1949

Relationship between size and strength of glued joints

Charles Everlin Hamlin

Iowa State College

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RELATIONSHIP BETWEEN SIZE AND STRENGTH OF GLUED JOINTS

by

Charles Everlin Hamlin

A Thesis Submitted to the Graduate Faculty in Partial Fulfillment of The Requirements for the Degree of

MASTER OF SCIENCE

Major Subject: Agricultural Engineering (Farm Structures)

Signatures have been redacted for privacy

Iowa State College 1949
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>The Project</td>
<td>1</td>
</tr>
<tr>
<td>History</td>
<td>1</td>
</tr>
<tr>
<td>Purpose</td>
<td>3</td>
</tr>
<tr>
<td>JUSTIFICATION OF THE STUDY</td>
<td>4</td>
</tr>
<tr>
<td>Farm Building Investment</td>
<td>4</td>
</tr>
<tr>
<td>Major Structural Damage to Iowa Farm Buildings Due to Wind</td>
<td>5</td>
</tr>
<tr>
<td>Wood as a Structural Material for Farm Buildings</td>
<td>10</td>
</tr>
<tr>
<td>Problems of Wood-Frame Construction</td>
<td>11</td>
</tr>
<tr>
<td>Glue as an Aid to Constructing Strong Joints</td>
<td>12</td>
</tr>
<tr>
<td>REVIEW OF LITERATURE</td>
<td>13</td>
</tr>
<tr>
<td>Distinction Between Adhesive and Glue</td>
<td>13</td>
</tr>
<tr>
<td>Early History of Adhesives</td>
<td>14</td>
</tr>
<tr>
<td>Classification of Adhesives</td>
<td>15</td>
</tr>
<tr>
<td>Water-Resistant and Waterproof Adhesives</td>
<td>15</td>
</tr>
<tr>
<td>Casein glue</td>
<td>16</td>
</tr>
<tr>
<td>Synthetic-resin glues</td>
<td>17</td>
</tr>
<tr>
<td>Structural Application of Glue to Farm Buildings</td>
<td>18</td>
</tr>
<tr>
<td>Laminated construction</td>
<td>19</td>
</tr>
<tr>
<td>The braced-rafter roof</td>
<td>22</td>
</tr>
<tr>
<td>Rigid-frame construction</td>
<td>23</td>
</tr>
<tr>
<td>Glued joints in tension</td>
<td>25</td>
</tr>
<tr>
<td>Some Factors Affecting the Strength of Glued Joints</td>
<td>26</td>
</tr>
</tbody>
</table>
Specific gravity of the wood .......................... 26
Moisture content of the wood .......................... 27
Dimensional changes of the wood ........................ 27
Surface condition of the wood .......................... 28
Assembly time ........................................... 29
Application of pressure during setting time of glue .......................... 30
Curing period ............................................ 32

How Glue Makes Wood Stick Together ....................... 33

Mechanical adhesion ....................................... 33
Specific adhesion ........................................ 33

Durability of Glued Joints .................................. 34

OBJECTIVES OF THE STUDY .................................. 36

THE INVESTIGATION ......................................... 37

Tests on Joints With Varying Glue Areas ............... 37

Equipment used ........................................... 37
Method of procedure ..................................... 37

Selection of wood ......................................... 37
Determination of moisture content of wood .............. 38
Determination of specific gravity of wood ............... 39
Construction of joints ................................... 41
Curing of joints .......................................... 44
Numbering of joints ...................................... 44
Testing of joints ......................................... 45

Tests on Photo-Elastic Models .............................. 48

Brief discussion of the principle of photo-elasticity .......................... 48
Equipment used .......................................... 50
Method of procedure ..................................... 50

Preparation of models .................................... 50
Testing of models ........................................ 53

Tests Using Strain Gages on Actual Glue Joints ........ 53

Equipment used .......................................... 53
Method of procedure .................................................. 55
Placement of strain gages on joints ............................... 55
Testing of joints ....................................................... 57

Tests on Glued Joints Subjected to Torsion Loads .......... 57
Equipment used ......................................................... 57
Method of procedure .................................................. 59
Construction of joints ................................................ 59
Curing of joints ......................................................... 61
Testing of joints ....................................................... 61

Tests on Glued Joints Subjected to Fatigue Stresses ...... 62
Equipment used ......................................................... 62
Method of procedure .................................................. 62
Construction of joints ................................................ 62
Construction of fatigue-testing machine ....................... 62
Testing of joints ....................................................... 66

ANALYSIS OF RESULTS ............................................. 68
Joints With Varying Glue Areas .................................. 68
General ................................................................. 68
Types of joint failures ............................................... 68
Failure of 1-inch members by compression .................... 68
Failure of 2-inch member by compression ...................... 72
Failure of 2-inch member by splitting ......................... 72

Corrections for variations in specific gravity of wood .... 74
Variation of unit strength with size of joint .................. 77
Statistical analysis .................................................... 77
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple linear regression equations</td>
<td>80</td>
</tr>
<tr>
<td>Multiple linear regression equations</td>
<td>80</td>
</tr>
<tr>
<td>Photo-Elastic Models</td>
<td>85</td>
</tr>
<tr>
<td>General</td>
<td>85</td>
</tr>
<tr>
<td>Definitions</td>
<td>85</td>
</tr>
<tr>
<td>Isoclinic line</td>
<td>85</td>
</tr>
<tr>
<td>Fringe line</td>
<td>85</td>
</tr>
<tr>
<td>Direction of principal stresses and shears in model</td>
<td>85</td>
</tr>
<tr>
<td>Strain Gages on Actual Glued Joints</td>
<td>93</td>
</tr>
<tr>
<td>General</td>
<td>93</td>
</tr>
<tr>
<td>Distribution of strain along glue line</td>
<td>93</td>
</tr>
<tr>
<td>Distribution of compressive strains in 2-inch and 1-inch members of joints</td>
<td>96</td>
</tr>
<tr>
<td>Joints Subjected to Torsion Loads</td>
<td>98</td>
</tr>
<tr>
<td>General</td>
<td>98</td>
</tr>
<tr>
<td>Load-deflection characteristics of nailed joints</td>
<td>105</td>
</tr>
<tr>
<td>Non-braced nailed joints</td>
<td>105</td>
</tr>
<tr>
<td>Nailed and braced joints</td>
<td>107</td>
</tr>
<tr>
<td>Load-deflection characteristics of glued joints</td>
<td>107</td>
</tr>
<tr>
<td>Nailed-glued joints</td>
<td>107</td>
</tr>
<tr>
<td>Bolted-glued joints</td>
<td>109</td>
</tr>
<tr>
<td>Glued and braced joints</td>
<td>109</td>
</tr>
<tr>
<td>Glued Joints Subjected to Fatigue Stresses</td>
<td>110</td>
</tr>
<tr>
<td>General</td>
<td>110</td>
</tr>
<tr>
<td>Glued joints subjected to fatigue loads close to maximum static loads</td>
<td>111</td>
</tr>
<tr>
<td>Glued joints subjected to fatigue loads less than maximum static loads</td>
<td>111</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>114</td>
</tr>
<tr>
<td>Joints With Varying Glue Areas and With Grain of Members Parallel</td>
<td>114</td>
</tr>
<tr>
<td>Glued Joints Subjected to Torsion Loads</td>
<td>115</td>
</tr>
<tr>
<td>Glued Joints Subjected to Fatigue Stresses</td>
<td>116</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>117</td>
</tr>
<tr>
<td>SUGGESTIONS FOR FURTHER STUDY</td>
<td>119</td>
</tr>
<tr>
<td>LITERATURE CITED</td>
<td>121</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>125</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>126</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Wind Damage to Iowa Farm Buildings</td>
<td>6</td>
</tr>
<tr>
<td>2.</td>
<td>Demolition as Per Cent of Total Wind Damage by Year and Major Structural Failures as Per Cent of Total Wind Damage by Year</td>
<td>8</td>
</tr>
<tr>
<td>3.</td>
<td>Demolition of Barns and Dwellings by Wind</td>
<td>9</td>
</tr>
<tr>
<td>4.</td>
<td>Construction Jig and Tag-Heppenstall Moisture Meter</td>
<td>40</td>
</tr>
<tr>
<td>5.</td>
<td>Equipment for Making Specific-Gravity Tests</td>
<td>42</td>
</tr>
<tr>
<td>6.</td>
<td>Range in Size of Joints Tested</td>
<td>42</td>
</tr>
<tr>
<td>7.</td>
<td>Details of Joints Used for Testing Effect of Joint Sizes on Unit Strength</td>
<td>43</td>
</tr>
<tr>
<td>8.</td>
<td>60,000 lb. Southward-Emery Testing Machine</td>
<td>46</td>
</tr>
<tr>
<td>9.</td>
<td>300,000 lb. Southward-Emery Testing Machine</td>
<td>46</td>
</tr>
<tr>
<td>10.</td>
<td>Testing Joint to Failure</td>
<td>47</td>
</tr>
<tr>
<td>11.</td>
<td>Testing Vise Used to Resist Spreading of Joints</td>
<td>47</td>
</tr>
<tr>
<td>12.</td>
<td>Schematic Drawing of Polarizing Instrument</td>
<td>49</td>
</tr>
<tr>
<td>13.</td>
<td>Polarizing Instrument With Model in Place for Testing</td>
<td>51</td>
</tr>
<tr>
<td>14.</td>
<td>Details of Photo-Elastic Models</td>
<td>54</td>
</tr>
<tr>
<td>15.</td>
<td>Strain-Recording Equipment</td>
<td>56</td>
</tr>
<tr>
<td>16.</td>
<td>Testing Apparatus for Torsion Load Tests</td>
<td>58</td>
</tr>
<tr>
<td>17.</td>
<td>Deflectometer</td>
<td>58</td>
</tr>
<tr>
<td>18.</td>
<td>Details of Joints Used for Torsional Tests</td>
<td>60</td>
</tr>
<tr>
<td>19.</td>
<td>Fatigue-Testing Machine</td>
<td>64</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>20.</td>
<td>Reduction Gear, Crank, and Linkage Assembly of Fatigue-Testing Machine</td>
<td>65</td>
</tr>
<tr>
<td>21.</td>
<td>Typical Failure of Joints With Small Glue Area</td>
<td>69</td>
</tr>
<tr>
<td>22.</td>
<td>Shear Failures of 1-inch Members of Glued Joints</td>
<td>69</td>
</tr>
<tr>
<td>23.</td>
<td>Joints Showing High Percentage of Glue Failure</td>
<td>70</td>
</tr>
<tr>
<td>24.</td>
<td>Joints Showing High Percentage of Wood Failure</td>
<td>70</td>
</tr>
<tr>
<td>25.</td>
<td>Failure of 1-inch Members by Compression</td>
<td>71</td>
</tr>
<tr>
<td>26.</td>
<td>Failure of 2-inch Members by Compression</td>
<td>71</td>
</tr>
<tr>
<td>27.</td>
<td>Failure of 2-inch Members by Splitting</td>
<td>73</td>
</tr>
<tr>
<td>28.</td>
<td>Actual Spliced Joint Showing 2-inch Members that Split Under Load</td>
<td>73</td>
</tr>
<tr>
<td>29.</td>
<td>Effect of Width of Joint on Unit Strength</td>
<td>78</td>
</tr>
<tr>
<td>30.</td>
<td>Effect of Length of Joint on Unit Strength</td>
<td>79</td>
</tr>
<tr>
<td>31.</td>
<td>Simple Linear Regressions Showing Effect of Width of Joint on Unit Strength</td>
<td>81</td>
</tr>
<tr>
<td>32.</td>
<td>Simple Linear Regressions Showing Effect of Length of Joint on Unit Strength</td>
<td>82</td>
</tr>
<tr>
<td>33.</td>
<td>Development of Isoclinics and Fringe Lines in Photo-Elastic Model</td>
<td>86</td>
</tr>
<tr>
<td>34.</td>
<td>Development of Isoclinics and Fringe Lines in Non-Uniformly Loaded Photo-Elastic Model</td>
<td>87</td>
</tr>
<tr>
<td>35.</td>
<td>Development of Isoclinics and Fringe Lines in Large Photo-Elastic Model</td>
<td>88</td>
</tr>
<tr>
<td>36.</td>
<td>Photo-Elastic Picture of Glued Model</td>
<td>88</td>
</tr>
<tr>
<td>37.</td>
<td>Diagram Showing Direction of Principal Stresses and Shears Along Isoclinic Lines of Photo-Elastic Model</td>
<td>90</td>
</tr>
<tr>
<td>38.</td>
<td>Curves Showing Distribution of Strains Along Glue Line Length for Various Loadings Applied to a Joint 4&quot; Wide and 8&quot; Long</td>
<td>94</td>
</tr>
</tbody>
</table>
Figure Page
39. Curves Showing Distribution of Strains Along Glue Line Length for Various Loadings Applied to a Joint 8" Wide and 8" Long .......................... 94
40. Curves Showing Distribution of Compressive Strains in 1" and 2" Members of a Joint 4" Wide, 7" Long .......................... 95
41. Glued Joint Showing Poor Glue Bond at Outer Edges ........................................ 102
42. Glued and Braced Joint Showing Poor Glue Bond Over Entire Area .......................... 102
43. Glue Joint Showing Excellent Glue Bond ........................................ 103
44. Bolted-Glued Joint Under Load of 1880 lbs ........................................ 103
45. Load-Deflection Curves for Timber Joints Under Torsion Loads ........................................ 106
46. Nailed and Braced Joint After Testing ........................................ 108
47. Glued and Braced Joint After Testing to Failure ........................................ 108
48. Glue Fracture Along Edge of Joint Being Subjected to Fatigue Stresses .......................... 113
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Correction Factors for Joints by Width</td>
<td>75</td>
</tr>
<tr>
<td>2. Corrected Average Strength of Joint Groups</td>
<td>76</td>
</tr>
<tr>
<td>3. Maximum Loadings and Deflections of Joints Subjected to Torsion Loads</td>
<td>99</td>
</tr>
<tr>
<td>4. Results of Fatigue Tests</td>
<td>110</td>
</tr>
</tbody>
</table>
INTRODUCTION

The Project

History

Project 23 of the Agricultural Experiment Station, Iowa State College, entitled "An Investigation of Farm Building Losses Due to Wind and Fire", is sponsored jointly by the Iowa Mutual Tornado Insurance Association and the Farmers Mutual Reinsurance Company. The project was established in 1930 when the two associations requested the Agricultural Engineering Section of the Iowa Agricultural Experiment Station to undertake a study directed towards the prevention of wind and fire losses through improved building design and improved construction standards.

The present study will consider only that part of the project devoted to the prevention of wind losses to farm buildings. In order to make a comprehensive study of both structural weaknesses in farm buildings and methods of eliminating these weaknesses this part of the project has previously been divided into the following 6 fields of investigation: (1) aerodynamics, (2) loss statistics, (3) field observations, (4) structural analysis, (5) laboratory tests, and (6) building design.
At the present time no actual aerodynamic studies have been made by persons working on this project. The work that has been done has primarily consisted of adapting to farm buildings results of researches carried on at the National Bureau of Standards relating to wind pressure against structures.

Statistical studies of wind losses to Iowa farm buildings have been made by Elmer F. Clark (4) and Marvin F. Schweers (34) for the period 1930 to 1933. A later study was made in 1947 by Merle L. Esmay (8) for wind losses to Iowa farm buildings during the year 1946. All 3 of these studies emphasized the urgent need of wind-resistant construction.

Field observations of buildings destroyed and damaged by wind have been made by Professor Giese and others of the Agricultural Engineering Section. This type of study is particularly beneficial, especially if the building is not completely destroyed, because evidence often remains as to the cause of the structure's failure. The results obtained from these observations indicated that many of the losses were the result of improper construction.

Considerable study has been made by structural analysis methods to determine the roof shapes that have the greatest stability under wind and dead loads. This phase of study has been important since many of the observed losses were attributed to failure in some roof member.

In the laboratory, models of barn rafters and trusses
have been tested under simulated live loads so as to gain information regarding the strength, rigidity, and points of weakness of various designs. In addition tests have been made on many types of timber framing joints. The fasteners used in the joint tests included nails, bolts, timber connectors, and glues.

The information gained from the first 5 fields of investigation has been used to formulate data upon which to base recommendations concerning new building designs and construction standards.

Purpose

The purpose of this study is to aid in the collection of data necessary for the intelligent use of glue as a means of designing wind-resistant farm structures.
FOUR

JUSTIFICATION OF THE STUDY

Farm Building Investment

Most of us are aware of the tremendous investments in the large buildings concentrated in our cities. Farm buildings, on the other hand, are comparatively small structures and are scattered over the entire country in little groups on our nearly 6 million farms. Because we cannot see the whole picture the investment in farm buildings appears insignificant; however, the combined value of these farm buildings amounted to a staggering $10,405,435,796 in 1940 (41). Such an investment in buildings was almost one-third greater than the total value of all the implements, machinery and livestock on the farms of the United States for that year.

Of the individual states Iowa ranks first with a total farm building investment of $794,901,864* (40). This represents approximately 8 per cent of the total investment for the entire United States.

The most recent United States Census of Agriculture (42) shows the sharp increases in the value of all farm property that occurred during the war. Although no separate value of farm buildings is shown, by assuming that they represent the

*Figures are for 1940.
same percentage of total farm investment as in 1940 their value has increased to about 15 billion dollars.

The fact that farm building investment is so great in the United States emphasizes their importance to agricultural enterprises. This investment does not insure, however, that all the buildings are of sound construction.

Major Structural Damage to Iowa Farm Buildings Due to Wind

The records of the Iowa Mutual Tornado Insurance Association of Des Moines, Iowa, indicate that wind loss claims for farm buildings have averaged $296,539 for the 7 years covered by the periods 1930-1933 and 1946-1948. The above average loss represents wind damage of all kinds; that is, major structural failures, broken glass, paint damage, shingles blown off, etc. The major structural failures, which are (1) demolition, (2) building out of plumb, (3) building off foundation, and (4) roof off, resulted in an average loss of $214,175 during the same years. Thus major structural failures to farm buildings amounted to approximately 72 per cent of the total average annual building wind loss for the years mentioned. Figure 1 shows the damage in dollars and the percent of total wind damage caused by each type of structural failure for the years 1930-1933 and 1946-1948.

Of the major structural failures occurring in farm buildings, demolition accounts for the greatest amount of damage
### FIG. 1 WIND DAMAGE TO IOWA FARM BUILDINGS

<table>
<thead>
<tr>
<th>Year</th>
<th>Type of Damage</th>
<th>Per Cent of Total Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1930</td>
<td>Roof Off</td>
<td>2.5%</td>
</tr>
<tr>
<td>1931</td>
<td>Roof Off</td>
<td>6.8%</td>
</tr>
<tr>
<td>1932</td>
<td>Roof Off</td>
<td>4.9%</td>
</tr>
<tr>
<td>1933</td>
<td>Roof Off</td>
<td>7.7%</td>
</tr>
<tr>
<td>1934</td>
<td>Roof Off</td>
<td>4.9%</td>
</tr>
<tr>
<td>1935</td>
<td>Roof Off</td>
<td>6.8%</td>
</tr>
<tr>
<td>1936</td>
<td>Roof Off</td>
<td>2.5%</td>
</tr>
<tr>
<td>1937</td>
<td>Roof Off</td>
<td>6.8%</td>
</tr>
<tr>
<td>1938</td>
<td>Roof Off</td>
<td>4.9%</td>
</tr>
<tr>
<td>1939</td>
<td>Roof Off</td>
<td>7.7%</td>
</tr>
<tr>
<td>1940</td>
<td>Roof Off</td>
<td>4.9%</td>
</tr>
<tr>
<td>1941</td>
<td>Roof Off</td>
<td>6.8%</td>
</tr>
<tr>
<td>1942</td>
<td>Roof Off</td>
<td>2.5%</td>
</tr>
<tr>
<td>1943</td>
<td>Roof Off</td>
<td>6.8%</td>
</tr>
<tr>
<td>1944</td>
<td>Roof Off</td>
<td>4.9%</td>
</tr>
<tr>
<td>1945</td>
<td>Roof Off</td>
<td>7.7%</td>
</tr>
<tr>
<td>1946</td>
<td>Roof Off</td>
<td>4.9%</td>
</tr>
<tr>
<td>1947</td>
<td>Roof Off</td>
<td>6.8%</td>
</tr>
<tr>
<td>1948</td>
<td>Roof Off</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Data compiled by M.L. Esmay from records of Iowa Mutual Tornado Insurance Assn.
and loss. For the years 1930-1933 and 1946-1948, as shown in Figure 2, demolition amounted to an average of 53.4 per cent and 43.7 per cent respectively of the total wind damage to farm structures in Iowa. At the same time, referring again to Figure 2, all types of structural failure, including demolition, amounted to 80.4 per cent and 66.7 per cent respectively. Not only then are major structural failures a high percentage of the total wind damage, but approximately one-half of the wind damage results in buildings being demolished or totally destroyed.

Barns, of all the types of farm buildings, account for the largest percentage of losses by demolition. Considering all buildings that were demolished, barns made up an average of 63.2 per cent of this loss. Dwellings, on the other hand, represent more than half of farm building investment (13), but account for an average of only 4.27 per cent of demolition losses. Giese (12)* states that:

For every house demolished by windstorm, more than 100 barns and other structures are thus destroyed. This shows that the extra strength and rigidity of the house make it almost immune to destruction, at least by anything short of a tornado. If barns were built and repaired with equal care this damage could also be greatly reduced.

The great difference existing between the percentage of barns and dwellings demolished by wind is shown, for a period of 7 years, in Figure 3.

*Quoted from introduction, no pagination.
Major structural failures are by:
- Demolition
- Off foundation
- Roof off
- Out of plumb

Data compiled by: M.L. Esmay from records of Iowa Mutual Tornado Insurance Assn.

Fig. 2 Demolition as percent of total wind damage by year and major structural failures as percent of total wind damage by year.
FIG. 3 DEMOLITION OF BARNs AND DWELLINGS BY WIND

DATA COMPILED BY M.L. ESMAY FROM RECORDS OF IOWA MUTUAL TORNADO INSURANCE ASSN.

PER CENT OF DEMOLITION OF ALL FARM BUILDINGS BY WIND

YEAR

1930 1931 1932 1933 1934 1935 1936 1937 1938

0.0 0.4 10.5 2.0 1.0 2.1 4.0 49.2
The data taken from the Iowa Mutual Tornado Insurance Association for wind damage to farm buildings in Iowa must of necessity be considered incomplete. While this Association is the largest insurer of farm buildings in Iowa, not all farmers choose to insure their buildings. In addition, some farm buildings are insured by local mutual associations. Consequently, wind damage to farm buildings in Iowa is even greater than that indicated by the records of the Iowa Mutual Tornado Insurance Association.

Wood as a Structural Material for Farm Buildings

Wood has long been the principal material for farm building construction. Among the reasons for the wide usage of wood are its availability, ease of fabrication, and relatively low cost. More important is the fact that the wood supply is unlimited. By proper practices of silviculture the yield of forests can be increased, just as food production has increased through good management, to a point where productivity of forests can meet any probable level of demand. Wood must be treated as a crop and harvested regularly for greatest yield. Glesinger (18,p.257) says:

There is nothing static about the relationship between the annual growth of a forest and the annual wood-cut taken out of it. A forest is the opposite of the cake in the adage, which you either eat or have. In order to have your forest cake, you must eat it; if you eat it properly, you get even more of it.
As a result of the tremendous use of wood as a substitute for steel during the last war, engineers have become more familiar with wood as an engineering material (19). Therefore it is not likely that the use of wood will decline in the future. Glesinger (18,p.12) states:

We are going to use more wood, in an ever-increasing variety of forms and applications, because we have recently made a substantial break-through into a limitless frontier that lies beyond the question: what is wood? We have not yet got all the answers. Lifetimes of work remain to be done. But even a brief review of what we know already will be enough to establish the fact that wood is the most nearly universal of all raw materials.

Problems of Wood-Frame Construction

The lack of uniformity of wood's structure and its different resistances to forces applied in various directions to the grain is a matter for the engineer to consider when using wood as a structural material. Unlike steel, which is strong in all direction, wood is strongest in compression in the direction of the grain and weakest across the grain. In spite of varying characteristics though, weight for weight wood is one of the strongest of structural materials.

The most critical problem of wood-frame construction is the matter of fastening structural members. Considering how long wood has been used as a framing material, it is surprising that information on the strength of wood joints is so meager. Giese (15) writes:
A building is no more substantial than its weakest joints, and joints ... the critical element in farm buildings ... have long been neglected.

Glue as an Aid to Constructing Strong Joints

At this time the only method of fastening wooden members so as to develop their full strength is by the use of glue. Nails, screws, bolts and timber connectors cannot develop full wood strength since none of these fasteners act over the entire bearing area of a joint and all of them damage or destroy part of the wood in their application.

The use of glue is rapidly increasing as builders and architects become aware of its advantages of increased strength and rigidity. Keith (22, p. 461) advises us that:

The art of gluing has made such strides recently that we are apt to see toenailing, the traditional ... and poor ... method of framing light wood structures, become obsolete.

Adequate answers regarding glue usage are not available at the present time on such outstanding considerations as: the durability of glue under farm conditions; the ability of glue to resist mold and fungus growths; the strength of glued joints under variable loading conditions; and the proper method of field application of glue. These answers must be furnished before the full possibilities of glue are obtained on the farm.
REVIEW OF LITERATURE

Distinction Between Adhesive and Glue

Adhesive is a broad term encompassing those materials capable of adhering or sticking to a surface and developing a permanent bond between that surface and another material (7). Glue then is classified as an adhesive, but not all adhesives are glue. Popular usage has, however, resulted in the term "glue" from "gluere" - meaning to draw together - being extended to include all solutions of substances exhibiting binding or adhesion (9). Actually, and in the strictest sense, glue includes only those substances manufactured from animal bones, animal tissues, and the bladders and certain membranes of fish. The glue product of animal tissues and fish membranes is a hard substance which possesses the property of absorbing cold water. The water causes the glue to soften and then swell. When heat is added the glue becomes soluble in the absorbed water and will gelatinize after standing and cooling a short time.

Gelatination is a property of all true glues, but many of the vegetable agglutinants, which contain starch, will gelatinize also when treated with boiling water. What distinguishes glue then is that if the jelly is allowed to dry, the result is practically the original hard glue, which in
turn can again be soaked, heated and gelatinized. On the other hand the vegetable adhesives, protein adhesives, and synthetic adhesives after drying are dissimilar to their original constituents and no amount of soaking will cause them to again gelatinize.

To classify under the broad heading of an adhesive a material must do more than produce a bond between two materials, it must produce a permanent bond between them (7). As an example, water and paraffin wax will produce a bond when they solidify, but the bond is temporary and therefore they cannot classify as adhesives.

Throughout this study the writer will conform to popular practice and use the terms "adhesive" and "glue" as synonymous.

Early History of Adhesives

The period when mankind first used adhesives is a matter of speculation. It has been established though that animal glue is the oldest known type of adhesive; stone cuttings bear evidence that the Egyptians were familiar with it more than 3000 years ago (46). There is evidence also that adhesives made from casein were used at an early date. However, it was not until 1690, in Holland, that the first commercial glue plant was established (29).

In the United States glue manufacture began in 1808. This was animal glue and it was not until about 1874 that fish
clues were produced in commercial quantities in this country. In 1875 the process of laminating thin-wood layers was introduced which multiplied the demand for glue many times. With increased demand for glue began the history of the modern adhesives. Since the beginning of the twentieth century we have seen new adhesives developed from casein, cassava, albumin, soybean meal, and only in the last few years, from the new synthetic resins.

Classification of Adhesives

It is possible to classify adhesives from several viewpoints; for example, they might be classified according to cold or warm adhesives, that is those adhesives requiring no heat during setting time or those requiring heat during setting time. Another example would be to classify them as to particular fields of application. The most common classification though is according to their origin.

Of the many types of adhesives that may be used for gluing wood, the most widely used ones may be grouped according to origin as follows: animal glues, vegetable glues, and synthetic-resin glues (2).

Water-Resistant and Waterproof Adhesives

Casein glue, which is of animal origin, and synthetic resin glue are the only glues at the present time suitable
for structural work since the rest of the animal glues and all of the vegetable glues show little resistance to deterioration by moisture and exposure.

**Casein glue**

Casein is the protein substance of milk. In the manufacture of casein glue the casein is precipitated from skim milk as a curd, which is then thoroughly washed, dried, and ground so as to pass a 20 mesh or finer screen. To the casein is added hydrated lime, sodium hydroxide, and possibly some other modifying agents, depending upon the particular manufacturer. When water is added to the prepared casein powder and the 2 thoroughly mixed, the glue is ready for use.

Casein glue offers many advantages to the construction industry among which are: water-resistance, ease of preparation, and ability to set without the application of heat. In addition casein glue can be mixed and used in any temperature in which men can work, provided the temperature is not too close to freezing. The workable life of the mixed glue ranges from 4 to 8 hours.

Casein glue joints do have the disadvantage of weakening rapidly when exposed to high humidities for any appreciable time, and for this reason the glue is not suitable where the relative humidity will be 90 per cent or higher (45). Also, since casein is a protein, the glue is subjected to damage and attack by mold and fungus growths. Recently it
has been found though that the addition of preservatives such as chlorinated phenols and their sodium salts improves the resistance of casein glue to high humidities and molds (44).

**Synthetic-resin glues**

In the last few years, especially during the war, there has been developed a myriad of synthetic-resin glues whose characteristics vary widely. In general these glues are divided into two groups: thermoplastic and thermosetting. The thermoplastic group is valuable in specialized work but of little value in structural work since they soften whenever the temperature is raised above a range characteristic for each resin. Thermosetting resin glues when dry will not soften even though exposed to temperatures higher than their setting temperatures.

The thermosetting group is divided according to composition as follows: Phenol-formaldehyde, Urea-formaldehyde, Resorcinol-formaldehyde and Melamine-formaldehyde (37). The Phenol and Melamine-resin glues are mostly high-temperature-setting or hot-press glues. This means that they require temperatures of 212°F or greater to effect their cure and consequently are not very practical for field use in constructing farm structures. Urea and Resorcinol-resins, on the other hand, are cold-setting and will cure at temperatures of 70° to 75°F (38). Therefore the latter two glues are better adapted to farm use.
Resorcinol-resin is the most recent development and holds the highest promise of the group of synthetic-resins for farm use because it cures at moderate temperatures and compares closely with the phenols and melamines in durability. This glue is marketed as a liquid consisting of a partially polymerized resin in alcohol or water. It must be mixed with a hardener, generally formaldehyde or paraformaldehyde, and a filler, walnut-shell flour, prior to use. The glue is dark in color and will stain wood.

The synthetic-resin glues are waterproof, highly resistant to cyclic soaking and drying, resistant to protracted periods of high humidity, and resistant to alternate periods of high and low humidity. They are not attacked by fungus growths and molds even under high humidity conditions, which are ideal for the growth of such micro-organisms.

The greatest disadvantage of this class of adhesives is their relatively high cost when compared to other types of adhesives. The use of flour extenders helps to reduce their cost, but a preservative must then be used or the glues become subject to attack by molds.

Structural Application of Glue to Farm Buildings

Structural use of glue has been prevalent in Europe since the turn of the century. In the United States, until recently, glue has been used chiefly in the paper box, wood
novelty, and furniture manufacturing industries. Glue as a structural material was discouraged since manufacturers and those familiar with glue felt that strong joints could not be made unless close control of temperature and pressure were maintained during the curing period of the glue. Also, before the advent of the "filler-type glue", of which casein glue is one type, it was felt that surfaces to be glued must be perfectly smooth, a condition which would be difficult to obtain in field construction.

Since 1930 numerous research projects have been carried on in the Agricultural Engineering Section, Iowa State College, under the direction of Professor Henry Giese for the express purpose of determining the practicability of using glue in the field to construct strong, wind-resistant farm buildings. Much valuable information has been gained from these projects, which are summarized below, that disputes the theory that closely controlled conditions are necessary for satisfactory glue joints.

Laminated construction

Laminated construction was originated, prior to World War I, by Otto Hetzer of Weimar, Germany (47). The popularity of this type of construction spread rapidly throughout the rest of Europe because of the scarcity of timber large enough for frame construction. Almost all of the laminated members used in Europe are made in the shop, few, if any, however, being
made at the site.

There is little information on the first use of glue in structural members in this country. Apparently the first application of glue for timber construction was in the gothic-roofed barn. Originally, the rafters of this type roof were cut in short segments from solid timber and the segments joined together. Such practice was eventually replaced by forming the rafters from several plies of thin lumber, usually 1 x 4. Nails were used to hold the plies together, design specifications requiring from 4 to 8 nails per linear foot of rafter (4). The rafters built in this manner proved to be quite inadequate in a short time. Most of the gothic roofs sagged near the center of the ridge since the nails were unable to withstand the horizontal shearing stresses occurring between the plies. Giese (14, p. 48) says:

When placed in shear, a nail joint begins to yield under a small load, crushes a few fibres in the adjoining surfaces, and the nail bends. Even if a sufficient number could be applied, without splitting the member, a vibrating load would loosen them and reduce the effectiveness of the joint.

Therefore, with nails, the laminations were permitted to slide over one another with the result that the rafter no longer acted as a single unit. This slippage between the laminations reduced the stiffness of the rafters and they sagged under load.

After repeated efforts to obtain structural stability in other ways, Giese (14) concluded that the gothic rafter
would offer an excellent test of glue. Furthermore, if the glue did fail in time the rafters would be no worse than those in common use. To construct the rafters casein glue was applied down the center of each ply covering about half its width. Nails furnished the only pressure during the setting time of the glue. Bending tests made on these rafters showed that glue, even when applied somewhat haphazardly, is capable of carrying the shearing stresses involved and that glued laminated members compare favorably with solid members. On the basis of these tests Giese and Clark (16, p.251) gave the following conclusion regarding the field application of glue:

The horizontal shearing strength of glue compares favorably to gluing specifications despite the fact that it was applied to a little more than one-half the width of the board and the laminations were nailed together without the use of clamps.

Further tests were made by Martin (25) on short segments of the rafters 7 years after their original fabrication. During the 7-year interval the rafters were stored in an unheated shed. The test results showed no deterioration of the joints and the glue to still be effective in resisting shear.

Since these early tests laminated construction has been used in many industrial buildings and farm buildings. During the war great quantities of steel were saved for urgent military use because laminated beams could be made for long spans for which it would be impossible to get solid wood beams (19). On the advantages of laminated members Hanarahan
(19, p. 906) says in part:

Structural members of a size, shape, and quality which could never be sawn as single pieces from the largest and best trees ever grown are commonplace today. Modern glues, as strong and durable as the wood itself, have made this possible.

An additional advantage of laminated construction is that it causes an upgrading of lumber because defects can be removed from the small pieces being used to build up a large member. This was not possible when connecting devices did not develop the full strength of the wood.

At the present time laminated beams and rafters are manufactured and sold under various trade names; however, many small contractors and farmers have undertaken to construct their own laminated members right on the job.

The braced-rafter roof

Pickard (30) made a study to determine the strength requirements of the braced-rafter roof and to develop a more wind-resistant construction. He investigated the strength relations between glued, ring-connected, bolted and nailed joints. The results indicated that glued joints were the most effective and nailed joints the least effective with regard to strength and rigidity. In studying conventional designs of braced rafters he concluded that the bracing material was not being used to the best advantage. Several systems of bracing were then developed which economically utilized the bracing...
material and resulted in rafters of greater strength. In some of the new designs glue was used to fabricate the joints and in others, timber connectors. From his work Pickard (30, p.98) came to the following conclusion regarding construction of joints in the braced-rafter roof:

Rafters in which casein glue or modern connectors were used with the new system of bracing showed ultimate strength from 2 to 5 times the strength of various conventional designs.

Because glued joints do not slip or yield until almost to the failing point, Pickard also found that the rafters constructed with glued joints approached rigid construction.

Rigid-frame construction

Rigid-frame construction has long been used to advantage in steel and reinforced-concrete construction. The whole purpose of rigid construction is to reduce bending stresses by distributing them over a larger portion of the frame. With conventional frame construction there is little rigidity at the joints, consequently the joints act much like a hinge and carry little or none of the bending stresses. If the joints are restrained, some of the bending stresses in the members of the frame are transferred to the joints. The resulting reduction of stresses in the framing members allows a reduction in their size with a corresponding reduction in building cost.

Rice (31) made a study to investigate the advantages of rigid-frame construction in farm buildings. In his study he
analyzed the 3 rafter gambrel barn roof as a 3-hinged arch and as a rigid frame. Both dead and live loads were considered and the results of the tests gave a comparison of the bending moments developed in the rigid frame and the 3-hinged arch. The rigid frame was made by using gusset plates which were glued and nailed at the rafter splices and at the mow floor line where the rafter was fastened to the stud. The 3-hinged arch was designed in the same manner except that bolts were used in the joints at the mow floor and at the ridge. From the findings of his analyses and tests Rice (31, p.78) advanced the following conclusions:

The analyses of the three rafter gambrel roof proves that effectiveness in use of lumber is increased by the use of rigid frame construction. The rafter tests show the advantages of rigid frame construction.

Rice also found that the rigid frame eliminated the need for a brace from the plate to the hay mow floor as well as obstructing braces at the rafter splices. Framing costs were estimated to be 20.5 per cent less than for the standard-gambrel roof.

A study of the structural requirements of grain storage buildings was made by Richardson (33). In his work he used glue and modern timber connectors to improve the design of such structures. He found that joints made with glue and nails had greater resisting strength in most instances than the members themselves. In addition the tests emphasized
the superiority of glue and nails used together over the other types of fasteners.

Crawford (6) studied and made tests on corn crib sections. In some of the tests the studs were glued to the sill and plate. Small wedges, fitted to the plate and sill and on the outside of the studs, prevented the studs from kicking out. This construction resulted in increased strength of stud joints. Also joints made in this manner were capable of carrying resisting moments; whereas, on the other hand, the common stud joints made by toe-nailing into the sill and plate caused the studs to behave merely as supports with no resisting moments at their ends. Gluing studs to sill and plate results then in corn crib sections of greater rigidity.

**Glued joints in tension**

In wood construction it is often desirable to join the end grain of one member to the side grain of another member, for example, studs to sill and plate. End grain to end grain is another situation which frequently occurs when long floor joists etc. are needed.

Richards (32) using resorcinol-resin glue and Douglas fir lumber made tension tests on end-grain to side-grain and side-grain to side-grain glued joints and found that they developed greater strengths than the allowable working stress of the wood in tension perpendicular to the grain. End-grain to end-grain glued joints when tested in tension developed
only 14.5 per cent of the working strength of the wood. However, by trying scarf joints with different slopes he was able to develop the full strength of the wood. Based on his results, Richards (32, p. 39) concludes that:

Scarf joints of 1:4 or flatter slope will develop strengths greater than the allowable working stress of Douglas fir in tension parallel to the grain. Scarf joints of 1:3 or steeper slope will not develop strengths equal to the allowable working stress.

Some Factors Affecting the Strength of Glued Joints

Specific gravity of the wood

Since modern glues are stronger than wood the strength of the wood becomes the dominant factor in the strength of glued joints. Wood strength is related to specific gravity because it is an index of the amount of wood substance in a piece of timber (24). The higher the specific gravity, therefore, the greater the strength of the wood.

Unfortunately the specific gravity of wood varies greatly, even among the same species. Some of the variables causing variation in the specific gravity of wood are the amount of springwood and summerwood, the rate of growth of the tree, the part of the tree from which the wood comes, and the geographic location of the tree. Because of this variation in specific gravity it is to be expected that large
variations in the strength of glued joints will occur.

**Moisture content of the wood**

Wood increases in strength as it dries (43). Therefore, since the strength of wood is related to its moisture content, it is to be expected also that the strength of glued joints is related to the moisture content of the wood. However, the wood should not be too dry for then it will absorb too much moisture from the glue and a weak joint will result.

According to Truax (39) the moisture content of wood to be used for gluing should be as near as possible to the moisture content expected in service. This is because moisture changes cause warping and checking of the wood, resulting in stresses that reduce the strength of the joint. Skinner (35) found that joints made with Douglas fir lumber with a moisture content of 30 per cent and tested at 22 per cent, were approximately 70 per cent as strong as those made from drier wood. His tests showed though that glued joints may be made successfully under field conditions over a wide range in moisture content of the wood.

**Dimensional changes of the wood**

Wood is a hygroscopic material which is always changing its moisture content in order to remain in equilibrium with its surroundings. This change in moisture content causes a change in the wood's dimensions. The wood shrinks as it dries
and swells when it picks up moisture. Using Douglas fir lumber and resorcinol-resin glue, Palmer (28) made a study to determine the effects of expansion, contraction, and warping of the wood on the strength and durability of glued joints. He also sawed kerfs in half of the joints containing 2-inch lumber to see if they would reduce the tendency of the wood to warp. All of the joints were subjected to a cycle of moisture contents ranging from 9 to 19 per cent. Palmer (28, p. 80) concluded from his study that:

Dimensional changes of the members of a glued joint occurring after the glue has become hardened are resisted by the glue line. The magnitude of the stress thus imposed on the glue line varies directly with the magnitude of the change in dimension. This stress subtracts from the ultimate strength of the joint.

Kerfing members of glued joints seemed to have little value in minimizing the effect of dimensional changes in the lumber and was not recommended. Palmer also noted that the unit strength of glued joints varies with their size and the present study is a continuation and expansion of that premise.

Surface condition of the wood

The ideal wood surface for gluing should be flat and smooth. For field construction though, it is not likely that the wood will meet such requirements. In order to study the practicability of glue for farm building construction Skinner (35) tested glued joints made with unsurfaced lumber. The
results indicated that the shear strength of such joints was from 50 to 70 per cent of the shear strength of joints made from surfaced lumber. In view of the above facts, Skinner (35, p. 46) recommends:

... that if a considerable amount of glue joint fabrication is to be undertaken, surfaced lumber be used or that rough lumber be prepared for gluing by planning.

Maxwell (26) also studied the effects of surface condition of wood on the strength of glued joints. He found that planed surfaces resulted in the strongest joints, followed in order of strength by sanded surfaces, sawn surfaces, burnished surfaces and combed surfaces.

Assembly time

Assembly time is the interval between the spreading of the glue on the wood surfaces and the application of pressure to the joint. The allowable assembly time varies widely among the different types of glues, but under no circumstances should the glue be allowed to harden before closure is made. Besides the type of glue, other factors affecting permissible assembly times are: the species of wood, the moisture content of the wood, and the temperature at the time of assembly.

The Casein Company of America (3, p. 5) suggests two ways to check assembly time; they are:

1. Just before pressure is applied, press a finger onto one of the first areas spread. If the glue is still moist or
tacky all the spread surfaces are still in good condition for gluing. If the glue is dry and smooth, it has precured and will not grip the opposite surface.

2. As pressure is applied, look for a slight squeeze-out of a bead along the edges of the first joint spread. This shows the glue was fluid when pressed.

Application of pressure during setting time of glue

Pressure is necessary during the setting time of glue in order to establish a thin, continuous film between the layers of the wood, force some of the glue into the pores of the wood, and hold the surfaces in close contact until the glue sets. Too little pressure results in a thick glue line, a condition that is undesirable regardless of the type of glue. According to McBain and Hopkins (27, p. 88):

The strength of a joint is dependent on the thickness of the adhesive film. The thinnest films yield the highest results provided complete contact is maintained between the surfaces.

While thick glue films are to be avoided if at all possible, there are synthetic-resin glues of the "filler-type" that will make successful joints with a glue line up to 0.05 inches in thickness (23). Casein glue, another "filler-type", will also make successful joints with a thick glue film. However, with both types, if the glue film is thick, there will be a moderate loss of strength and a tendency to shear in the glue line.

Many of the glue companies recommend pressures
approximating 200 pounds per square inch during the setting of glue. A study was made by Maxwell (26) to find out if pressures well under this pressure might not be just as effective in making satisfactory joints. He tested joints made with pressures ranging from 5 to 250 pounds per square inch. The results indicated that the strength of the joints increased only slightly with pressures above 25 pounds per square inch.

The impracticability of obtaining high pressure devices for making glued joints in farm building construction led Giese and Henderson (17) to make a study of low-pressure casein glued joints held with 7d box nails only during the curing period. Their results indicated that glued joints utilizing nail pressure were just as strong as those in which clamps were used to apply the pressure. The fact that satisfactory glued joints can be made with nail pressure only makes it possible to speed up glued construction, since erection can take place immediately after assembly of the joints.

Countryman (5) made a comparative study between nailed and pressure-glued plywood beams. He found that objections to nailed gluing are that joint strength is somewhat erratic and that, since nail pressures are low, if a board is twisted or irregular in thickness an open spot in the glue joint may occur. His tests showed that nail-glued beams using both casein and low-temperature phenolic glue averaged about 87½ per cent as strong as similar beams made by conventional
pressure gluing. Countryman (5, p. 626) has the following to say about the slight reduction in strength of nail-glued joints:

This slight relative reduction in strength apparently was not attributable to a weaker glue bond in the nailed beams, but was probably related to the large number of butt joints and perhaps to a weakening effect of the closely spaced nails.

**Curing period**

The curing period is the minimum time required for the glue to harden and develop enough strength so that the pressure can be removed from the joint. Length of curing period varies with the type of glue used, the thickness of wood, the moisture content of the wood, and the temperature of the wood.

In the last few years the introduction of radio-frequency heating and other methods of rapid heating have made possible curing periods as short as 30 seconds. However, the equipment for this type of curing is very expensive and impractical for farm construction.

Giese and Henderson (17) found that casein glued joints made of lumber with a moisture content of 7 per cent or less and cured at 70° F reached maximum strength in 18 hours. With lumber of 11 per cent moisture content and a curing temperature of 50° F, 3 days were required to develop the full strength of the joints.
How Glue Makes Wood Stick Together

It is strange, in view of the fact that man has been using glues of various kinds for centuries, that so little was known about adhesive action until the 1920's. About that time scientific articles appeared which classified the major factors of adhesion as "mechanical adhesion" and "specific adhesion" (29). These two factors still represent the acceptable theories of adhesion.

**Mechanical adhesion**

The oldest and most widely accepted view about the adhesiveness of glue is that it finds its way, while still fluid, into the cell cavities of the wood through the open ends of the cut surface, after which it solidifies and clinches the joint together with literally millions of little tentacles. The remarkable strength of the joint is attributed then to the interlocking of the two solids, wood and glue.

**Specific adhesion**

The fact that optically smooth surfaces, which rule out any mechanical embedding of the glue, may be made to adhere satisfactorily with certain types of glue clearly indicates another type of adhesion, namely specific adhesion. In this case the glue is adsorbed by the wood, or in other words, the surfaces of the wood and glue are held together by the
molecular attraction existing between them. True specific adhesion is independent of any protrusion of the glue into the surfaces being glued together.

When wood is glued, both mechanical and specific adhesion take place. The two together result in a joint that is considerably stronger than either type by itself.

Durability of Glued Joints

Because of the comparatively short time in which glued construction has been in use in this country, little information is available on the durability of glue. Long usage in Europe though offers some tangible evidence. During the summer of 1936 Wilson (47) visited Europe and examined some 50 structures employing laminated construction and varying in age up to 25 years. The laminated members were carefully checked for evidences of decay, checking, opening of glued joints, deterioration of glue, and change of shape of the member. From such observations Wilson (47, p.95) states:

Lack of examples of members that have failed or have seriously deteriorated under such exposure during the third of a century of the history of this type of construction precludes any but optimistic estimates of length of life and permanence. From experience to date it seems safe to assume that casein-glued laminated construction will last as long as solid wooden members of any but the more durable species or of preservatively treated material.
Giese and Henderson (17) tested laminated rafters that had been stored for 13 years on a concrete floor in an unheated building with a leaky roof. The ranges in temperature and humidity which these rafters underwent were probably much greater than would have occurred in an actual structure. When tested, these joints sheared at a load of 765 pounds per square inch of glue area. It was concluded from this that casein-glued joints have a high degree of durability if protected from the direct action of water.
OBJECTIVES OF THE STUDY

The specific objectives of this study were:

1. To determine the effect of glue area on the strength of glued joints.

2. To determine the effect of joint width on the unit strength of glued joints with the grain of the joint members parallel.

3. To determine the effect of joint length on the unit strength of glued joints with the grain of the joint members parallel.

4. To explain, by qualitative analysis of photo-elastic models, the effects of width and length on the unit strength of glued joints.

5. To verify the photo-elastic analysis by the use of SR-4 strain gages on actual glued joints.

6. To make a preliminary investigation of glued joints under torsion loads.

7. To make a preliminary investigation of the effect of fatigue stresses on glued joints.
THE INVESTIGATION

The investigative work of this study was conducted in the laboratory and consisted of the following series of tests: (1) tests on joints with varying glue areas, (2) tests on photo-elastic models, (3) tests using strain gages on actual glue joints, (4) tests on glued joints subjected to torsion loads, and (5) tests on glued joints subjected to fatigue stresses.

Tests on Joints With Varying Glue Areas

Equipment used

The equipment necessary for constructing and testing the joints in these tests consisted of: (1) a construction jig, (2) a Tag-Heppenstall moisture meter, (3) a vise for reducing the effects of eccentric loading on the joints during testing, (4) a 60,000 lb. hydraulic testing machine, and (5) a 300,000 lb. hydraulic testing machine.

Method of procedure

Selection of wood. In order to reduce to a minimum the variation in the wood used to construct the joints for this phase of the study, effort was made to select wood with as nearly uniform properties as possible. The actual selection
of the wood was made at the lumber yards from 1-inch and 2-inch kiln-dried lumber. All of the 1-inch boards were vertical grain of B or better grade. The 2-inch boards were mostly from select-structural grade since higher grades were unavailable in this thickness. Care was taken, however, to select these 2-inch boards with the grain vertical or nearly vertical.

The lumber used was Douglas Fir. This species was selected because of its wide application in structural work and because of its property of high strength. Wood of high strength was necessary if the full strength possibilities of glued joints were to be studied.

To avoid a wide range in specific gravity of the lumber selected, a rough approximation for obtaining uniformity was made by counting the number of annual growth rings per inch. Because of the large amount of lumber necessary, however, the growth rings varied among the individual boards from approximately 16 to 22 per inch.

Determination of moisture content of wood. Prior to the construction of the joints the wood was stored in the Structure's Laboratory of the Agricultural Engineering Building. In this laboratory the temperature and humidity variations were slight and it was felt that the moisture contents of the various boards would not change radically.

At the time of construction of the joints moisture-content determinations were made on each piece of wood making
up a joint assembly. A Tag-Heppenstall moisture meter, shown
in Figure 4, was used to determine these moisture contents.
The average of the moisture contents so found was 9 per cent
with a maximum variation among individual pieces of 2 per cent.

**Determination of specific gravity of wood.** In spite of
careful selection, the specific gravity of wood is such a
variable (see page 26) that it must be taken into account when
comparing the strength of glued joints. Therefore test spe-
cimens were cut from each end and the middle section of every
board. For the 1-inch boards these test specimens were 2
inches x 1 inch x 4 inches. The actual determination of spe-
cific gravity was in accordance with A.S.T.M. Standards (1)
except for size of test specimen. A.S.T.M. Standards require
a 2-inch x 2-inch x 6-inch test specimen.

All specific gravity determinations were made on an oven-
dry basis. The test specimens were placed in a controlled-
temperature oven at 100°C until they ceased to lose weight.
Then the specimens were weighed on a balance scale, after which
and while still hot they were immersed in paraffin and imme-
diately withdrawn. Coating with paraffin while the specimens
were hot insured a thin coverage that prevented moisture from
being picked up by the wood. The volumes of the test speci-
mens were determined by immersion. A small pan of water was
placed on a scale and the scale balanced. Then a specimen was
placed in the water and forced beneath the surface by a pointed
Fig. 4. Construction Jig and Tag-Heppenstall Moisture Meter.
rod stuck into the wood, the other end of the rod being held by a ring stand. The scale was again balanced and the number of grams required to balance the scale was also the volume of the specimen in centimeters. The specific gravity of the specimen then was its weight in air divided by its volume.

The equipment used to make the specific-gravity tests is shown in Figure 5.

Construction of joints. Details of the joints constructed for this part of the study are given in Figure 7. The widths and lengths of the joints were varied from 1 to 8 inches in 1-inch increments. Each width was combined with each length making a total of 64 sizes of joints. For each size of joint there were 20 samples making a total of 1280 joints to be tested. Figure 6 shows the extremes in sizes of joints tested.

Except for the larger joints all of the 1-inch and 2-inch members of each group of joints were cut from single lengths of 1-inch and 2-inch stock so as to reduce the variation of wood within a group. A table saw was used to saw all of the lumber in order to insure square cuts.

The type of glue used was Casco Grade A, Casein glue. This glue may be mixed by volume measure or by weight measure of the glue powder and water. In this case the glue was mixed by weight measure, 1 lb of glue powder to 2 lbs. of water. By doing this a more uniform glue was produced from batch to batch since volume measure of the powder is likely to vary as a result of bulking. Mixing of the glue was
Fig. 5. Equipment for Making Specific-Gravity Tests.

Fig. 6. Range in Size of Joints Tested.
FIG 7 DETAILS OF JOINTS USED FOR TESTING EFFECT OF JOINT SIZES ON UNIT STRENGTH.
accomplished by pouring the powder slowly into the water and beating the mixture rapidly with a wooden paddle. The glue was then allowed to set for 15 minutes after which it was again beaten until smooth and free of lumps.

The glue was applied to the wood with a stiff-bristled point brush and the joint assembled immediately using the jig shown in Figure 4. The grain of the members of all joints were placed parallel. Pressure was applied to the glue line by 4d box nails, 1 for each 5 square inches of glue area. These nails were not withdrawn when the joints were tested.

No special equipment was used in the construction of these joints. The only precautions taken were to spread the glue as uniformly as possible over the areas in contact and to keep the joints square for testing purposes, otherwise construction simulated field conditions.

Curing of joints. The joints were cured in the Structure's Laboratory of the Agricultural Engineering Building for a period of 13 days. Hygro-thermograph readings taken in the laboratory for an interval of 2 weeks showed a maximum variation in temperature of 14 degrees and a maximum variation in humidity of 18 per cent. Random moisture readings made on the joints prior to testing, however, showed no appreciable changes in moisture content of the wood.

Number of joints. Individual joints were designated by a number consisting of 3 digits. The 1st digit represented the width of the joint in inches; the 2nd digit the length of the glue line in inches; and the 3rd, separated
from the 1st two by a dash, the sample number which ranged from 1 to 20 for each group of joints. For example, the joint designated 57-7 was the 7th joint of a group with a width of 5 inches and a glue line length of 7 inches. The true length of a joint was always 2 inches greater than indicated by the 2nd digit because of the 1-inch extensions of the wood at top and bottom of the joint.

Testing of joints. The smaller joints were loaded to failure in a Southwark-Emery testing machine having a capacity of 60,000 lbs. For the larger joints a Southwark-Emery testing machine of 300,000 lb. capacity was used. These two machines are shown in Figures 8 and 9.

Load was applied to all joints as shown in Figure 10 and at a rate of approximately 20,000 lbs. per minute. The tendency of the joints to spread due to the eccentric loading was resisted by the vise shown in the aforementioned Figure and in detail in Figure 11. It was felt that offering resistance to spreading of the joints under load would result in a closer approximation to actual spliced joints in which the outside splice plates would be restrained over their entire area.

During the testing of these joints complete failure was considered only when the joints refused to carry additional load. This procedure was followed because in many cases partial failure of the joints occurred at loads somewhat below
Fig. 8. 60,000 lb. Southwark-Emery Testing Machine.

Fig. 9. 300,000 lb. Southwark-Emery Testing Machine.
Fig. 10. Testing Joint to Failure.

Fig. 11. Testing Vise Used to Resist Spreading of Joints.
their final maximum strength.

Tests on Photo-Elastic Models

Brief discussion of the principle of photo-elasticity

Stress analysis by photo-elasticity is particularly attractive since it gives an immediate and tangible picture of the stress distribution in the model being investigated. The basic principle underlying photo-elasticity is the property of certain transparent materials to be double refractive when under stress. If polarized light is passed through such a material, the light is broken up into 2 components which emerge as waves polarized in directions at right angles to one another. These waves also coincide with the planes of the principal stresses in the material. The velocity of the light through the model is a function of the intensity of the principal stresses. When double refraction occurs, one of the waves emerging from the model passes through the material slower than the other. Thus to the right of the analyzer disk, as indicated in Figure 12, there are 2 waves polarized at right angles to each other and with a certain relative retardation between them. It is seldom that the axis of the analyzer disk coincides with the axis of the waves emerging from the model. Consequently, the 2 waves after passing the analyzer disk are polarized in the same plane. Because of the retardation between the waves interference bands are produced that may be
FIG 12 SCHEMATIC DRAWING OF POLARIZING INSTRUMENT
"REPRODUCED FROM PRODUCT ENGINEERING 19:122 APRIL 1942."
interpreted as stresses. In most instances the interference pattern from the analyzer disk is recorded on a photographic plate (see Figure 12) for later study. The stress conditions indicated by tests on a photo-elastic model are generally identical to the conditions existing in a full sized unit under a similar load.

For a complete treatment on the theory and practice of photo-elasticity the reader is referred to texts by Hendry (21), Filon (10), and Frocht (11).

Equipment used

The equipment used for the photo-elastic tests consisted of a polariscope, a testing frame for loading the models, and a camera for recording the photo-elastic stress patterns. The component parts of the polariscope were: a monochromatic light source, a condensing lens, two polarizing plates, and two mica quarter-wave plates. The details of the polariscope and the loading frame are shown in Figure 13.

Method of procedure

Preparation of models. The models tested were made from a photo-elastic material known as Columbia Resin, CR-39. Chemically termed, CR-39 is allyl diglycol carbonate and belongs to the thermosetting class of synthetic resins. The material is available in sheets of various thicknesses, sheets 1/4-inch thick being chosen for this study.
Fig. 13. Polerizing Instrument With Model in Place for Testing.
A total of 4 models were made for these tests. The 1st 3 models were made to a scale of 1/3 inch equals 1 inch. These were scale models of actual joints with a glue line length of 2 inches, 5 inches, and 7 inches respectively. Larger models were not possible because of limitations in size of the polariscope lenses. The entire photo-elastic study was limited to 2-dimensional models because of the extreme technical and equipment problems involved in 3-dimensional work.

Producing models that were free of stresses was an extremely difficult task. Many models were made before 3 were produced that were satisfactory. Attempts to cut models using a milling machine and a cutter grinder were unsuccessful because of the heat stresses introduced by the machining. Efforts to remove these machining stresses by annealing were useless. In addition, because of the extreme brittleness of CR-39 trouble was encountered in preventing chipping of the edges of the models.

Stress-free models were finally made by marking off the models on a specimen sheet. A coping saw was used to rough out the models to within 1/8 inch of the scribe marks. Templates, made from 1/8-inch mild-steel sheet, were then clamped to both sides of the models and the models brought to dimension by filing with a fine flat-bastard file. These models were made in 1 piece, consequently they represented the conditions of a perfect glue joint.

For the fourth model, strips of CR-39 were cut to scale
and glued together. The glue used in this case was made by dissolving "Lucite" in ethyl acetate. The latter model was made in order to observe an actual glue line under polarized light.

Details of the photo-elastic models are illustrated in Figure 14.

Testing of models. The models were tested by placing them in the loading frame of the polariscope as shown in Figure 13. A metal bearing plate, 3/4-inch long, 1/2-inch wide, and 1/4-inch thick, was placed on top of the models to insure uniform load distribution. Load was applied to the models by means of weights placed on the small platform attached to the end of the loading beam. For study purposes pictures were taken of the photo-elastic patterns set up in each of the models by different loadings and angular positions of the analyzer disk. Particular attention was paid to obtaining data on the stress conditions along the imaginary glue line.

Tests Using Strain Gages on Actual Glue Joints

Equipment used

The necessary equipment for the strain gage tests on glued joints consisted of a SR-4 Type K Portable Strain Indicator and a 6-channel SR-4 Bridge Balance Unit. This
MODELS MADE FROM SHEET OF COLUMBIA RESIN CR-39

MODEL MADE IN ONE PIECE

MODEL MADE FROM THREE PIECES GLUED ALONG THESE LINES WITH A GLUE MADE FROM LUCITE DISSOLVED IN ETHYL ACETATE.

MODELS MADE FROM $\frac{1}{4}$" SHEET OF COLUMBIA RESIN CR-39

FIG. 14 DETAILS OF PHOTO-ELASTIC MODELS
equipment is shown in Figure 15.

**Method of procedure**

**Placement of strain gages on joints.** SR-4 type A-1 strain gages were used in these tests. Before placement of the strain gages the wood surfaces were sanded smooth and then treated with Baldwin's pre-coat cement. After the pre-coat cement had been allowed to dry for 15 minutes a liberal coat of SR-4 cement was applied to the surfaces where strain gages were to be placed. The gages were then pressed against the surfaces until the excess cement was squeezed out. Small 1 lb. weights were placed on the gages for a period of 24 hours while the cement dried. Solid, No. 18 copper wires were attached to the leads of the strain gages by soldering. The leakage resistance between the lead wires and the ground was measured by a megger and in all cases was greater than 50 megohms, which was in accordance with specifications stated by the Baldwin Locomotive Works for SR-4 strain gages.

Placement of gages was made right on and along the length of the glue line in the manner shown in Figure 15. The gages were located so that strain readings could be taken at the following points measured down from the top of the glue line: 3/4 inch, 2 3/4 inches, 4 inches, 5 1/4 inches, and 7 1/4 inches. On two of the joints tested gages were placed on the longitudinal center line of the 1-inch and 2-inch members in order to find out the magnitude and distribution of
Fig. 15. Strain-Recording Equipment.
compressive strains in these members. These gages were located so that readings were obtained at the top, middle, and bottom of the members.

A temperature-compensating gage was mounted on a 2-inch x 2-inch x 6-inch piece of Douglas Fir and the lead wires from this gage hooked into the circuit of the 6-channel SR-4 Bridge Balance unit. In this manner 1 compensating gage served all of the active gages.

Testing of joints. The joints were tested in the same manner as mentioned previously under "Tests on Joints With Varying Glue Areas", except that loading was interrupted at 5000-lb. intervals for purposes of making strain recordings. A total of 8 joints were tested with strain readings being taken up to failure of the joints.

Tests on Glued Joints Subjected to Torsion Loads

Equipment used

The testing apparatus for the torsion load tests consisted of a deflectometer, a Buffalo Scale, and a variable speed winch. This equipment was set up for testing as shown in Figure 16. The deflectometer, shown in detail in Figure 17, was designed by A. G. Hazen (20) for measuring the deflection of fence posts.
Fig. 16. Testing Apparatus for Torsion Load Tests.

Fig. 17. Deflectometer.
Method of procedure

Construction of joints. The joints for torsion load tests were constructed from 2-inch x 10-inch and 2-inch x 6-inch No. 1 Common Douglas Fir lumber. Selection of the above sized lumber was made so that the joints tested would be similar to the common joist to stud joints occurring in most barns. The 2-inch x 6-inch material was used to simulate a stud member and the 2-inch x 10-inch material, a floor joist. Both the stud member and the joist member were 54 inches in length. The 2 lengths were joined at right angles 12 inches from one end of the 2-inch x 6-inch piece as shown in Figure 18. A total of 25 joints were constructed. Joints 1 through 5 were nailed only, using eight 10d nails. Joints 6 through 10 were nailed also, but with the addition of a 2-piece 2-inch x 6-inch knee brace. Joints 11 through 14 were nailed and glued using six 10d nails to apply pressure to the glue line. The fifteenth joint was nailed and glued using thirty-one 10d nails for pressure application. The latter five joints each had a glue area of 50.5 square inches. Joints 16 through 20 were knee-braced glued and nailed joints. Total glue area of each of these joints was 224.2 square inches. The remaining 5 joints were glued and bolted; 3 made with four ½-inch bolts and 2 with two ½-inch bolts.

General details of the braced and non-braced joints are shown in Figure 18.
FIG. 18 DETAILS OF JOINTS USED FOR TORSIONAL TESTS
All of the glued joints were made with Casco Grade A, Casein glue. The glue was mixed and spread on the wood surfaces as described previously. Joint assemblies were made immediately after application of the glue.

**Curing of joints.** The joints were cured at room temperature for a period of 30 days prior to testing.

**Testing of joints.** Testing of the joints was accomplished by first clamping the stud members to a horizontal track made up of 2 steel angles, 2 inches x 2 1/2 inches, bolted together back to back. The stud was not restrained over its entire length but only at points 4 inches from each end. At the points of restraint a steel plate was placed under the track and another one over the stud. These plates, which were 1/2 inch x 3 1/2 inches x 8 inches, were then tightened against the stud and track by 2 bolts 8 inches in length and 1/2 inch in diameter.

Loads were applied to the joist member of the joints by means of a ½-inch steel cable connected to a Buffalo scale and a variable speed winch. The point of application of the loads was 46 inches from the center of the glue area, as shown in Figure 18. The procedure for loading the joints consisted of applying loads in increments of 100 lbs. until failure started, at which time loads were applied in smaller increments to insure an accurate determination of the loads at which failures occurred. Deflection of the joist at a point 40.5 inches above the center of the glue area was
measured for each 100-lb. increment of load by means of the deflectometer. This instrument made permanent and direct recordings of deflection on the data sheet attached to the recording board. The recording board with a data sheet in place may be seen in Figure 17. After the joints failed, a load was again applied to the joist to determine if the joints would still carry some load.

Tests on Glued Joints Subjected to Fatigue Stresses

Equipment used

A fatigue-testing machine providing completely reversed shearing stresses to the glue area of the joints was used in these tests. The construction of this machine is described below. A Buffalo scale was used to load each joint statically after the completion of the fatigue cycles.

Method of procedure

Construction of joints. The joints tested in fatigue were identical to the non-braced glued and nailed joints used in the torsion tests with one exception, instead of six 10d nails only 5 were used to apply pressure to the glue line. All joints were cured at room temperature for a minimum of 7 days.

Construction of fatigue-testing machine. The fatigue-
testing machine is illustrated in Figure 19. The frame of the
team was made from an 8-inch wide-flanged steel beam 16
feet in length. A 6-foot length was cut from this beam and
welded in an upright position to the top flange of the 10-
foot section. To increase rigidity a diagonal brace was
welded to the flanges of both sections of the frame.

A 12:1 reduction gear was mounted on the horizontal mem-
ber of the frame as shown in Figure 19. Power was supplied
to this reduction gear by means of a V-belt connected to a 1
hp., 110 volt, single-phase motor. By the use of suitable
sized sheaves on the motor and reduction gear, a greater re-
duction in revolutions per minute was obtained than with the
reduction gear alone. Thus the rated 1760 revolutions per
minute of the motor was reduced to 47 revolutions per minute at
the output shaft of the reduction gear.

A crank and connecting rod were mounted on the output
shaft of the reduction gear. The connecting rod was pin con-
ected to a collar which fitted over the joist or cantilever
member of the joint. A close-up of the reduction gear, the
crank, and linkage assembly is shown in Figure 20. Set screws
in the side and end pieces of the collar permitted centered
adjustments to be made for slight discrepancies between indi-
vidual joints.

Preliminary static tests on the joints indicated that
loads of 400 lbs. and 1000 lbs. resulted in deflections at
the point of load application of approximately 0.125 inches
Fig. 19. Fatigue-Testing Machine.
Fig. 20. Reduction Gear, Crank, and Linkage Assembly of Fatigue-Testing Machine.
and 0.375 inches respectively. These loads were applied at a distance of 46 inches from the center of the glue area. Because of the varying elasticity of wood the deflections resulting from these loads differed somewhat between joints, but the above deflections were selected and used throughout the fatigue tests made in this study. Therefore, two cranks, 1 with an eccentricity of 0.125 inches and the other with an eccentricity of 0.375 inches, were constructed so as to be interchangeable on the output shaft of the reduction gear. Lubrication of the crank and connecting rod was provided by oil being centrifugally forced from an oil-filled hollow in the crank through small openings leading to the bearing surfaces.

The joints were held in place for testing by a 44-inch cover plate that was tightened against the stud member of the joint by means of 3/4-inch bolts welded to the flange of the upright portion of the frame. This cover plate was 5/8 inch in thickness and 6 inches in width. A 5/8-inch x 1 1/4-inch stiffener was welded along the length of the plate to prevent its bending during testing. The plate was notched to fit around the 2-inch x 10-inch joist.

Testing of joints. A total of 14 joints were subjected to completely reversed fatigue stresses. This means that the extreme fibres of the cantilever members of the joints were subjected alternately to equal compressive and tensile stresses and the glue area to equal reversals of shear stresses.
The joints were divided into two groups A and B of 5 joints and 9 joints respectively.

Group A was tested using the crank with an eccentricity of 0.375 inches and the latter, Group B, by using the crank having an eccentricity of 0.125 inches.

The joints were set up for testing as shown in Figure 19. All joints in Group A failed immediately upon starting the testing machine. The joints of Group B were subjected to a minimum of 250,000 cycles at a rate of 47 cycles per minute. At the completion of the fatigue cycles the joints of Group B were loaded statically using the Buffalo Scale shown in Figure 19, in order to ascertain the ability of the joints to still carry load.
ANALYSIS OF RESULTS

Joints With Varying Glue Areas

General

The results of the tests on joints with varying glue areas are given in the Tables located in the Appendix.

Types of joint failures

Most of the joints failed in a plane along the glue line as shown in Figure 21. Others failed by the 1-inch members shearing in a plane adjacent and parallel to the glue line as illustrated in Figure 22. Those joints failing along the glue lines showed varying amounts of wood and glue failure. For example, Figure 23 shows 2 joints with about 80 per cent glue failure while Figure 24 shows 2 joints with very high percentages of wood failure. Many of the larger joints, however, failed in one or more of the ways discussed below.

Failure of 1-inch members by compression. This type of failure is shown in Figure 25. Notice that failure of this type always occurred across the 1-inch members at a point adjacent to the bottom of the glue line. This is a definite indication of the rigidity of glued construction, since if the pieces slipped, failure in compression would not have
Fig. 21. Typical Failure of Joints With Small Glue Area.

Fig. 22. Shear Failures of 1-inch Members of Glued Joints.
Fig. 23. Joints Showing High Percentage of Glue Failure.

Fig. 24. Joints Showing High Percentage of Wood Failure.
Fig. 25. Failure of 1-inch Members by Compression

Fig. 26. Failure of 2-inch Members by Compression.
occurred. In general the line of failure slants slightly upward towards the outside of the 1-inch pieces indicating that rigidity decreased away from the glue line which in turn permitted compressive failure to occur higher up in the member.

**Failure of 2-inch member by compression.** Failure of this type is shown in Figure 26. Note that failure was similar to the 1-inch failures in that the 2-inch members failed approximately adjacent to the beginning of the glue line. Since the cross-sectional area of the 2-inch piece was approximately the same as the total cross-sectional area of the 1-inch pieces, compressive failure of the 2-inch piece in one instance and the 1-inch pieces in another is explained by variations in wood strength. In one case the 2-inch members were weaker and thus failed in compression and vice versa for the 1-inch members.

According to Markwardt (24), the maximum compressive strength of Douglas Fir ranges from 6060 psi to 7420 psi. A check of the compressive stresses in the 1-inch and 2-inch members of group 87 gave an average compressive stress in these members of 6510 psi, thus accounting for the high percentage of compressive failures in this group.

**Failure of 2-inch member by splitting.** Examples of this type of failure are shown in Figure 27. Such failure was caused by the tendency of the joints to spread under load, consequently, tensile stresses occurred across the bottom of the 2-inch members resulting in cleavage of these members at
Fig. 27. Failure of 2-inch Members by Splitting.

Fig. 28. Actual Spliced Joint Showing 2-inch Members that Split Under Load.
right angles to the tensile stresses.

It was felt that splitting of the 2-inch piece might not occur in actual spliced joints. To check this type of failure several spliced joints were made and tested. Figure 28 shows one of these joints after testing. It can readily be seen that the 2-inch members split in a manner identical to that occurring in the joint specimens used in this study.

**Corrections for variations in specific gravity of wood**

For comparative purposes it was necessary to make strength corrections to each group of joints so that all groups could be considered as having been constructed from wood of the same strength. The variation of the strength of wood in relation to its specific gravity is given by the following equation (24):

$$ S = K G^{3/2} $$

where:

- $S$ = the unit strength of the specimen
- $K$ = a constant varying with species
- $G$ = the specific gravity of the specimen

Corrections were made on the average unit strengths of the joints by widths. For example, the correction factor for 1-inch wide joints was based on the average specific gravity of wood samples taken from joints ranging from 1 inch in width and 1 inch in length to 1 inch in width and 8 inches in length. A value of unity was assigned as the correction factor for the joints 8 inches wide since the average specific
gravity of these joints was the lowest. The correction factors for joints of other widths were found then by dividing the average specific gravity of the joints of each width by the average specific gravity of the joints 8 inches wide and raising the resulting number to the three-halves power. Table 1 gives the average specific gravity of each width of joint and the corresponding correction factor computed as above. These correction factors simply mean that the wood used in the joints of a particular width is so many times as strong as the wood used in the joints 8 inches wide.

Table 1

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The average of the actual and corrected unit strengths of each group of joints is given in Table 2. The value for the corrected average unit strength of each group was found by dividing the actual average unit strength of each group by the correction factor given for the width of the group in.
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</tr>
<tr>
<td>33</td>
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<td>647.6</td>
<td>73</td>
<td>906.6</td>
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<td>690.2</td>
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</tr>
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<td>76</td>
<td>840.7</td>
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<td>77</td>
<td>766.7</td>
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<td>653.9</td>
<td>588.0</td>
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<td>685.4</td>
<td>81</td>
<td>637.3</td>
<td>637.3</td>
</tr>
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<td>82</td>
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<td>584.6</td>
</tr>
<tr>
<td>43</td>
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<td>968.8</td>
<td>83</td>
<td>731.6</td>
<td>731.6</td>
</tr>
<tr>
<td>44</td>
<td>745.6</td>
<td>685.9</td>
<td>84</td>
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</tr>
<tr>
<td>45</td>
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<td>85</td>
<td>822.8</td>
<td>822.8</td>
</tr>
<tr>
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<td>686.1</td>
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<td>86</td>
<td>730.4</td>
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</tr>
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<td>87</td>
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<td>721.2</td>
</tr>
<tr>
<td>48</td>
<td>651.9</td>
<td>599.7</td>
<td>88</td>
<td>550.2</td>
<td>550.2</td>
</tr>
</tbody>
</table>
Variation of unit strength with size of joint

The corrected average unit strengths of the joints given in Table 2 indicate that glue area alone has little effect on the unit strength of glued joints. For example, joints 34, 43, 62, and 26 all had the same area but the average unit strengths of these joints were 891.4, 1053.1, 873.9 and 737.8 psi respectively.

In an attempt to show the relationship between unit strength and width of joint and unit strength and length of joint, the corrected data in Table 2 were used to plot the graphical presentations shown in Figures 29 and 30. Unfortunately these graphs are not particularly enlightening although Figure 30 does seem to indicate a general decrease in unit strength with increase in length of joint. Because of this difficulty in interpreting the results the data were subjected to a statistical analysis.

Statistical analysis

Throughout the statistical analysis the following designations were used:

\[ u = \text{unit strength in psi} \]
\[ \hat{u} = \text{estimate of unit strength in psi} \]
\[ W = \text{width of joint in inches} \]
FIG. 29 EFFECT OF WIDTH OF JOINT ON UNIT STRENGTH

NOTE:
EACH POINT REPRESENTS AVERAGE UNIT STRENGTH OF A GROUP OF 20 JOINTS.
NOTE: EACH POINT REPRESENTS AVERAGE UNIT STRENGTH OF A GROUP OF 20 JOINTS.

Fig. 30 Effect of length of joint on unit strength.
\[ L = \text{length of joint in inches} \]
\[ G = \text{specific gravity of the wood} \]

**Simple linear regression equations.** The corrected average unit strengths of Table 2 were used to obtain simple linear regression equations of the effect of \( W \) on \( u \) for each \( L \) and of the effect of \( L \) on \( u \) for each \( W \). The equations so found were plotted and are shown graphically in Figures 31 and 32. Referring to Figure 31 it can be seen that the effect of width on the unit strength of glued joints is not determinate by means of simple linear regressions. On the other hand, Figure 32 shows a definite relationship between length of joint and unit strength, i.e., a decrease in unit strength with an increase in length of joint.

Since each of the lines plotted in these graphs were fitted to only 8 points, any test of the significance of the regression coefficients would not be sensitive. Time did not permit treatment of the 20 points obtained for each group of joints. Such treatment of the data is contemplated at a later date in addition to investigation of a possible curvilinear relation between \( u \) and \( L \) which seems to be indicated by the graphs of Figure 30.

**Multiple linear regression equation.** In order to obtain a significant indication of the effects of width of joint and length of joint on unit strength a multiple linear regression equation of \( u \) on \( W \), \( L \), and \( G \) was fitted to the data by the method of least squares; the equation is
FIG. 31 SIMPLE LINEAR REGRESSIONS SHOWING EFFECT OF WIDTH OF JOINT ON UNIT STRENGTH.
Fig. 32 Simple linear regressions showing effect of length of joint on unit strength.
Actual average unit strengths of the joints were used in the determination of this expression. Strength variations of the wood were accounted for by including the average specific gravity of each joint group in the calculations.

Referring to the equation, it can be seen that the partial regression coefficients of \( u \) on \( W, L, \) and \( G \) give in turn the change in \( u \) per unit change of \( W, L, \) or \( G \). Notice the regression coefficients of \( W \) and \( L \) are negative while \( G \) is positive. This means that \( u \) decreases with increases in \( W \) and \( L \) and increases with increases of \( G \). Thus the equation seems logical since we have already noticed a decrease in unit strength with increases in length of joint and we would certainly expect an increase in unit strength with an increase in specific gravity of the wood.

The partial regression coefficients in standard measure are:

\[
\begin{align*}
\beta'_{Wu, IG} &= -0.0670 \\
\beta'_{Lu, WG} &= -0.4897 \\
\beta'_{Gu, WL} &= 0.0532
\end{align*}
\]

An explanation of the subscripts is given by the following example: \( \beta'_{Wu, IG} \) means the partial regression coefficient of \( W \) on \( u \) holding \( L \) and \( G \) constant. As these coefficients are in standard units of measure they are directly comparable. It is seen then that \( \beta'_{Lu, WG} \) is about 8 times as large as the other two, hence length is of more importance in predicting \( u \)
than W or G.

A t-test was made on the 3 partial regression coefficients. The t-values are: $t = 0.5977, 4.3606, \text{ and } 0.4720$ for $b'_{Wu.LG}$, $b'_{Lu.WG}$, and $b'_{Gu.WL}$ respectively. Only $b'_{Lu.WG}$ was significant and it was highly significant (36,p.349). This means that there is evidence of a real linear relation between $u$ and $L$ in the population of which the data of this study are a sample.

Multiple $R$, i.e., the correlation between the observed unit strengths and the predicted unit strengths from the multiple regression equation was found to be $R = 0.5022$. According to Snedecor (36,p.351) this $R$ is highly significant. This means that there is a real linear correlation in the population between the actual unit strengths and the unit strengths determined from such a linear equation.

The simple correlation coefficients of $u$ with $W$, $L$, and $G$ are:

$$r_{Wu} = -0.0624$$
$$r_{Lu} = -0.4955$$
$$r_{Gu} = 0.1011$$

Notice that $r_{Lu}$ is much larger than the other two. Again we find that the relation is mainly between $u$ and $L$. There is little difference between this simple $r_{Lu}$ and the multiple $R$.

The results of the statistical analysis warrant the following deductions:

1. The over-all size of a glue joint has little effect on its unit strength.
2. The width, length and specific gravity of the wood all influence the unit strength of glued joints, however, the influence of width of joint and specific gravity are small in comparison to the influence of length of joint.

Photo-Elastic Models

General

The results of the photo-elastic tests are shown in Figures 33, 34, 35, and 36.

Definitions

Before proceeding with the analysis of the results it is necessary to define several terms used in photo-elasticity.

Isoclinic line. An isoclinic line is the locus of points at which the principal stresses in a model all have an inclination $\theta$ to a fixed direction of reference. The angle $\theta$ being the angle which the axes of the polarizer and analyzer make with the fixed direction.

Fringe line. The fringe line is the locus of points where the difference between the principal stresses is the same. In photo-elastic models the fringe pattern shows up critical points and sections.

Direction of principal stresses and shears in model

Figure 33 (a), (b), (c), (d), and (e) show the isoclinic
(a) $90^\circ$ Isoclinics, 
Load 4 oz.

(b) $90^\circ$ Isoclinics, 
Load 3 lbs, 4 oz.

(c) $90^\circ$ Isoclinics and Fringe Lines, 
Load 6 lbs, 4 oz.

(d) $30^\circ$ Isoclinics and Fringe Lines, 
Load 6 lbs, 4 oz.

(e) $45^\circ$ Isoclinics and Fringe Lines, 
Load 6 lbs, 4 oz.

Fig. 33. Development of Isoclinics and Fringe Lines in Photo-Elastic Model.
Fig. 34. Development of Isoclinics and Fringe Lines in Non-Uniformly Loaded Photo-Elastic Model.
Fig. 35. Development of Isoclinics and Fringe Lines in Large Photo-Elastic Model.

(a) 90° Isoclinics, Load 1 lb, 8 oz.

(b) Quarter Wave Plate Inserted Showing Development of Fringe Lines for a Load of 18 lbs, 8 oz.

Fig. 36. Photo-Elastic Picture of Glued Model.

(a) 90°, No Load on Model

(b) 90°, Model Under Load of 14 lbs, 8 oz.
lines and fringe patterns for one of the models. This model was chosen for analysis since symmetrical patterns were produced. The other models produced patterns unsuitable for analysis because of difficulties in loading them correctly. Figures 33 (a), (b) and (c) show the 90° isoclinic lines for loads of 4 oz., 3 lbs. 4 oz., and 6 lb. 4 oz. respectively. In addition, Figure 33 (c) shows the beginning of the fringe pattern at the top and bottom of the imaginary glue line. In Figures 33 (d) and (e) the 30° and 45° isoclinics are shown for a load of 6 lbs. 4 oz. The isoclinics we are interested in in this analysis are indicated in the Figures by the arrows marked 1 and 2. The fringe lines are marked by the arrows numbered 3, 4, and 5.

For clarity the isoclinics marked 1 and 2 are shown diagramatically in Figure 37 with small elements placed along the lines to indicate the directions of the principal stresses. The isoclinic down the center of the model is for 90°. Therefore, the compressive forces act along this line and the tensile forces at right angles to it. Taking the small element \( \Delta C \) out and enlarging it in (C) of Figure 37, we have the compressive forces indicated by vectors marked \( Q \) and tensile forces by vectors marked \( P \). The maximum shears in the element occur at 45° to the principal stresses and are indicated by the vectors \( S_1 \) and \( S_2 \). The isoclinic lines do not show the magnitude of stress but only their direction, however, from mechanics we know that at free boundaries the principal stresses are parallel.
Fig. 37 Diagram showing direction of principal stresses and shears along isoclinic lines of photoelastic model.
and normal to the boundary, and the latter is equal to zero. From the 90° isoclinic down the center of the model, therefore, it is possible to verify the assumption that tensile forces caused splitting of the 2-inch member in the actual joints. At the bottom of the isoclinic is a free boundary and the compressive stress is normal to this boundary and equal to zero; on the other hand, the tensile stress is parallel to the boundary and of maximum magnitude. Just the opposite occurs at the point of load application, here the compressive stress is a maximum and the tensile stress is a minimum.

Referring now to the isoclinic along the imaginary glue line. This is a 30° line, consequently the principal stresses act at 30° and 60° to the glue line and the maximum shears at 15° and 75° to the glue line. The direction of these stresses may be seen clearly from the small element ΔA which is enlarged in (A) of Figure 37. From this isoclinic then it is evident that the shear developed in the glue line is somewhat less than the maximum shears occurring in this portion of the model. In Figure 33 (d) the 30° isoclinic appears on only one side of the model. If the polarizing disk and analyzer disk were rotated 60°, the isoclinic would appear on the other side of the model.

From the fringe lines it is possible to determine the critical sections in the model. As stated before, the fringe lines are shown in Figures 33 (c), (d), and (e) by the
numbered arrows 3, 4, and 5. Notice that these fringe lines start at the upper and lower ends of the glue line indicating that stresses are maximum at these points. Fringe lines are distinguishable from isoclinics as they appear at all positions of the polarizer and analyzer disks. Note that the fringe lines in Figure 33 (d) are partly obscured by the isoclinic line blending in with them.

The fact that the extreme ends of the glue line are critical stress points proves there is uneven stress distribution along the glue line thus accounting for variation of unit strength with changes in size of glued joints.

Figures 34 and 35 show 2 other models under load. Notice the evidence of non-uniform load distribution across the tops of the models shown. It can readily be seen why these models were unsuitable for analysis, however, they do emphasize the critical points in the glue line indicating again that the extreme ends of the glue line are the points of maximum stress. In each Figure fringe lines originate at the top and bottom of the glue line. Figure 35 (b) is of particular interest because quarter-wave plates were inserted to obtain the pattern shown. The quarter-wave plates remove all isoclinics leaving only fringe lines. Notice that all of the fringe lines emanate from the ends of the glue line.

In Figure 36 (a) the photo-elastic picture of the glued model is shown. There is no load on the model. Figure 36 (b) shows the same model subjected to a load of 14 lbs. 8 oz.
These pictures help to explain some of the variations in strength occurring among glued joints of the same size. Obviously there is no such thing as a perfect glue joint since evidence is produced here that glue tends to bond intermittently along the glue line. It is to be expected then that strength differences will exist between supposedly identical glued joints not only because of moisture and density differences of the wood, but also because of unevenness of glue bonding.

**Strain Gages on Actual Glued Joints**

**General**

The results of the tests on 3 joints are shown graphically in Figures 38, 39, and 40.

**Distribution of strain along glue line**

Figures 38 and 39 show the distribution of strains along the glue line for various loadings applied to 2 different sized joints. While the graphs show strain versus glue line lengths, it is possible to consider the curves as representing a qualitative view of the magnitude of the shears along the glue line. The reason for such an assumption is that the strain gages were actually attached to both the 2-inch and 1-inch members of the joint. As a result the strains recorded by the gages were the strains produced close to the glue line.
FIG. 38 CURVES SHOWING DISTRIBUTION OF STRAINS ALONG GLUE LINE LENGTH FOR VARIOUS LOADINGS APPLIED TO A JOINT 4" WIDE AND 8" LONG.

FIG. 39 CURVES SHOWING DISTRIBUTION OF STRAINS ALONG GLUE LINE LENGTH FOR VARIOUS LOADINGS APPLIED TO A JOINT 8" WIDE AND 8" LONG.
Fig. 40 Curves showing distribution of compressive strains in 1" and 2" members of a joint 4" wide, 7" long.
in both the 2-inch and 1-inch members. If it were not for the glue, the surfaces of the 2 members would slide past one another, therefore, since the thin sections along the glue line moved together slippage had to be resisted by shear forces in the glue line equal to the wood fibre stresses on either side of the glued surfaces.

The ideal shear curve would appear similar to the 70,000 lb. curve in Figure 39. However, because of the variations in wood and the possibility that slight slippage between wood fibres occurred, most of the curves were somewhat erratic. Nevertheless the trend of the curves verified the photo-elastic analysis in that stress is a maximum at the ends of the glue line and a minimum at the middle.

Distribution of compressive strains in 2-inch and 1-inch members of joints

Figure 40 shows the distribution of strain along the center lines of the 2-inch and 1-inch joint members for various loadings. The ordinate of the curves shows the strain readings from the top of the joint down. At each loading, therefore, it will be noticed that in the 2-inch member the compressive strain is a maximum at the top and tapers to zero at the bottom. Just the reverse is true of the 1-inch members. Such distribution is logical since it is to be expected that strain would be maximum at the loading points of both members.
It must be remembered that the strain curves represent the strains along the vertical center lines of the members and not across their entire section. It has already been shown that the strains in both members along the glue line are quite different than those shown in Figure 40. The latter curves illustrate the rate at which one member transmits internal stresses to the other member. It will be noticed that the maximum transfer of strain occurs at both ends of the glue line. Therefore the shearing forces in the glue line must be maximum at these points. Actually the difference in strain between the 2 members at any point gives an indication of the relative magnitude of the shear in the glue line at that point. Theoretically then, the point where the 1-inch and 2-inch curves cross should be a point of zero shear in the glue line. Such a condition probably never occurs, however, because of slight slippage either in the glue line or in the wood fibres.

Distribution of strains in the members of the joints should be similar to the curves for the 10,000 lb. load. The erratic curves for the 2-inch member for loads above 10,000 lbs. most likely is the result of the strain gage at the top of the member being defective or improperly bonded to the wood.

The shear pattern developed in glued joints explains the decrease in unit strength with an increase in length of joint. When length is added to a joint, glue area is added that never becomes stressed to its maximum, consequently unit strength
decreases. With an increase in width of joint unit strength is affected very little since the added area will be stressed close to the maximum shear strength of the glue.

Joints Subjected to Torsion Loads

General

The results of the torsion-load tests are given in Table 3. Reference to this table readily shows the poor performance to be expected when nails alone are used to fasten a joint to a stud. The best nailed joint failed at a load of only 444 lbs. with a deflection of 9.90 inches. Because of the ability of nailed joints to continue to carry some load until completely pulled apart, it was necessary to consider them as having failed when their load-carrying capacity reached a maximum and then decreased.

The best nailed and braced joint had a maximum load-carrying capacity of 1782 lbs. with a deflection of 7.75 inches. The average strength of these joints was 1646 lbs. at a deflection of 6.71 inches.

The joints made with six 10d nails and glue had a maximum strength of 1370 lbs. and a minimum strength of 740 lbs. Deflections of the high and low strength joints were 0.56 inches and 0.68 inches respectively. The average strength of this group was 1135 lbs. with a deflection of 0.58 inches. It will be noted above and in other cases that the largest
Table 3
Maximum Loadings and Deflections of Joints Subjected to Torsion Loads

<table>
<thead>
<tr>
<th>Joint No.</th>
<th>Type of Joint</th>
<th>Load at Failure (lbs.)</th>
<th>Deflection at Failure (in.)</th>
<th>Maximum Load After Failure (lbs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>nailed</td>
<td>444</td>
<td>9.90</td>
<td>376</td>
</tr>
<tr>
<td>2</td>
<td>nailed</td>
<td>402</td>
<td>8.18</td>
<td>384</td>
</tr>
<tr>
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<td>340</td>
<td>6.82</td>
<td>302</td>
</tr>
<tr>
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<td>nailed</td>
<td>408</td>
<td>6.20</td>
<td>394</td>
</tr>
<tr>
<td></td>
<td>Av.</td>
<td>404.0</td>
<td>8.03</td>
<td>372.4</td>
</tr>
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<td>5</td>
<td>braced</td>
<td>1552</td>
<td>6.08</td>
<td>1366</td>
</tr>
<tr>
<td>6</td>
<td>nailed &amp; braced</td>
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<td>5.12</td>
<td>1500</td>
</tr>
<tr>
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<td>nailed &amp; braced</td>
<td>1656</td>
<td>5.91</td>
<td>1652</td>
</tr>
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<td>8</td>
<td>nailed &amp; braced</td>
<td>1732</td>
<td>8.70</td>
<td>1645</td>
</tr>
<tr>
<td>9</td>
<td>nailed &amp; braced</td>
<td>1782</td>
<td>7.75</td>
<td>1708</td>
</tr>
<tr>
<td>10</td>
<td>nailed &amp; braced</td>
<td>1464.0</td>
<td>6.71</td>
<td>1574.0</td>
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<tr>
<td></td>
<td>Av.</td>
<td>1135.0</td>
<td>0.58</td>
<td>217.5</td>
</tr>
<tr>
<td>11</td>
<td>Glued</td>
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<td>0.52</td>
<td>236</td>
</tr>
<tr>
<td>12</td>
<td>Glued</td>
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<td>0.68</td>
<td>210</td>
</tr>
<tr>
<td>13</td>
<td>Glued</td>
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<td>0.54</td>
<td>270</td>
</tr>
<tr>
<td>14</td>
<td>Glued</td>
<td>1370</td>
<td>0.56</td>
<td>154</td>
</tr>
<tr>
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<td>0.58</td>
<td>217.5</td>
</tr>
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<td>31-10d nails &amp; glued</td>
<td>2260</td>
<td>1.00</td>
<td>1234</td>
</tr>
<tr>
<td>16</td>
<td>Glued &amp; braced</td>
<td>2650</td>
<td>0.52</td>
<td>1918</td>
</tr>
<tr>
<td>17</td>
<td>Glued &amp; braced</td>
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<td>0.46</td>
<td>1934</td>
</tr>
<tr>
<td>18</td>
<td>Glued &amp; braced</td>
<td>4300</td>
<td>1.10</td>
<td>1975</td>
</tr>
<tr>
<td>19</td>
<td>Glued &amp; braced</td>
<td>3700</td>
<td>0.92</td>
<td>1938</td>
</tr>
<tr>
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<td>Glued &amp; braced</td>
<td>2700</td>
<td>0.88</td>
<td>1770</td>
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<td>1907.0</td>
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<td>0.76</td>
<td>1728</td>
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<tr>
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<td>1950</td>
<td>0.66</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>Av.</td>
<td>1975</td>
<td>0.71</td>
<td>1614.0</td>
</tr>
<tr>
<td>23</td>
<td>4-1/2&quot; bolts &amp; glued</td>
<td>2750</td>
<td>1.20</td>
<td>1300</td>
</tr>
<tr>
<td>24</td>
<td>4-1/2&quot; bolts &amp; glued</td>
<td>2500</td>
<td>1.50</td>
<td>1590</td>
</tr>
<tr>
<td>25</td>
<td>4-1/2&quot; bolts &amp; glued</td>
<td>2400</td>
<td>1.26</td>
<td>1760</td>
</tr>
<tr>
<td></td>
<td>Av.</td>
<td>2550.0</td>
<td>1.32</td>
<td>1550.0</td>
</tr>
</tbody>
</table>
* Failure of nailed joints assumed when load-carrying capacity began to decrease.

+ Measured at a point 40.5 inches from center of joint.
deflections did not always occur in those joints that had the maximum strength. This may be explained by variations in the modulus of elasticity of the wood used in the various joints and by poor glue bonds such as those illustrated in Figures 41 and 42.

Joint number 15, which was made with thirty-one 10d nails and glue, failed at 2260 lbs. with a deflection of 1 inch. The high strength of this joint was the result of an excellent glue bond, particularly around the outside edges of the joint where the stresses were the greatest. Reference to Figure 43 shows the high percentage of wood failure, which is indicative of a good glue bond, that occurred when the joint was tested to failure. The fact that 31 nails were used accounts for the exceptionally good bond since they held all portions of the joint in close contact during the setting time of the glue.

The glued and braced joints averaged 3060 lbs. with a deflection of 0.78 inches. These joints were far superior in strength and rigidity to all joints tested under torsion loads.

The joints made with two ⅜-inch bolts and glue averaged 1975 lbs. Those made with four ⅜-inch bolts were the strongest of the non-braced joints and averaged 2550 lbs. Average deflections at failure were 0.71 inches for the former and 1.32 inches for the latter. The test results of the group
Fig. 41. Glued Joint Showing Poor Glue Bond at Outer Edges.

Fig. 42. Glued and Braced Joint Showing Poor Glue Bond Over Entire Area.
Fig. 43. Glue Joint Showing Excellent Glue Bond.

Fig. 44. Bolted-Glued Joint Under Load of 1880 lbs.
of joints indicate that bolted-glued joints are superior to nailed-glued joints. This is not surprising since bolts are capable of applying a greater pressure to the glue line than is possible with nails. In addition, if the pieces composing a joint are slightly warped, continued tightening of the bolts draws the surfaces into close contact.

Illustrated in Figure 44 is the relatively small deflection that occurs in glued joints under load. A plumb bob was placed along one edge of the joist member as may be seen from close examination of the picture. The joint shown was loaded to 1880 lbs. The slight deflection that did occur at this load occurred along the upper portion of the joist. No deflection or rotation was apparent at the joint itself. The line appearing close to the lower-left edge of the joist is caused by the shadow of the plumb line since the flash bulb was held to the left when the picture was taken. The position of the plumb bob in the lower portion of the picture shows that the plumb line was in line with the joist prior to loading the joint.

With the exception of the nailed-glued joints, all of the glued joints continued to carry greater loads even after failure than joints of the same type made with nails only. The substantial strength of these glued joints after failure may be explained by the fact that glued joints using nails or bolts for pressure application to the glue line become simply nailed or bolted joints after failure, but with one
important difference. Frictional resistance between the surfaces in contact is increased by the wood fibres that are pulled loose when the glued surfaces fail. This increased resistance adds to the strength of the joints. In the case of the nailed-glued joints it must be remembered that they were constructed with only 6 nails while the nailed joints contained 8 nails. Therefore, no direct comparisons can be made between these two groups in regard to load-carrying capacity after failure.

In these tests no attempts were made to calculate moments and stresses. The tests were made for the express purpose of comparing the strength and rigidity characteristics of nailed joints and glued joint. To make the comparisons, load-deflection readings, for loads up to 2500 lbs. and deflections up to 1 inch, of the high and low strength joints of each group were plotted and are shown in Figure 45. These curves are discussed below.

Load-deflection characteristics of nailed joints

The nailed joints will be discussed under two headings: (1) non-braced nailed joints and (2) nailed and braced joints.

Non-braced nailed joints. Reference to Figure 45 indicates that the load-deflection characteristics of nailed joints under torsion loads are: (1) relatively low load-carrying capacities and (2) large deflections. There is little or no rigidity in joints of this type. In all cases the joints
Fig. 45 Load-deflection curves for timber joints under torsion loads.

Load applied to 2" x 10" timber at a point 45" from the center of the joint. Deflection measured at a point 40.5" from the center of the joint.
rotated and this rotation accounted for all of the deflection measured by the deflectometer. This lack of rigidity of the nailed joints was emphasized by their inability to return to their original position after the load was removed.

Nailed and braced joints. The addition of bracing to nailed joints resulted in a strength increase of approximately 4 times that of non-braced joints. Also for the same amount of deflection the braced joints carried much higher loads. Nevertheless, slight increases in load resulted in relatively large increases in deflection of the joints. There was little indication of rigidity since most of the deflection was caused by rotation of the joint members. Figure 46 shows the large deflection that occurred in one of the nailed and braced joints tested.

Load-deflection characteristics of glued joints

The glued joints will be discussed under the following three headings: (1) nailed-glued joints, (2) bolted-glued joints, and (3) glued and braced joints.

Nailed-glued joints. The nailed-glued joints are represented in Figure 45 by the curves marked "Glued" and "31-10d nails and Glued". It is apparent from the slope of these curves up to the point of failure that the nailed-glued joints were much stiffer than either type of nailed joint. The maximum strength of those nailed-glued joints that contained
Fig. 46. Nailed and Braced Joint After Testing.

Fig. 47. Glued and Braced Joint After Testing to Failure.
only 6 nails was, however, considerably less than that of the nailed and braced joints (see Table 3). This was not so with the glued joint containing 31 nails; it was both stronger and stiffer than the nailed and braced joints. Deflection of the nailed-glued joints was the result of deformation of the stud and joist members only since no rotation of these members around the center of the joint was observed.

**Bolted-glued joints.** The curves for bolted-glued joints show still greater increases in both rigidity and load-carrying capacity. While the use of 4 bolts results in a stronger joint there is apparently little increase in rigidity over those glued joints containing only 2 bolts.

**Glued and braced joints.** High strength and rigidity were characteristic of the glued and braced joints. The steep slope of the curves for these joints show large increases in load with correspondingly small increases in deflection. No rotation of the joints occurred prior to failure and all deflection was the result of deformation in the 2 members composing the joint. This lack of rotation in all the glued joints tested indicates that they approach the conditions of rigid-fixed joints. Nailed joints, on the other hand, rotate and approach the conditions of hinged joints. Figure 47 shows a glued and braced joint after failure. By comparing Figures 46 and 47 the much greater deflections occurring in nailed joints under load are immediately apparent. Recalling
that Figure 47 shows a glued and braced joint after failure makes the comparison even greater since the majority of the deflection shown resulted from rotation of the members after failure of the glued surfaces.

Glued Joints Subjected to Fatigue Stresses

General

The results of the fatigue tests are given in Table 4. Joints of Group A are not included in this Table because, as mentioned previously, these joints failed immediately upon starting the fatigue testing machine.

Table 4

Results of Fatigue Tests

<table>
<thead>
<tr>
<th>Group</th>
<th>Joint No.</th>
<th>Deflection* (inches)</th>
<th>No. of Fatigue Cycles</th>
<th>Maximum Static Load After Fatigue Cycles (lbs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>1</td>
<td>0.125</td>
<td>257,755</td>
<td>1150</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>0.125</td>
<td>283,880</td>
<td>1075</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>0.125</td>
<td>272,130</td>
<td>390</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>0.125</td>
<td>270,720</td>
<td>625</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>0.125</td>
<td>276,360</td>
<td>510</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>0.125</td>
<td>277,770</td>
<td>872</td>
</tr>
<tr>
<td>B</td>
<td>7</td>
<td>0.125</td>
<td>316,075</td>
<td>435</td>
</tr>
<tr>
<td>B</td>
<td>8</td>
<td>0.125</td>
<td>282,000</td>
<td>420</td>
</tr>
<tr>
<td>B</td>
<td>9</td>
<td>0.125</td>
<td>274,080</td>
<td>530</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td>278,974</td>
<td>667.4</td>
</tr>
</tbody>
</table>

*This deflection subjected the joints to a load of approximately 400 lbs.
Glued joints subjected to fatigue loads close to maximum static loads

From the torsion load tests joints of this type were found to be capable of carrying an average load close to 1200 lbs. Joints of Group A were deflected 0.375 inches which subjected them to loads approximating 1000 lbs. Therefore the joints were fatigue loaded very close to their maximum load-carrying capacity under static conditions. The fact that this group of joints all failed before they could be subjected to more than 1 fatigue cycle warrants the following deduction: static-load tests are not a satisfactory criterion of the behavior of glued joints subjected to fatigue stresses.

Glued joints subjected to fatigue loads less than maximum static loads

Since a deflection of 0.125 inches produced a load of approximately 400 lbs. on the joints of Group B, the joints of this group were fatigue loaded only to about one-third of their maximum load-carrying capacity under static conditions. Of the 9 joints tested 3 of them indicated complete failure of the glue area after completion of the fatigue cycle. The remainder of the joints were still capable of carrying static loads after fatigue stressing that were greater than the load-carrying capacity of joints made with nails only.

The low performance of some of the joints tested was not wholly the result of the glue areas failing during the fatigue
stressing cycles. Prior to testing several of the 2-inch x 10-inch members of the joints warped considerably. This warpage produced splitting in the members and caused some failure in the glue line.

Figure 48 shows the progress of a failure crack along one edge of a glue joint. In most cases this fracture line was limited to the thick glue bead that was forced out of the glue line when the joint was constructed. Such cracks developed almost immediately in all joints and did not always indicate failure of the entire joint.

While the fatigue tests were not extensive and therefore not conclusive the results do seem to indicate that the fatigue limit of glued joints may be as low as one-fourth to one-third the static limit of the joints.
Fig. 48. Glue Fracture Along Edge of Joint Being Subjected to Fatigue Stresses.
Joints With Varying Glue Areas and With Grain of Members Parallel

1. The unit strength of a glued joint varies with its size.

2. The influence of length of joint on the unit strength of glued joints is approximately 8 times as great as that of width of joint or specific gravity of the wood (see page 83).

3. An increase in length of joint results in a decrease in the unit strength of glued joints.

4. An increase in the specific gravity of the wood used to construct glued joints results in joints of higher strength.

5. The unit strength of glued joints may be predicted from the following equation:

\[ u = -0.375W - 27.417L + 158.445G + 825.385 \]

where \( u \) = unit strength in psi, \( W \) = width of joint in inches, \( L \) = length of joint in inches, and \( G \) = specific gravity of the wood.

6. Allowing a safety factor of at least 2, a length of 5 inches for any width of glued joint from 1 inch to 8 inches will permit design of the joints on a basis of an allowable compressive stress of 1700 psi for Douglas Fir. The stresses in the glue line may be neglected when using the above allowable working stress for joints 5 inches in length or greater.
7. An increase in length of joint beyond 5 inches serves only to increase the safety factor of a glued joint since the allowable compressive working stress of Douglas Fir does not permit design loads which would result in high shearing stresses in the glue line.

8. For glued joints less than 5 inches in length, an allowable glue line shearing stress of 200 psi will provide a safety factor of 2 or above.

9. The load applied to glued joints is not distributed uniformly over the glue area.

10. Shear stresses in glued joints are a maximum at points closest to the application of load.

11. The results of the tests on joints with varying glue areas apply only to:
   1. Joints made with main members having a nominal thickness of 2 inches and splice plates having a nominal thickness of 1 inch.
   2. Joints in which the main members are subjected to direct compressive loads.

Glued Joints Subjected to Torsion Loads

1. Glued joints are superior in strength and rigidity to nailed joints.

2. Bolted-glued joints are superior to nailed-glued joints in strength and rigidity.

3. The greatest advantage of glued joints over nailed
joints is stiffness. By using glue the stiffness of a joint is increased as much as 8 to 14 times.

4. The added strength and rigidity of joints made with knee-braces warrants the additional cost of the bracing.

5. When constructing glued joints that will be subjected to torsion loads, care should be taken to obtain a good glue bond around the outside edges of the joint. The greatest resistance to failure of the joints is offered by the glued surfaces nearest the edges.

Glued Joints Subjected to Fatigue Stresses

1. The fatigue-load limit of glued joints is approximately one-fourth to one-third of the static-load limit.

2. Static-load tests on glued joints are not a satisfactory criterion of the behavior of the joints under fatigue stresses.
SUMMARY

This study was justified by the large investment in farm buildings, the magnitude of farm building losses as a result of wind, the importance of wood as a structural material, and the inadequacy of present farm building construction methods.

Previous studies of the use of glue for structural improvement of farm buildings were reviewed.

Glued joints ranging in size from 1 inch in width and 1 inch in length to 8 inches in width and 8 inches in length were constructed and tested. These tests were made to observe the effect of size of joint on unit strength.

Photo-elastic models of the glued joints were made and tested in order to determine the causes for variations in unit strength of glued joints with changes in size.

Strain gages were placed on actual glued joints in order to obtain data that could be analyzed and used to verify the photo-elastic analysis.

Tests were run on glued joints that were subjected to torsion loads. A comparison was made between nailed joints, nailed-glued joints, and bolted-glued joints. The increases in strength and rigidity resulting from the addition of knee braces to the joints were studied and discussed.

Non-braced glued joints were subjected to completely
reversed stresses for a minimum of 250,000 cycles. The fatigue load applied to one group of joints was close to their maximum load-carrying capacity under static conditions. A second group of joints were fatigue loaded to approximately one-third of their maximum static-load capacity. From the results of the fatigue tests a comparison was made between the fatigue-load limit and the static-load limit of glued joints.
SUGGESTIONS FOR FURTHER STUDY

It is the writer's opinion that the full possibilities of glued construction have hardly been realized. However, to realize these possibilities requires a knowledge of the limitations as well as the capabilities of this type of construction. Therefore, several of the problems encountered during this study are offered as possible suggestions for further investigation. By presenting these problems it is hoped that those who continue this project will find them sufficiently interesting and important to be investigated.

The suggested studies are as follows:

1. A further study of the relationship between size and strength of glued joints made by machine pressure instead of nail pressure and with:
   a. grain of joint members parallel
   b. grain of joint members perpendicular

   The elimination of erratic pressures caused by nails should reduce somewhat the large variations in strength among individual joints of a group as found in the present study. Consequently the effects of size, length, and width of joints could be more closely correlated.

2. A study to determine if strength differences exist between flat-grain to flat-grain glued joints and vertical-grain to vertical-grain glued joints.

3. A quantitative study by photo-elastic methods of the stresses occurring in glued joints.
4. The determination of the coefficient of restraint of glued joints subjected to torsional loads. The coefficient of restraint may be defined as the relation existing between the moment developed at the supports of a uniformly loaded beam with a constant moment of inertia and the moment at the supports of the same beam if the ends were perfectly restrained. This coefficient, therefore, would then be a measure of the efficiency or effectiveness of the joint in carrying moment.

5. A study of the effect of size of joint on the unit strength of glued joints subjected to torsional loads in order to determine the following:
   a. the most efficient sized joint
   b. the allowable design unit stresses for various sized joints.

6. A comprehensive study of the endurance limit of nail-glued joints subjected to completely reversed stresses to determine the ratio between maximum fatigue-breaking stress and maximum static-breaking stress. It is further suggested that all nails be pulled prior to fatigue testing to facilitate the detection of joint failure.

7. A study of the behavior of glued joints subjected to near maximum loads for long periods.

8. A study to determine the effectiveness of glued joints to resist impact loads.

9. A study to evaluate the effectiveness of protective coats of aluminum paint, varnish, etc. in preventing moisture changes in the wood and consequent warpage and reduction in strength of glued joints.
LITERATURE CITED


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ACKNOWLEDGMENTS

The author wishes to express his appreciation to Professor Henry Giese of the Agricultural Engineering Department for his interest, constructive criticisms, and beneficial suggestions during the course of this study.

The assistance and cooperation extended by Professor Hobart Beresford, Head of the Department of Agricultural Engineering, and other members of the Agricultural Engineering staff is deeply appreciated.

To Professor M. G. Spangler and Dr. D. T. Davidson of the Civil Engineering Department the author is indebted for use of the testing machines in the Soil Engineering Laboratory.

The author also wishes to express his gratitude to Dr. G. Murphy and Professor R. T. Othmer of the Theoretical and Applied Mechanics Department for use of the Polariscope and assistance in the Photo-Elastic Study.

Grateful acknowledgment is made to the Iowa Mutual Tornado Insurance Association and the Farmers Mutual Reinsurance Association for financial support of this study.
Relation between size and unit strength of glued joints made with grain of members parallel
Relation between size and unit strength of glued joints made with grain of members parallel.