weight of the shingles and sheathing will be considered, which were determined as follows:

**Weights per square foot of Roof-Surface**

- Common shingles: 2½ lbs.
- Yellow pine sheathing: 4 lbs.
- Spacing: 3 ft. O.C.

\[
(6.5) (28.66) (2) = 357.3 \text{ lbs.}
\]

\[
\frac{1}{8} \text{ scale model reduces the volume by } 1/8
\]

\[
357.3 - 8 = 46.7 \text{ lbs. for model.}
\]
Method of Applying Loads

The wind loading for each point of application was worked out as in the preceding section and recorded in Table A. The diagram, Fig. B, above the table shows the point of application and direction of pull for the various loads. Each point where the load was applied was marked by letter beginning on the left or windward side which corresponds to the assumed direction of the wind.

Since the loads were to be applied by flexible wire rope and ball bearing pulleys, it was necessary to determine the friction in rope and pulleys. The problem being this - if 500 lbs. is hung on the wire rope and transferred over two pulleys with certain angles of binding, will 500 lbs. be applied at the other end? The set-up shown in Fig. C was used to make the test. The results obtained were plotted on the graph in Fig. D. The plotted points gave a straight line and a percentage of error of nearly 1\(^\circ\) for 500 lbs. The correction, however, was not made on the wind loadings as the dead load over each section would amount to nearly 3\% of the total applied load and this counteracts the friction loss, leaving only 1\(^\%\) which is well within experimental percentage of error. Since the wind loads are only assumptions, this is considered close enough.

Construction of the Models

A bent rafter is constructed by the bending to shape and nailing of successive laminations of one inch lumber with the joints between the laminae parallel to the roof surface. The plan is seen in Fig. E. In order that the rafters may have a uniform shape, and also to aid in construction, requires the use of form or templet as seen in Fig. F in making them.

A skeleton frame work was built and on this was laid out the desired arc. Every 12 inches along this line 2 x 3 blocks were fastened to the cross pieces on the frame by large screws. A space was left between the blocks wide enough to admit the desired number of strips required to build the rafter and wedges to hold them together for nailing.

In building the rafter the first two laminations were held by wedges to the inside radius and nailed together, then the successive plies were nailed and bolted to these as detailed on the specifications. The rafter was then moved to the outer radius, which was the true radius, and marked for sawing. The blocks on each end were guides by which the rafter was marked at the plate and ridge.
Table A Test Loads

<table>
<thead>
<tr>
<th>Load A</th>
<th>Load B</th>
<th>Load C</th>
<th>Load D</th>
<th>Load E</th>
<th>Load F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Vel</td>
<td>Load</td>
<td>Dif</td>
<td>Load</td>
<td>Dif</td>
<td>Load</td>
</tr>
<tr>
<td>0.5</td>
<td>25.5</td>
<td>2.5</td>
<td>38.5</td>
<td>3.5</td>
<td>37.5</td>
</tr>
<tr>
<td>1.0</td>
<td>50.0</td>
<td>5.0</td>
<td>38.5</td>
<td>3.5</td>
<td>37.5</td>
</tr>
<tr>
<td>1.5</td>
<td>75.0</td>
<td>7.5</td>
<td>38.5</td>
<td>3.5</td>
<td>37.5</td>
</tr>
<tr>
<td>2.0</td>
<td>100.0</td>
<td>10.0</td>
<td>38.5</td>
<td>3.5</td>
<td>37.5</td>
</tr>
<tr>
<td>2.5</td>
<td>125.0</td>
<td>12.5</td>
<td>38.5</td>
<td>3.5</td>
<td>37.5</td>
</tr>
</tbody>
</table>

Fig. B Position and Direction of Load
Fig. C Method Used in Determining Friction in Pulleys

Fig. D Graph Showing Results of Friction Tests
Fig. E  Plan for Construction of Rafters
When constructing the glued rafter a strip of glue about one-half of the width of the board was applied to each lamination before nailing, Fig. F. The glue was Waterproof Casco Glue mixed with cold water in the proportion of 1 lb. of glue to 2 lbs. of water. A brush was used to apply the glue as might be done in actual construction. An average of .15 lbs. of dry glue was used per rafter. The extra time required to spread the glue was about 10 minutes per rafter.

The Testing Frame

The steel frame work of the testing frame shown in Fig. G. was designed and built during the summer of 1932. The frame was constructed especially for the testing of barn rafters. The rest of the apparatus was designed to suit the particular needs in testing the bent rafters. The frame construction makes an excellent place to test a truss of any type built to 1/2 scale. The pulleys may be shifted so that a load can be applied at any point on the truss.

The pulley blocks were made to fit the ball bearing sheaves which were special equipment for this project. The loads were applied by means of a 1/8" 19 strand aircraft special flexible cable on which baskets were hung to place the sand bags used for the loads, Fig. G.

A special device was made to record the deflection of the rafter at three points. A copper tube with a compression spring in one end was soldered to a plate and this apparatus was fastened to the rafter with screws. A pencil in the tube recorded the deflection on the graph paper, which can be seen in photo on Fig. G, for every load which was applied. A line was placed on the board backing with a carpenter's level so that the graph paper was level with the frame to give the true direction as well as the actual amount of deflection.

Procedure in Testing Rafters

The rafters were placed in the testing frame with eveners connected to apply loads and the pencils to record the deflection at three points. The fastenings at the plate were rigid and the ridge was semi-rigid. This system made similar conditions for the testing of each rafter.

In order that all the play be taken up in the apparatus it was necessary to choose a certain wind load to start the test. A 45 mile per hour wind was selected and the respective loads were applied by use of sand bags placed in the baskets as shown, the loads being determined from Table A. When load
Fig. F Constructing a Glued Rafter

Fig. G Testing Frame
"1" had been applied (corresponding to a 45 mi/hr wind load) a line was drawn on the deflection charts where the pencil stood and marked "1". Load "2" was placed in each basket and the deflection chart marked. The successive loads were placed in the baskets in regular order and the deflections were marked after each load until all the loads were applied up to a load corresponding to a 170 mi/hr wind, or the rafter had failed. When any noticeable change occurred in the testing a note was made on the chart.

A regular system was used also in placing the bags in the baskets. It will be noticed that loads at points C & D on Fig. C are nearly equal and on opposite sides of the rafter. The sand bags were placed in these baskets first, then at points B & E and lastly the loads for points A & F. This system was used for each loading so that the deflections would be fairly constant for the various rafters. The same system in opposite order was used to unload the baskets.

The measurement of deflection on the deflection charts is accurate providing the frame is rigid and does not deflect when loaded. A transit was set up during two tests to check the amount the frame would deflect under full load. This was found to be such a small amount that it was negligible.

Besides the record of deflection taken on the charts, pictures were taken at various times to show the different shapes of the rafter under different loadings, some of which were traced from projections and shown in Fig. K.
Fig. H Recorded Deflections
DISCUSSION OF RESULTS

The results obtained from the tests will be discussed separately for each individual test. Then an analysis will be made of all the tests.

Analysis of Deflection Charts

The recorded deflections taken at three points, Fig. J, are shown on the diagram in Fig. H. The H, K, and L at the top of the figure have reference to the points at which the deflections were recorded. The members on the curves indicate the position of the pencil after each load was applied. Each test, together with the type of rafter tested, is indicated on each curve.

Test No. 1

The rafter in Test No. 1, comprising 5 plies unglued, was not as uniform in deflection as the other unglued rafters. This is due to the fact that in the first test the system for loading was not fully worked out and caused an uneven deflection in the rafter. This rafter did not fail under full load which was equivalent to a 170 mi/hr velocity wind.

Test No. 2

The rafter in Test No. 2 shows a more even deflection for each successive loading. This rafter also was loaded to full load without failure.

Test No. 3

The rafter of 5 plies in Test No. 3 was glued. The deflection was less for each successive loading than in the case of the unglued specimen until load 14, representing a wind velocity of 125 mi/hr was reached; then a glue joint broke causing a greater deflection. The plan of failure was about one-third the distance from the plate line on the left rafter where the shear is high due to the change in the forces acting on the rafter. The rafter did not fail completely at full load.

Test No. 4

The rafter of 6 plies in this test was glued. Nearly the same result was experienced in this test as in the preceding test. A glue joint failed when load 14 was applied making a jump in the deflection. The rafter continued to take load
until the left side broke off where it was fastened in the
frame.

Test No. 5

This glued rafter of 6 laminations is comparable to the
one in Test No. 4. However, it took even more load before
failing. Some additional data were taken on this rafter.
The mark IRr on the curve indicates the point to where the de-
flection returned after being subjected to load No. 6 and then
these loads were removed down to No. 1. This is the only
glued specimen on which this test was made, but it indicates
the elasticity of the glued rafter since it returned to nearly
its original position. The deflection had a small increase
between loads 8 and 9 which was not due to a glue joint break-
ing but to a fastening which slipped. The glued joint broke
on the same loading as those in the preceding tests. The
inside lamination on the left half of the rafter failed in
the tension after load 17 was applied.

Test No. 6

The rafter constructed of 6 laminations unglued was
loaded to test its elasticity in the same manner as the preced-
ing glued rafter. The unglued rafter showed very little elas-
ticity. This rafter took all the loads without failure.

Test No. 7

This rafter of 6 plies unglued reacted much the same
as the rafter No. 6.

Analysis of the Composite Graph

Since, as previously stated in this report a 70 mi/hr
wind velocity was considered as maximum for design purposes,
it is on this basis that the deflection of the rafters will
be compared.

The curves in this graph, Fig. I, are plotted as averages
of the two tests of similar rafters.

Unglued rafters. The curves show the deflection to be
nearly the same for the 5 - 1"x4"s as the 6 -1"x3"s, the
former having a slight advantage in stiffness. This can be
accounted for by the fact that the nails used in each case
were the same length and didn't reach as far through the
6 - 1"x3"s. The horizontal shear is greatest at the center
of the member, consequently the nails were not as effective
as in the 5 - 1"x4"s.
Fig. I Composite Deflection Graph

Fig. J Elasticity of Rafters
Glued rafters. Comparing the deflection curves of the 6 - 1\"x3\" and the 5 - 1\"x4\" rafters, the former has greater stiffness as would be expected since the depth of the beam increases stiffness more than the width. The curves are fairly straight to the point where the glue joints broke, but the curve shows that the rafter took up the load again and came back nearly to the original line.

A comparison of the glued and unglued rafters shows that at a wind velocity of 70 mi/hr the glued rafters had a deflection of about 7/16\", while the unglued ones showed a deflection of 3/4\", or that the glued specimens were 1.7 times as stiff as the unglued rafters.

The curves in Fig. J show the comparative elasticity of the 6 - 1\"x3\" glued and the 6 - 1\"x3\" not glued. As explained before, the rafter was loaded to load 8, then the loads removed, the glued rafter returned nearly to its original position while the unglued rafter retroceded very slightly. This helps to explain why these rafters sag at the ridge. The force of the wind slides the laminations one over the other so that they deflect outward at the center letting the ridge sag. Even though the deflection in a long slender beam, such as a rafter, does not show as great a difference as might be expected between the glued and unglued specimens, the elasticity is very important and will aid materially in keeping the roof from sagging at the ridge.

Deformation of the Rafter Under the Load

The deformation of the rafter under load, which is shown by the diagrams in Figs. K & L is one very interesting result of the tests. The diagrams, which were reproduced from pictures taken during the tests, are of the rafter used in Test No. 1. The photographs taken of the various tests show that Test No. 1 is fairly representative of all tests so no others were reproduced.

In order to make the diagram as accurate as possible, the pictures were enlarged and the diagrams traced from the enlargements, which were in turn reduced in the photostat.

The diagram, as seen in Fig. K, shows the deformation resulting from a load of about an 80 mi/hr velocity wind. It is noticed that the shape of the rafter is nearly the same as the original except that it shows some deflection.

The diagrams in Fig. L indicate the deformation after all the loads were applied. The left half of the rafter is under the greatest strain due to the direction of the forces
Deflections

\[ H = 1\frac{1}{8}'' \]
\[ K = 1\frac{3}{8}'' \]
\[ L = 1\frac{1}{2}'' \]

Above for model where \( 6'' = 1'\cdot0'' \)

Fig. K: Deformation of a Rafter

Deflections

\[ H = 8\frac{7}{8}'' \]
\[ K = 4\frac{3}{8}'' \]
\[ L = 6'' \]

Above for model where \( 6'' = 1'\cdot0'' \)

Wind Velocity 80 mi/hr

Wind Velocity 170 mi/hr

Fig. L: Deformation of a Rafter
on one end acting in one direction and those on the other end in the opposite direction. This causes a point of inflection and develops a very high shear. The right half of the rafter is subjected to deflection which tends to develop a high horizontal shear.

The only difference in the deformation of the glued rafters from those which were not glued was that up to the loading which caused the glued joint to fail, the left rafter held nearly its original shape except for deflection, then took on the shape as indicated. The deformation of the unglued rafters was gradually increased as the loads were applied.

This analysis indicates some important facts which should be considered in the design of the bent rafter. Extra bolts added to the center portion of the rafter will help transfer the tensile stress which comes on the inside lamination to the other plies in the rafter. Also, the fact that the inside lamination failed in tensile stress in two of the rafters indicates that the best lumber should be used for this part of the rafter.

The Economic Feasibility of Casein Glue

In order to justify the use of glue the cost and labor to apply must be considered.

In building the specimens it was found that it took approximately .30 pounds of dry glue per rafter. A rafter to full scale would require 4 times this amount or 1.2 pounds. The glue can be purchased for 50¢ per pound in 10 pound lots. This would amount to 60¢ per rafter.

For a barn 34'x60' the expenses of using glue to construct the rafters would amount to (31) (.60) = $18.60.

Two men applied the glue to each lamination in less than one minute. The glue could be applied to a full scale rafter by two men in about five minutes. Thus, the extra labor required to use the glue is a small item.

The Durability of Casein Glue

The animals housed in the barn excrete considerable moisture so the durability of the glue may be a problem. The tests conducted at this station show that the glue used on laminated beams stored in a damp shed for one year was not affected by the moisture.
The use of glue in aircraft manufacture (13) has shown that in wood up to a moisture content of 12 percent no deterioration takes place. Under conditions where wood retains a moisture content of 30 percent there is no assurance of the permanence of glue without special treatment.

However, the Casein Glue Company incorporates a special preservative fungicide to protect the glue under conditions of unusual exposure. This is not regularly put in the glues for general use, however, when informed of such a condition this preservative is added.

After considering the results obtained from these tests, the writer wishes to state that results obtained were satisfactory insofar as they were carried out. Since a satisfactory procedure in testing has been worked out further tests should be made including rafters with different types of nailing and bolting. This is necessary to determine the number of nails and bolts to be used. Also, in a glued rafter theoretical analysis should be made on the rafter to check the results.
SUMMARY AND CONCLUSIONS

A summary of the work reported in this includes the following points:

1. The determination of loads placed on a rafter such as used in a curved arch barn roof.

2. Analysis of present designs from which an improved design was made.

3. The design of the apparatus and establishment of a method of procedure to test present types of construction in comparison to the improved type of construction.

4. The results of the tests discussed in detail from which the conclusions were drawn.

Conclusions

1. The wind load assumptions arrived at from the experimental tests can be considered nearly representative of actual conditions.

2. Analysis of present designs showed a large variance in the specifications for construction of bent rafters.

3. The apparatus and procedure followed in making the tests proved to be satisfactory.

4. The glued rafters were found to be 1.7 times as stiff as the unglued specimens.

5. The failure of the glued joint occurred at a load equal to a wind velocity of 125 mi/hr giving a factor of safety of 3.3 considering the maximum wind velocity at 70 mi/hr.

6. The glued rafters showed more elasticity than the unglued rafters.

7. It is believed that the use of a water-resistant glue in construction of bent rafters will prevent the rafter from sagging at the ridge.

8. The cost of glue amounts to 60 cents per two feet linear length of the barn.

9. Very little extra labor is required to apply the glue.

10. The water-resistant glue is believed to be durable under conditions to which it is exposed in a barn roof.
LITERATURE CITED


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