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REPORT No. 145

INTERNAL STRESSES IN LAMINATED CONSTRUCTION

By A. L. HEIM, A. C. KNAUSS, and LOUIS SEUTTER

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SYNOPSIS OF REPORT NO. 145,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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By
A. L. Heim, A. C. Knauss,
and Louis Seutter.

Report No. 145 of the National Advisory Committee for Aeronautics reviews the procedure employed in an investigation of the sources and influence of internal stresses in laminated construction, and discusses the influence of shrinkage and swelling stresses caused by atmospheric conditions upon the tensile strength across grain in laminated construction with special reference to airplane propellers.

The investigation covered three sources of internal stress, namely, the combination of plain-sawed and quarter-sawed material in the same construction, the gluing together of laminations of different moisture contents, and the gluing together of laminations of different densities.

Glued specimens and free specimens, made up under various manufacturing conditions, were subjected to various climatic changes inducing internal stresses and then were tested. The strength of free unstressed pieces served as a standard of comparison for glued pieces and indicated what internal stresses were developed in the glued construction.

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INTERNAL STRESSES IN LAMINATED CONSTRUCTION.

By Forest Products Laboratory.

INTRODUCTION.

This report, submitted to the National Advisory Committee for Aeronautics for publication, covers work conducted by the Forest Products Laboratory of the United States Forest Service at the request of and with funds provided by the Bureau of Engineering of the Navy Department.

SUMMARY.

The report reviews the procedure employed in an investigation of the sources and influence of internal stresses in laminated construction, and discusses the influence of shrinkage and swelling stresses caused by atmospheric conditions upon the tensile strength across grain in laminated construction with special reference to airplane propellers.

The investigation covered three sources of internal stress, namely, the combination of plain-sawed and quarter-sawed material in the same construction, the gluing together of laminations of different moisture contents, and the gluing together of laminations of different densities. The following species were studied:

Central American mahogany (*Swietenia mahogani*).
African mahogany (*Khaya senegalensis*).
Philippine mahogany (*Shorea sp.*).
Yellow poplar (*Liriodendron tulipifera*).
Hard maple (*Acer saccharum*).
Yellow birch (*Betula sp.*).
Red gum (*Liquidambar styraciflua*).
Northern white oak (*Quercus sp.*).
Northern red oak (*Quercus sp.*).

Glued specimens and free specimens, made up under various manufacturing conditions, were subjected to various climatic changes inducing internal stresses and then were tested. The strength of free unstressed pieces served as a standard of comparison for glued pieces and indicated what internal stresses were developed in the glued construction.

The following recommendations as to propeller specifications are made for the species studied:

1. That all propellers be covered with aluminum leaf coating or other approved finish which will prevent, so far as possible, any gain or loss in moisture content of the propeller.
2. That for the most extreme conditions of service propellers be made entirely of quarter-sawed material.
3. That for moderate conditions of service propellers made entirely from plain-sawed stock be permitted, provided they are well protected against moisture change.
4. That for species in which the ratio of radial to tangential shrinkage exceeds 0.75 the mixing of plain-sawed and quarter-sawed stock be permitted in propellers for moderate service, provided that they are well protected against moisture change.
5. That all propeller stock be allowed to come to equilibrium under fixed conditions of temperature and relative humidity before gluing.
6. That density specifications be such as to eliminate all brash material, but not to require matching for density.
7. That moisture content of wood, gluing conditions, and protective coating be such that the mositure content of the propellers will not exceed 15 per cent at any time. Beyond this point animal glue is not likely to give satisfactory results.

These recommendations are based on the following conclusions, which appear to be warranted from a careful analysis of the data obtained in this study:

1. Tensile strength across grain (across the face of the board) for quarter-sawed lumber is greater than for plain-sawed lumber. Plain-sawed lumber may be from 20 to 50 per cent weaker across the grain, depending upon the species and method of drying.

2. The gluing together of plain-sawed and quarter-sawed stock gives rise to internal stresses through the unequal swelling and shrinking which takes place with changes in moisture content and results in a weakening across grain of the laminated structure.

3. The gluing together of laminations of different moisture contents gives rise to internal stresses on account of the unequal swelling or shrinking which takes place as all the laminations approach a common moisture content, and results in a weakening across grain of the structure, which may be of sufficient magnitude to cause rupture of members of the laminated structure.

4. When a laminated structure containing both quarter-sawed and plain-sawed members is subjected to conditions which cause a change in moisture content, the unequal swelling or shrinkage of the different members induces stresses. These stresses reach a maximum and then, if the moisture content remains constant, gradually die out. The structure is then free from internal stresses but has assumed new dimensions. If the elastic limit of the wood has not been exceeded, the strength has not been affected. With each change of moisture content new stresses will be developed.

5. When a laminated structure is composed of members all plain-sawed or all quarter-sawed of unequal moisture contents, the moisture in the wood tends to equalize, and stresses are set up in the structure through the unequal shrinking or swelling of the members. These stresses eventually die out, leaving the structure stress-free but with changed dimensions. If the elastic limit of the wood has not been exceeded the strength has not been affected. If the structure is subjected to further moisture change no stresses are induced, since all members have reached the same condition and thereafter act together.

6. When laminations of very high and very low densities are glued together to form a laminated structure, change of moisture content induces stresses on account of the unequal shrinkage or swelling of the members. These stresses eventually disappear; and, if the elastic limit has not been exceeded, only a change in dimensions results. Further changes in moisture content induce new stresses. Within a single species the stresses so induced are relatively small, however, and are not likely to be serious except in extreme cases.

7. Animal glue used in these tests does not set properly when the laminations are of high moisture content. The exact point where unsatisfactory results occur can not be determined from the data available, but it appears to be between 15 and 18 per cent. Also, in glued specimens placed under atmospheric conditions tending to produce a moisture content of from 15 to 18 per cent in the wood, the glue softens and permits the laminations to be easily pulled apart.

GENERAL APPLICATION OF THE INVESTIGATION.

Warping and twisting and the opening of glued joints are of great importance to industries using material consisting of small pieces of wood joined together to form a larger structure. The degree to which such changes in the manufactured products are detrimental varies, but in many cases a slight change is sufficient to cause rejection or at least necessitate extensive repairs.

Ordinarily the furniture industry is most affected by such failures, and when furniture manufacturers undertook to produce airplane propellers on a commercial scale the same difficulties appeared in a magnified form. The smallest changes in shape or track and any opening of glued joints were reasons for rejection; and the rejected propellers could not be repaired as could articles of furniture.

The cause of warping of built-up products is not thoroughly understood. Several factors are commonly credited with the cause of most failures, and these may appear singly or in combination. But all changes of form or opening of joints are the result of the development of stresses within the manufactured article.

THE PROBLEM TO BE INVESTIGATED.

Stress is defined [1] as the internal force, which, when a body is subjected to external forces, tends to hold the molecules in their original relation and to preserve the integrity of the body.

Applying external loads to a wood structure changes its shape and develops proportionally resistant stresses until the elastic limit is reached, beyond which the rate of deformation increases until rupture occurs.

Stresses may also be developed in wood which are not caused by external loading, but rather from conditions within the wood. While they probably do not affect the mechanical properties of the wood fiber, they do combine with loading stresses and reduce the magnitude of the safe external load, for the sum of both stresses can not exceed the strength of the wood fiber. Such stresses, caused by factors other than external loading, are properly called "internal stresses" and are important becauses of their influence on the quality and strength of wood construction.

Wherever strength properties of wood are involved, internal stresses must be considered. In the seasoning of wood, the methods and rates of drying and the quality and strength of the product turned out of the kilns depends largely upon the extent to which the magnitude and character of internal stresses can be controlled.

The development of internal stresses is due largely to the hygroscopic properties of wood. Wood contains water in two forms—as free water in the cell cavities, which is given off first, and as moisture absorbed by the cell tissues, which is not given off until the free moisture is lost. The point at which moisture begins to leave cell tissues is called the fiber saturation point. Below this point wood shrinks with loss of moisture and swells with gain in moisture, coming to an equilibrium with every climatic condition to which it is subjected for a sufficient length of time. Any moisture content up to fiber saturation can be maintained in wood by proper control of the temperature and relative humidity of the surrounding atmosphere.

The magnitude of shrinking and swelling with moisture changes differs not only for every species of wood, but also in each of the three directions in a tree—longitudinally (along the grain of the wood, radially (along the radius of a transverse face), and tangentially (along the circumference of an annual ring). Longitudinal shrinkage is so small as to be negligible when compared to radial and tangential shrinkage values, which are given in Table 1.

TABLE 1.—*Shrinkage from green condition to oven-dry condition.*

Species.	Percentage of dimensions when green.	
	Radial.	Tangential.
Northern white oak [1]	5.3	9.0
Northern red oak [1]	3.9	8.3
Yellow birch [1]	7.4	9.0
Red gum [1]	5.2	9.9
Yellow poplar [1]	4.1	6.9
Hard maple [1]	4.8	9.2
Central American mahogany [2]	3.5	4.2
African mahogany [2]	4.8	5.5
Philippine mahogany [2]	5.0	5.7

[1] Bulletin No. 556, U. S. Department of Agriculture, "Mechanical Properties of Woods Grown in the United States," by J. A. Newlin and T. R. C. Wilson.

[2] Results of more recent tests made at Forest Products Laboratory, Madison, Wis.

The magnitude of the shrinkage across the face of a board varies with the manner of cutting from the log. Purely quarter-sawed lumber (radial face) has the least shrinkage. Where unequal shrinkage or swelling with moisture changes occurs, as in boards containing both plain-sawed and quarter-sawed material, twisting and cupping result.

In laminated construction, the danger of unequal shrinking and swelling is even greater, for material differing widely in shrinkage properties may be combined, and since each member

[1] Merriman's "Civil Engineers Pocket Book," 1916 edition, p. 272.

can not swell or shrink independently (the structure must change as a whole) the excessive swelling of some members is restrained by the more moderate swelling of others, equal and opposite stresses being developed within the individual members. In a structure so stressed, the internal stresses will combine with loading stresses and precipitate failure earlier than in a structure not stressed. A comparison of the maximum strength of two structures, one stressed and the other unstressed, would therefore indicate the magnitude of internal stress which had been developed.

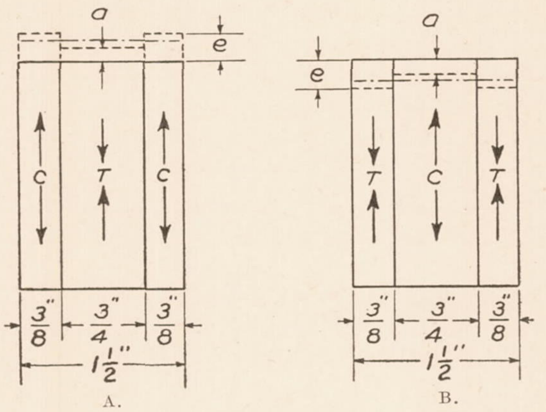


FIG. 1.—Combining plain-sawed and quarter-sawed material in laminated construction.

A.—Swelling of laminated construction with increase in moisture content.

e = free swelling of plain-sawed member.

a = free swelling of quarter-sawed member.

Since members are glued together, they must swell together and final swelling $= a + \frac{e-a}{2}$ (shown by fine dotted line). This develops compression in plain-sawed member and tension in quarter-sawed member.

B.—Shrinkage of laminated construction with loss in moisture content.

e = free shrinkage of plain-sawed member.

a = free shrinkage of quarter-sawed member.

Since members are glued together, they must shrink together and final shrinkage $= a + \frac{e-a}{2}$ (shown by fine dotted lines). This develops tension in plain-sawed member and compression in quarter-sawed member.

The influence of internal stresses on the strength of wood construction is of particular importance in airplane propellers, where maximum strength with minimum weight and permanency of shape are prime requisities. This investigation was planned, therefore, to cover those sources of internal stress most commonly encountered in the manufacture and use of airplane propellers.

The series of investigations of the strength of laminated construction includes comprehensive tests to determine [2]—

Series A: Influence of combining plain-sawed and quarter-sawed material.

Series B: Influence of combining material of unequal moisture content.

Series C: Influence of combining high-density and low-density material.

METHOD OF INVESTIGATION.

One of the sources of internal stress is the variation in shrinkage properties in different directions in a tree, the effect of which is noticeable in combining plain-sawed and quarter-sawed material. In such a combination, unequal shrinking and swelling tend to take place with moisture changes, and, being restrained, cause internal stresses. Figure 1 shows the character of stress developed with a change in moisture content in a test specimen, such as is shown in figure 2.

The normal free swelling of the plain-sawed faces is the distance "e," and the normal free swelling of the quarter-sawed core is "a." Being bound together, the faces are restrained and the core is stretched, developing compressive stresses in the faces and tensile stresses in the core; and the final position of the structure is indicated by the dotted line. A loss in moisture results in stresses of opposite character.

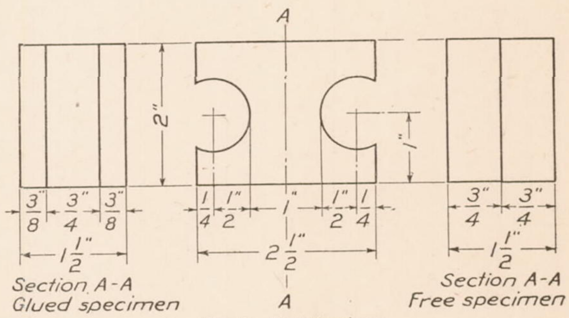


FIG. 2.—Test Specimen.

In either case, the member of the glued specimen subjected to internal tensile stress will fail under a smaller external load than if it were free from internal stresses. After such failure the entire load is shifted to the remaining member, and complete rupture takes place at a comparatively low load. The whole glued structure has failed then under an external load smaller than the sum of the loads required to break the individual free members.[3]

[2] In the original working plan (Appendix B) Series A is designated as Series I, Series B as Series III, and Series C as Series II.

[3] "External load" and "strength" as used in this report refer to test conditions such as are obtained in the test shown in figure 6.

For the first part of this study, specimens similar to those shown in figure 2 were manufactured, in which plain-sawed and quarter-sawed material were combined, moisture and density variables being eliminated. Moisture changes were introduced to develop internal stresses in glued specimens, and the strength at test was compared with that of matched unstressed specimens.

The second source of internal stress investigated was the unequal shrinkage developed by gluing together laminations differing in moisture content. All wood subjected for a sufficient time to the same atmospheric condition will come to practically the same moisture content. If the common moisture content is not reached before assembly into laminated construction, it is attained after assembly, and the resultant unequal swelling and shrinking of the component parts develop internal stresses as shown in figure 3, just as in the combining of plain-sawed and quarter-sawed material.

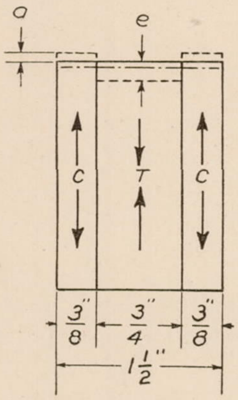


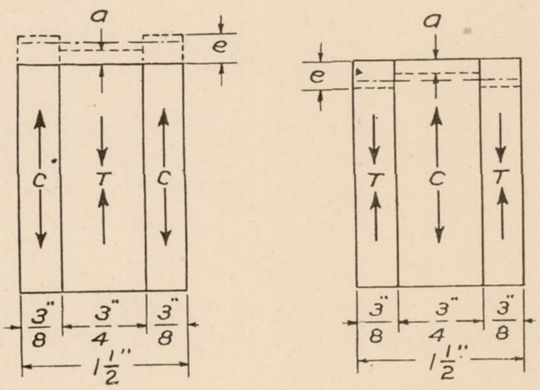
FIG. 3.—Combining material not uniform in moisture content in laminated construction.

Dry faces and wet core glued together and allowed to condition to equilibrium.

e= free shrinkage of wet core.

a= free swelling of dry faces.

Final position shown by dotted line. Since members are glued together, they must move together. This develops compression in faces tending to swell and tension in core tending to shrink.



A. B.

FIG. 4.—Combining high density and low density material in laminated construction.

A.—Swelling of laminated construction with increase in moisture content.

Faces= High-density material.

Core= Low-density material.

e= free swelling of high-density member.

a= free swelling of low-density member.

Since members are glued together, they must swell together and final swelling $=a+\frac{e-a}{2}$ (shown by fine dotted line).

This develops compression in high-density member and tension in low density member.

B.—Shrinkage of laminated construction with loss in moisture content.

Faces= High-density material.

Core= Low-density material.

e= free shrinkage of high-density member.

a= free shrinkage of low-density member.

Since members are glued together, they must shrink together and final shrinkage $=a+\frac{e-a}{2}$ (shown by fine dotted line).

This develops tension in high-density member and compression in low-density member.

Specimens were made of laminations differing in moisture content at assembly, other variables being eliminated, and these specimens were conditioned under constant atmospheric conditions before being tested, permitting all members to come to a common moisture content. The strength of internally stressed glued pieces was then compared to the strength of unstressed free pieces.

The third source of internal stress investigated was the combination of material of different densities. High density wood has been found [4] to shrink and swell more than low density wood; hence, combining material of different densities leads to the development of internal stresses with moisture changes through unequal shrinking or swelling. (See fig. 4.)

[4] Bulletin No. 676, U. S. Department of Agriculture, "The Relation of the Shrinkage and Strength Properties of Wood to its Specific Gravity, by J. A. Newlin and T. R. C. Wilson.

Specimens were manufactured of material of different densities, other variables being eliminated. Moisture changes were introduced to develop internal stresses and the strength of the glued pieces subjected to internal stresses was compared with the strength of the free unstressed specimens.

MATERIALS USED IN INVESTIGATION.

LUMBER.

Lumber for the investigation was taken from the stock obtained for the manufacture of experimental propellers. It was handled with extreme care, and all pertinent information concerning the particular stock was obtained and recorded. A brief description of the material follows:

Central American mahogany.
African mahogany.
Yellow birch.

Part of the material of each species was purchased in the form of logs and sawed at the laboratory. The remainder was sawed at outside mills under laboratory supervision. All of the stock was kiln dried at the laboratory.

Northern white oak (quarter-sawed).
Northern red oak (quarter-sawed).

Part of the material was thoroughly air-dried stock purchased from dealers. The remainder was sawed at outside mills under laboratory supervision and kiln dried at the laboratory.

Red gum (quarter-sawed).

This stock was sawed at outside mills under laboratory supervision and kiln dried at the laboratory.

Yellow poplar.

This stock was purchased in log form, and sawed and kiln dried at the laboratory.

Philippine mahogany.

This material was from War Department stocks in the form of 1-inch kiln-dried lumber.

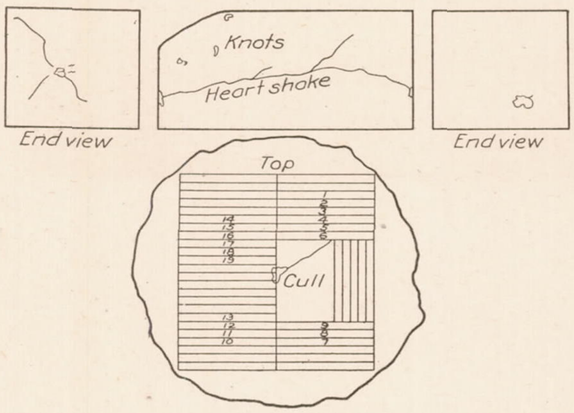


Fig. 5.—African Mahogany.

A cutting diagram was made for each log sawed at the laboratory or under laboratory supervision at outside mills. Each board was numbered for future identification, and these numbers were recorded on the boards and cutting diagram. A sample record is shown in figure 5.

The kiln drying in each case was done according to specifications for propeller stock.

Upon receipt at the shop, all stock was surfaced and stored under constant conditions of temperature and relative humidity. Samples were taken from both ends of each 40-inch stick for use in making density determinations.

TYPE OF GLUE.

The glue used for the manufacture of the laminated specimens was an animal glue, certified in accordance with Bureau of Aircraft Production specification No. 14000–A. It was mixed in the proportion of 1 part of glue to 2½ parts by weight of water and heated to 140 to 145° F. before being applied.

SPECIAL EQUIPMENT.

The same shops and storage rooms were used for carrying out this investigation as were provided for the propeller manufacturing and storage tests which are being conducted at the Forest Products Laboratory.[5] In these rooms the temperature and relative humidities are constantly maintained at the following values:

Woodworking room, 70° F., with 55 per cent relative humidity.
Glueroom, 90° F., with 65 per cent relative humidity.
Storage room, No. 3, 80° F., with 30 per cent relative humidity.
Storage room, No. 2, 80° F., with 60 per cent relative humidity.
Storage room, No. 1, 80° F., with 90 per cent relative humidity.

SPECIMENS.

The test specimens used were the standard specimens for tension across the grain, having the dimensions shown in figure 2. Each test piece was made of three laminations.[6] a core $\frac{3}{4}$ inch thick, and faces $\frac{3}{8}$ inch thick.

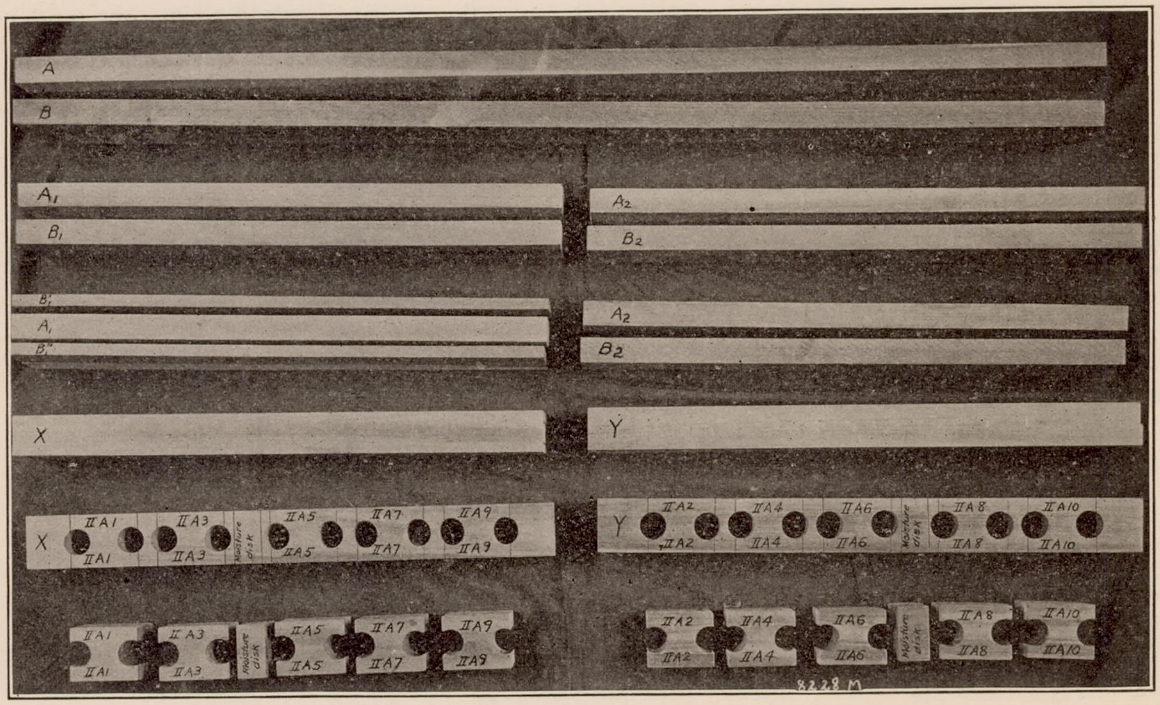


PLATE 1.—Laminated test specimens for tension across the grain, showing steps in manufacture.

The laminations for the glued-up and free (not glued) test specimens, shown in plate 1, were matched end to end and taken as near each other as possible. Two sticks, A and B (about 40 inches in length), carefully selected and matched for density, furnished material for test specimens, five of which were glued and five not glued, or free. Stick B was resawed longitudinally, making the two face pieces B_1 and B_2. The 40-inch block was then marked X and Y as shown and cut in two, making two 20-inch blocks. Block X was then glued and kept in the glue press 24 hours. The gluing operation was conducted in a room kept under constant conditions of temperature (90° F.) and relative humidity (65 per cent). The laminations of block Y were fastened together with metal staples. The marked end of block Y was placed opposite the marked end of block X and the specimens laid out and numbered as shown. Odd numbers indicate specimens that are glued-up and even numbers those not glued. The free specimens serve as a standard of comparison for the glued-up specimens.

[5] A complete description of this equipment is given in a report, "Automatic regulation of temperature and humidity in an experimental airplane propeller plant and its application to commercial conditions," by A. C. Knauss, June 2, 1919.

[6] In some of the latter free specimens they were made of two pieces each $\frac{3}{4}$ inch thick.

METHOD OF TESTING.

The method of testing these specimens is indicated in figure 6, which illustrates a standard test used at the Forest Products Laboratory for the determination of tensile strength across the grain.

The selection of material, marking, care of specimens, and courses of conditioning before testing are explained in detail in the original working plan, a copy of which is included as Appendix A of this report.

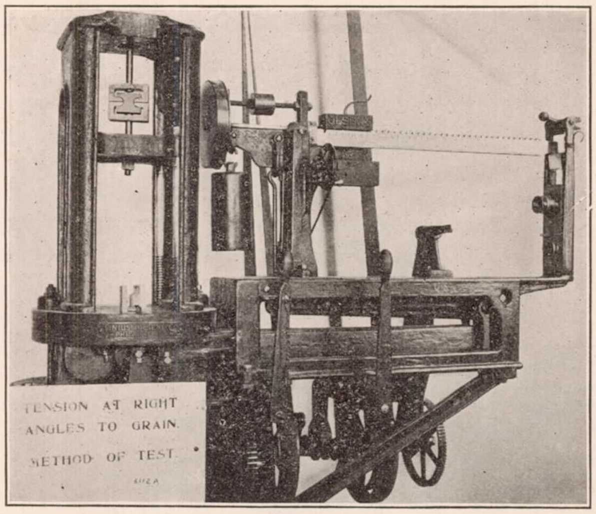


FIG. 6.

In conditioning specimens they were considered at equilibrium with the constant conditions in which they were stored, when they ceased to change weight. So far as moisture content is concerned, this assumption is correct, but from a standpoint of stresses induced by the method of manufacture many had not reached their ultimate condition. Stresses tend to die out, and if all specimens had been allowed to remain in any one condition of storage for an indefinite period, tests would have shown them to be stress free. This fact was not fully appreciated in the beginning of this work, and care was not taken to test the specimens immediately after reaching apparent equilibrium. Sometimes delay was necessary because testing machines or operators were otherwise engaged.

RECORD FORMS.

Several special forms were used in recording data. A sample of each of these with descriptive title is included as appendix B of this report.

ANALYSIS OF RESULTS OF SERIES A.

THE INFLUENCE OF COMBINING PLAIN-SAWED AND QUARTER-SAWED MATERIAL ON THE STRENGTH OF LAMINATED CONSTRUCTION.

The following species were studied:

Central American mahogany.
Philippine mahogany.
Yellow birch.
Yellow poplar.
Red gum.
Northern red oak.

Specimens were made with plain-sawed faces and a quarter-sawed core, of uniform density and conditioned to uniform moisture content before gluing. After manufacture, the specimens were successively subjected to several atmospheric conditions, remaining in each until constant weight was reached. Upon leaving each condition a number of the specimens were tested, the remainder passing to the next condition, according to the following schedules:

Schedule No. 1—Glue room: Room No. 1, room No. 2, room No. 3.

Schedule No. 2—Glue room: Room No. 3, room No. 2, room No. 1.

Relation between radial and tangential tensile strength across the grain.—The members of the free specimens were tested independently, giving separate data on the tensile strength across the grain of the plain-sawed material and the quarter-sawed material. The average of the unit strengths of the individual members was then taken as the strength of the free specimen. The glue specimens were necessarily tested as a unit. As shown in figure 7, the tensile strength across grain (across the face of the board) of plain-sawed material is designated as radial tensile strength, and that of quarter-sawed material is designated as tangential tensile strength, on account of the nature of the failure.

The ratio of radial to tangential tensile strength across the grain obtained in this investigation, for these species, is shown in plate 2, in which each plotted value is the average of five tests. This ratio seems to be independent of moisture content up to 20 per cent, but varies over a comparatively large range at all moisture contents. The average relations found for each species in this test are given in Table 2.

TABLE 2.—*Ratios between radial and tangential strength across grain.*

Species.	$\frac{R}{T}$	$\frac{G}{T}$	$\frac{G}{R}$
Central American mahogany	0.73	0.87	1.17
Philippine mahogany	.80	.90	1.12
Yellow birch	.81	.91	1.11
Yellow poplar	.70	.85	1.22
Red gum	.70	.84	1.23
Northern red oak	.56	.78	1.39

R = unit radial tensile strength across grain, pounds per square inch.
T = unit tangential tensile strength across grain, pounds per square inch.
G = unit tensile strength across grain of glued specimens, pounds per square inch.

These ratios indicate that plain-sawed lumber is weaker in tension across the face of the board than quarter-sawed lumber, particularly in red oak. The medullary rays of oak are very large and prominent, and checking often occurs along these rays in drying lumber. This fact may account for the extremely low ratio of $\frac{R}{T}$ for oak. It also indicates how easily drying may reduce the radial strength across grain of plain-sawed oak lumber.

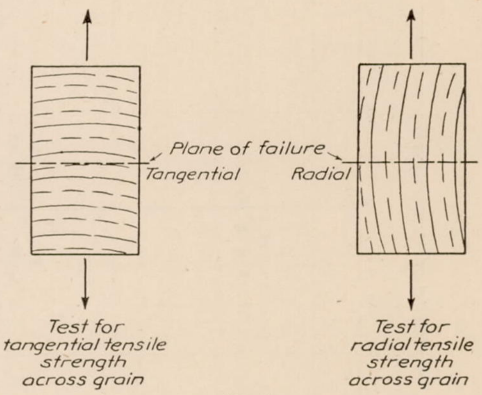


FIG. 7.

Comparison of tensile strength across grain with changes in moisture content.—Results of the test on series covering this study are shown in plates 3 and 4. Ratios of maximum unit loads carried by glued specimens to maximum unit loads carried by free specimens are shown at values of $\frac{2G}{R+T}$, and are plotted against change in moisture content after gluing.

It will be seen that values of $\frac{2G}{R+T}$ do not always equal unity, indicating a difference in strength between glued specimens and free specimens. This may be due either to the presence of internal stresses or to the elastic properties of the wood. If internal stresses are present, the capacity of the specimen to sustain external loading is ordinarily reduced, giving a ratio less than unity. A similar ratio is also obtained if the elastic properties of the members making up the glued specimens are not the same. The strongest member receives maximum load and fails, thus throwing the whole load on the remaining members and producing failure. The total load which the piece will therefore support may be less than the combined capacity of all the members. In any case, $\frac{2G}{R+T}$ could not exceed unity unless the glue film adds strength, and could reach unity only if internal stresses were so distributed that the maximum strength of all members is reached at the same deformation, which would be rather unusual.

Heavy lines at values of unity for $\frac{2G}{R+T}$ are drawn on plates 3 and 4. In Central American mahogany, Philippine mahogany, and yellow poplar, the values of $\frac{2G}{R+T}$ do not vary far from

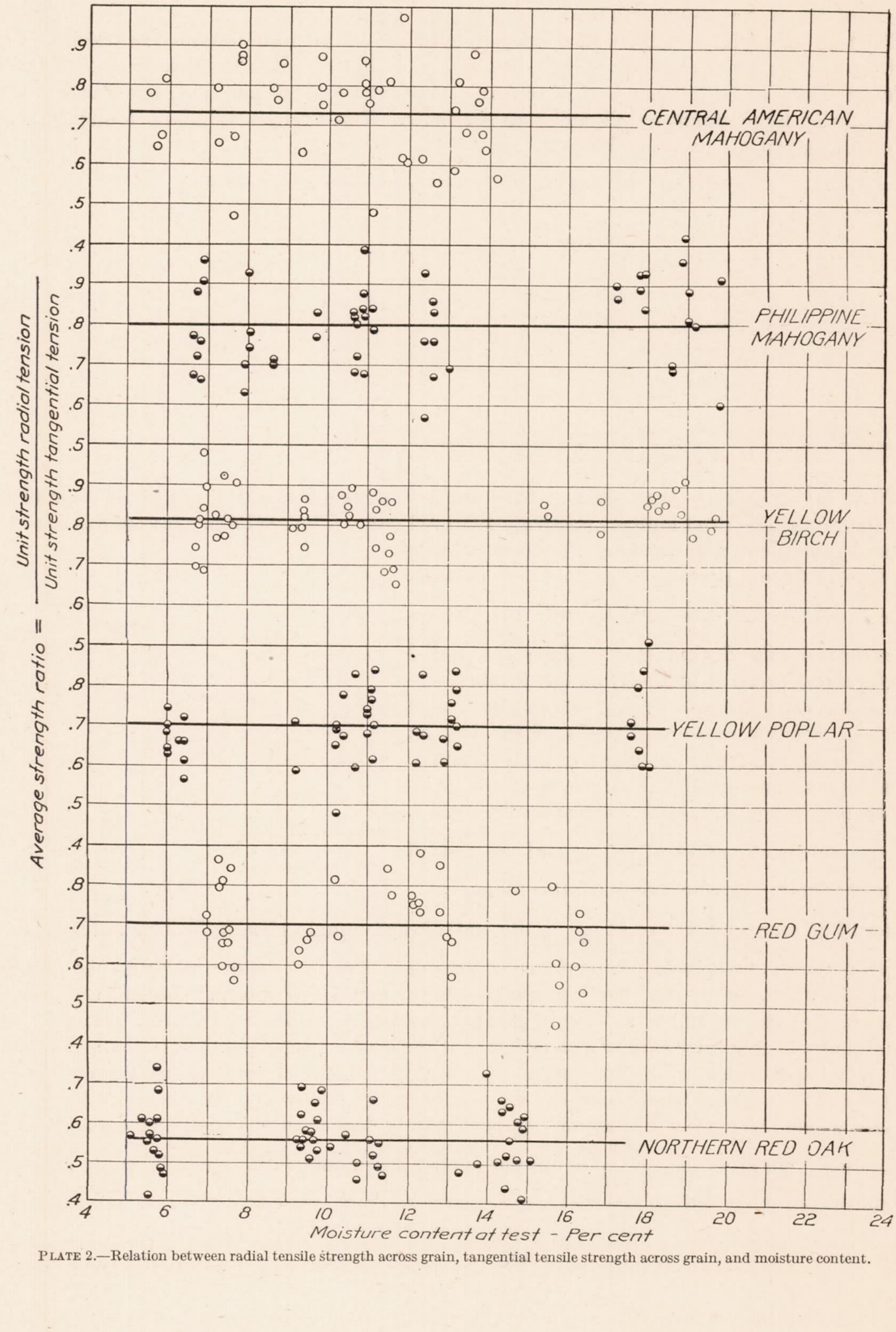


PLATE 2.—Relation between radial tensile strength across grain, tangential tensile strength across grain, and moisture content.

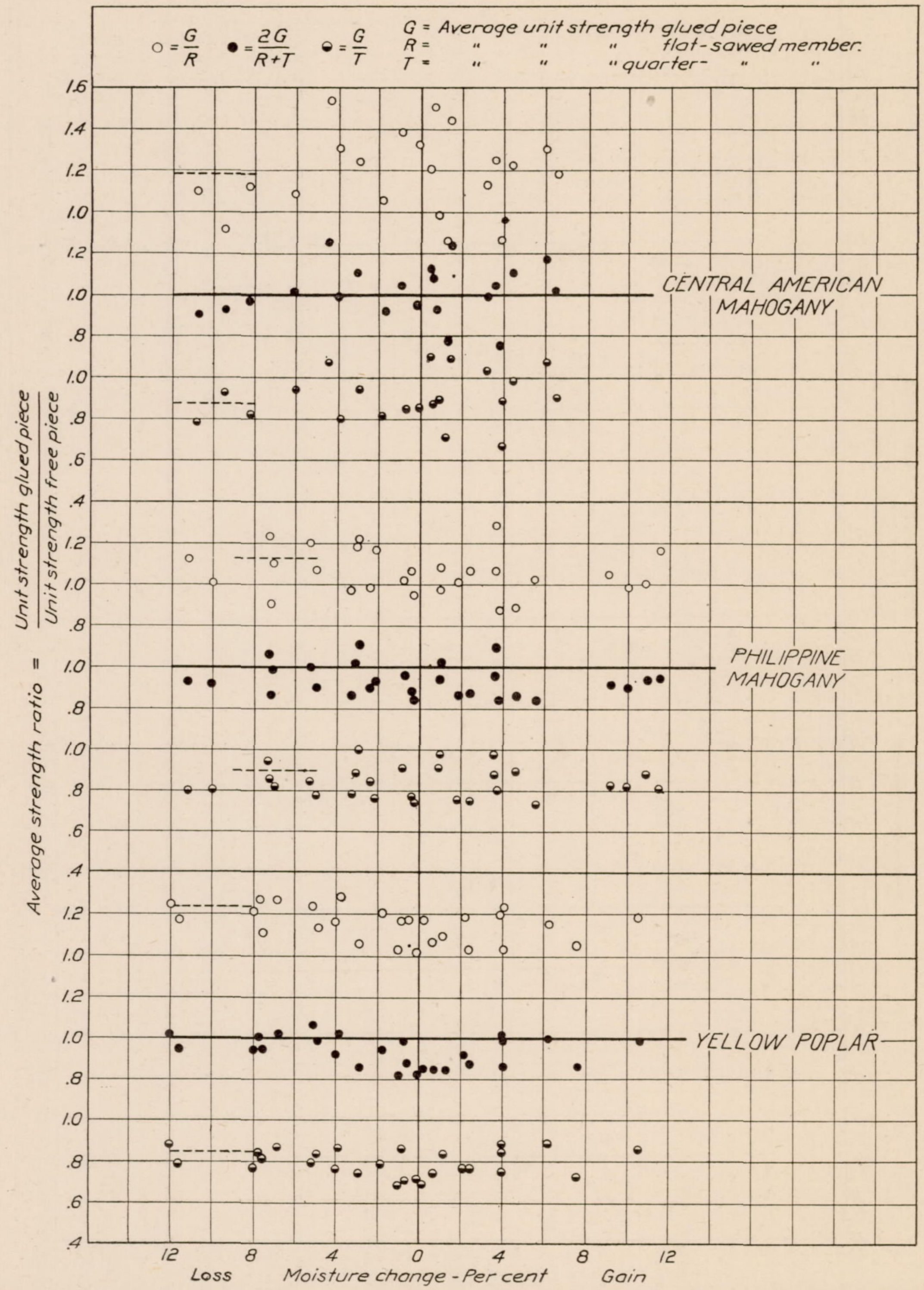


PLATE 3.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued of plain-sawed and quarter-sawed material) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

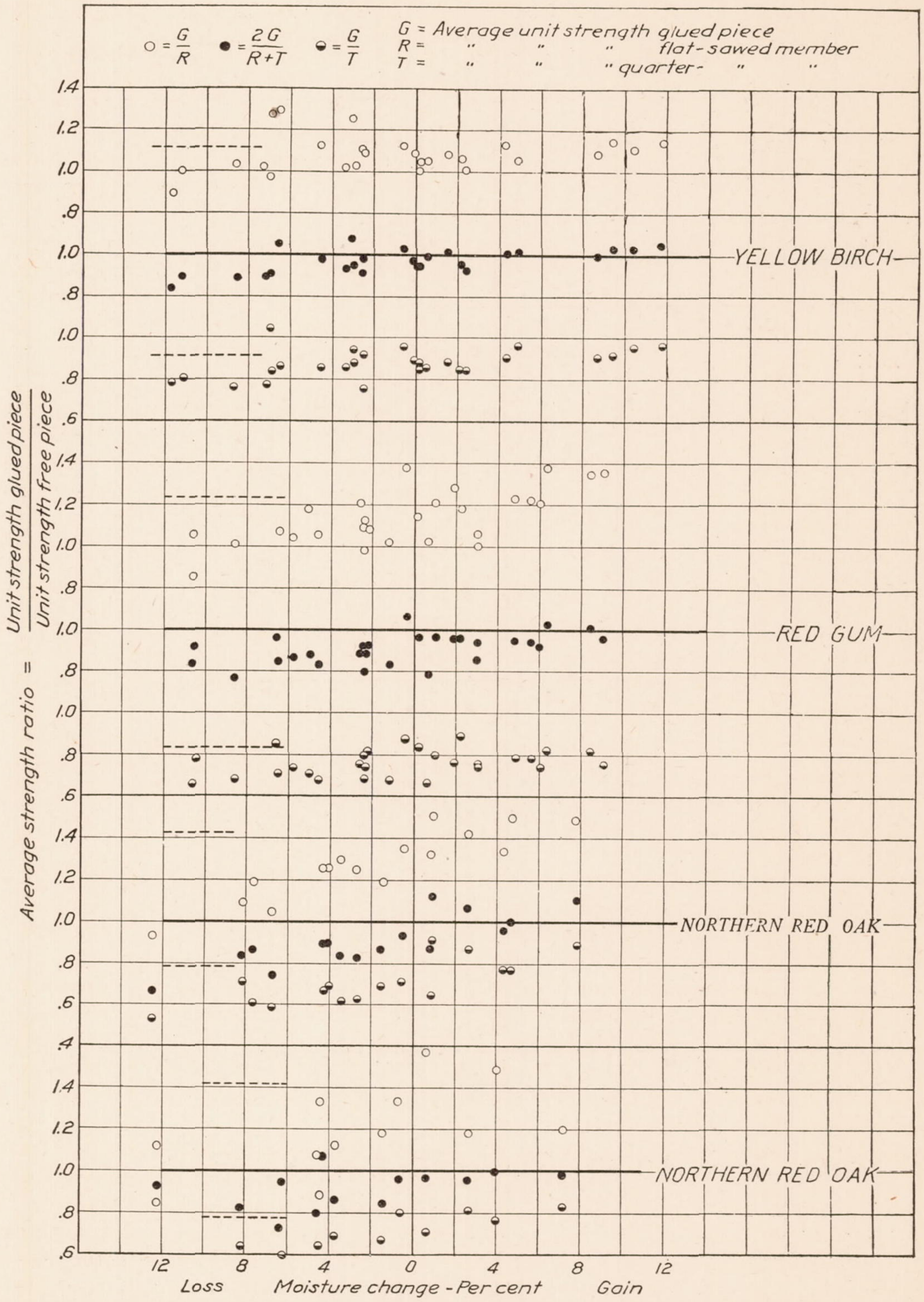


PLATE 4.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued of plain-sawed and quarter-sawed material) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

unity, and are not appreciably affected by change in moisture content after gluing. In the values for yellow birch, red gum, and northern red oak, however, there seems to be a reduction in strength as losses in moisture content take place after gluing. This inclination can not be due to difference in elastic properties of members in glued pieces, for such differences would be practically the same for all changes in moisture content. It is more likely due to the presence of internal stresses.

The specimens of plate 3 were manufactured and conditioned similar to those of plate 4. The shrinkage properties of all species are similar although different in degree; hence, if internal stresses are developed in one species, they might reasonably be expected in others, and the presence of internal stresses in some species but not in others seems inconsistent. The period of conditioning before test, however, was not uniform for all specimens. Central American mahogany, Philippine mahogany, and yellow poplar are species of wood which change moisture content rapidly and reach equilibrium in a constant atmospheric condition in a comparatively short time. The species in plate 4 are of greater density, change moisture content more slowly, and have greater radial and tangential shrinkage than those of plate 3, and would consequently develop greater stresses with moisture changes.

The conditioning data show that specimens of yellow poplar and Philippine mahogany were allowed to remain under constant atmospheric conditions for some time after constant weight had been reached, being tested after periods of 13 to 25 days in the final conditioning room. The values of 0.91 and 0.93 at moisture losses of 10.8 amd 9.5 per cent in Central American mahogany are from specimens tested after a period of only five to seven days, and the periods for values shown on plate 11 range from five to eight days. Apparently, where ratios of $\frac{2G}{R+T}$ have fallen off, indicating the presence of internal stresses, the specimens were tested after having been subjected to climatic change for only a short period, while in those permitted to condition under uniform atmospheric condition for longer periods before test, internal stresses were not present. Since the species for which these ratios showed internal stress require longer periods to reach equilibrium with climatic changes than the species for which the ratios showed no internal stress, the results indicate that the magnitude of internal stresses changes with time. The internal stresses are set up as swelling or shrinkage takes place, which in turn depends on the change in moisture content. After constant weight is reached, however, further stresses are not set up, and, judging from the results of this test, those already set up seem to die out.

Had the specimens for values in plate 4 remained in conditioning rooms for longer periods before test, their ratios would no doubt have approached unity, and if allowed to remain for comparatively long periods, would probably have equaled the ratio of specimens in which no moisture change took place.

The results of these tests do not permit us to study the rate of change of internal stress, either while in development, or while dying out. Neither can the maximum internal stress developed be determined from these results, for some tests were perhaps made while stresses were not fully developed, and in others the stresses at the time of test had already fallen below the maximum. Maximum internal stresses, however, would in all cases be as great or greater than any shown in this study.

Relation between tensile strength across grain of blocks made of all quarter-sawed boards as compared to blocks of all plain-sawed boards.—The relation between the tensile strength across grain of flat-sawed and of quarter-sawed material has already been given in Table 2. The tensile strength across grain (across the face of the board) of quarter-sawed material being greater, laminated stock of quarter-sawed material will develop the greatest strength in the direction of glue joints, and, because of its lesser shrinkage, will develop smaller internal stresses, acting parallel to the glue joints. Purely plain-sawed constructions produces the weakest structure in the direction of the glue joints.

The maximum strength that can possibly be developed in laminated construction is obviously the sum of the maximum strengths of the individual members. Where plain-sawed and quarter-sawed material are both used in the laminated construction, the maximum unit strength G occurs when it equals $\frac{R+T}{2}$, or $\frac{2G}{R+T}=1$. Using this maximum strength value of G as 1, the maximum unit strength of laminated construction containing both plain-sawed and quarter-sawed material compared to the unit strength of purely quarter-sawed construction becomes $\frac{R+T}{2T}=\frac{G}{T}$. Values of $\frac{G}{T}$ from the test are shown in Table B, and plotted in plates 10 and 11. This value was always found to be less than unity.

Values of $\frac{G}{T}$ and $\frac{G}{R}$ when $G=1$ are shown as dotted lines in plates 3 and 4. In the specimens made of northern red oak, values of $\frac{G}{R}$ were more variable when conditioned from a high moisture condition directly to a dry condition (lower set of data for northern red oak, plate 4) than when conditioned from a high to a low moisture content by successive steps (upper set of data for northern red oak, plate 4). This is perhaps due to the ease with which this species checks along the medullary rays in rapid drying. When once formed, these checks permanently reduce the radial tensile strength of the wood, for although swelling may again close the checks and make them invisible the loss in strength is permanent. Values of $\frac{G}{T}$ are not so affected since incipient shakes occur less frequently in this direction.

CONCLUSIONS FROM SERIES A TESTS.

From this series of tests it is concluded that—

1. Tensile strength across grain (across the face of the board) for quarter-sawed lumber is greater than for plain-sawed lumber. Plain-sawed lumber may be from 20 to 50 per cent weaker across the grain, depending upon the species and method of drying.

2. The gluing together of plain-sawed and quarter-sawed stock gives rise to the development of internal stresses through unequal swelling and shrinkage with changes in moisture content, and results in a weakening across grain of the laminated structure.

3. When a laminated structure containing both quarter-sawed and plain-sawed members is subjected to conditions which cause a change in moisture content, the unequal swelling or shrinkage of different members induce stresses. These stresses reach a maximum and then gradually die out. The structure is then free from internal stresses but has assumed new dimensions; and, if the elastic limit of the wood has not been exceeded, the strength has not been affected. With each change of moisture content new stresses will be developed.

ANALYSIS OF RESULTS OF SERIES B.

THE INFLUENCE OF COMBINING MATERIAL OF UNEQUAL MOISTURE CONTENT ON THE STRENGTH OF LAMINATED CONSTRUCTION.

Test specimens for this series of tests were made of the following species, as outlined in the working plan:

Central American mahogany.
Philippine mahogany.
Hard maple.
Yellow poplar.
Yellow birch.
African mahogany.
Northern white oak.
Northern red oak.
Red gum.

Specimens were manufactured in which the moisture content of the core differed from that of the faces by various amounts. The material for any species was either entirely plain sawed or entirely quarter sawed and within specimens was uniform in density. Specimens as before described were subjected successively to various atmospheric conditions before test.

The properties of hide glue were found to affect materially some of the results of this test. Hide glue is hygroscopic, and its strength varies rapidly with moisture changes. When exposed to a 90 per cent relative humidity, this glue softens until it has very little strength, and glue joints open, as shown in plate 5. Plate 6 shows the result of attempting to glue together laminations of red oak at 18 per cent moisture content. Sufficient water did not leave the glue to permit it to set and develop its full strength.

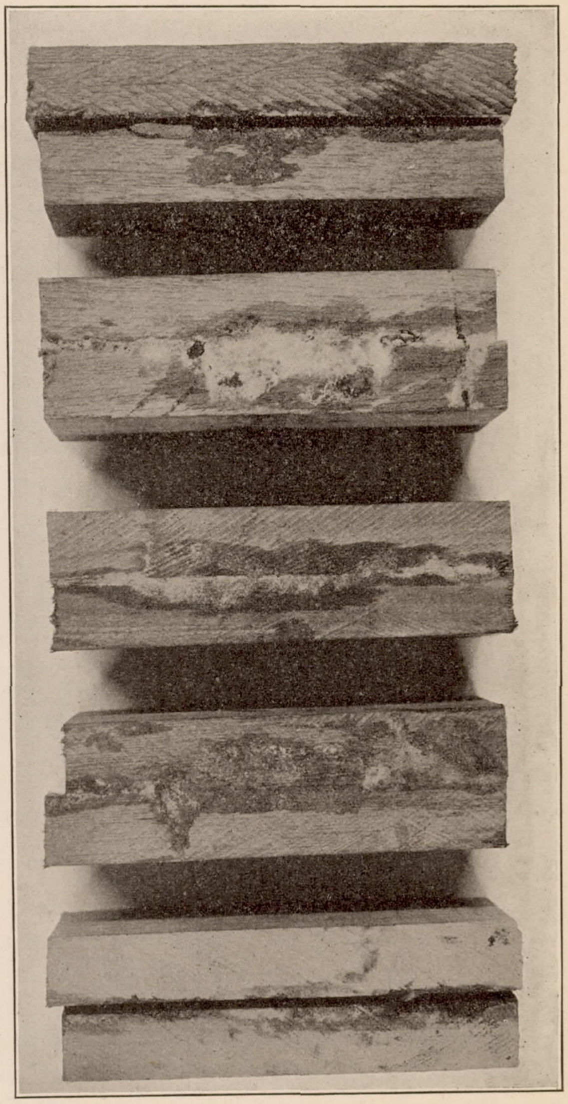


PLATE 5.—Showing failure of glue joints when subjected to high humidity conditions.

In this series the specimens glued at 18 per cent moisture content showed no adhesion until the moisture content of the wood had been reduced to the point of setting. By this time, the dry members of the series had absorbed moisture and the actual difference in moisture content between core and faces at the time when the glue was able to transmit stress was much less than when the pieces were first assembled. The development of internal stress in these specimens would therefore correspond to moisture difference when the glue had set enough to transmit stresses, rather than to the original moisture difference.

In the conditioning of specimens, this factor again appeared. Upon entering an atmosphere of 90 per cent relative humidity, the glue softened within a few days, and members of specimens under stress were permitted to move over each other, thereby relieving the stress. The initial stress having disappeared and no further source of internal stress being present, all subsequent tests would show complete regain in strength.

HARD MAPLE (pl. 7).

Specimens of this species were made of plain-sawed material. Those glued with moisture differences of 11 per cent began to check and split open soon after gluing, as illustrated in plate 8. The shrinkage of the wet member and the swelling of the dry member in coming to a common moisture content were so rapid in these specimens that stresses beyond the strength of the wood were developed and failure resulted. Specimens similarly manufactured which did not check and split open showed low strength ratios upon being tested from the glue room, but after being conditioned in room 1 or 3, showed a considerable regain in strength, and continued to regain strength with further conditioning. Similar results were obtained on specimens glued at smaller moisture differences, indicating that the magnitude of the internal stresses was decreasing with continued conditioning. In practically all cases, specimens conditioned in a high humidity showed remarkable regain in strength, due probably to softening of the glue and consequent release of stresses.

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Results of tests on specimens glued at uniform moisture content were quite uniform, indicating that where stresses are not developed, variations for the species are quite small. The elastic properties of members of glued specimens being quite similar, no variation in strength ratios would be expected from this source.

Philippine mahogany (pl. 9).

Specimens of this species were made of plain-sawed material. Results of these tests were much more uniform than in maple and no failures directly after gluing were recorded. Even with initial moisture differences of 8 and 11 per cent, specimens tested from the glue room showed a maximum of only 10 to 20 per cent reduction in strength, and this was reduced by further conditioning until it fell within the strength variations for this species. As in the series

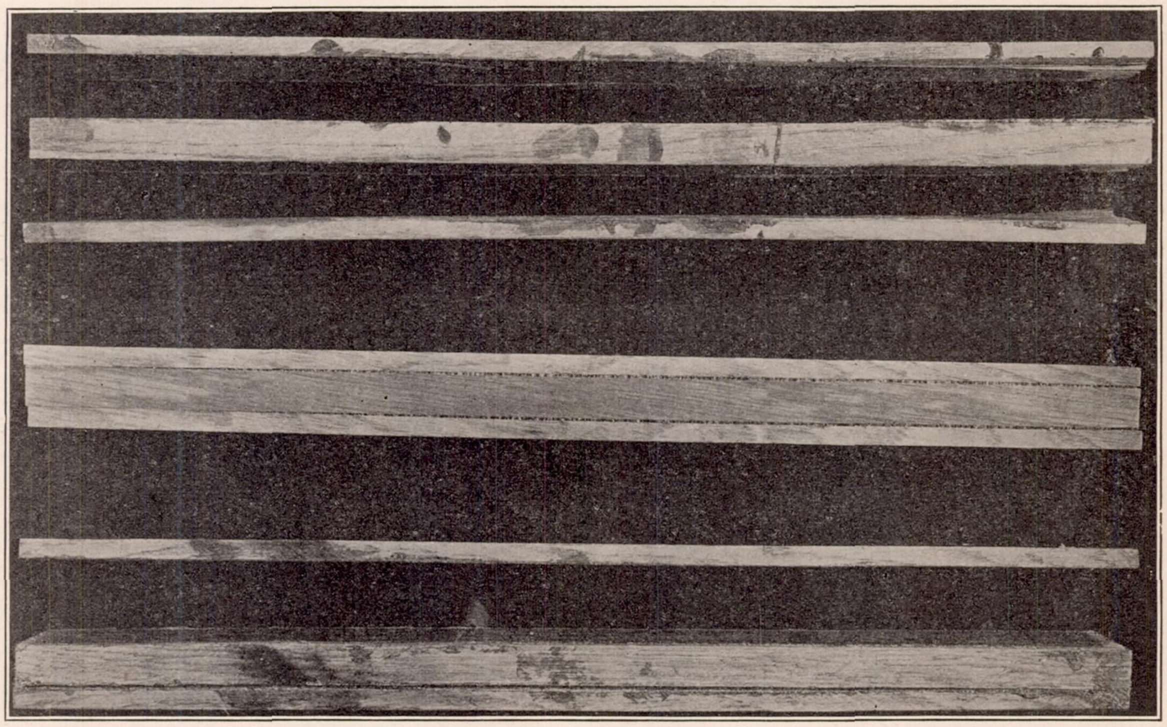

Plate 6.—Showing glue joint failures (northern white oak). Pieces glued at 18 per cent moisture content and held under pressure for 24 hours.

of plain-sawed and quarter-sawed specimens, a comparatively longer period of conditioning was given specimens of Philippine mahogany, permitting reduction in internal stress to take place before test.

Central american mahogany (pl. 10).

Specimens of this species were made of plain-sawed material. This species changes moisture content rapidly, and its radial tensile strength across grain is low and somewhat variable, resulting in a large variation in strength ratios, even when the specimens were glued at uniform moisture content. In specimens glued with moisture differences between face and core, results were more variable, regain in strength being found in some specimens and apparent loss in strength being found in others.

There seemed to be a general inclination toward higher strength ratios at low moisture contents. If the glue film adds any strength, its effect on the strength ratio would be most apparent in species of low tensile strength, across grain and at low moisture contents, at which glue has its greatest tensile strength. This may be partly responsible for such inclination in this species.

Yellow birch (pl. 11).

Specimens were made of plain-sawed naterial. Moisture changes take place comparatively slowly in this species, and the radial tensile strength across the grain is comparatively high.

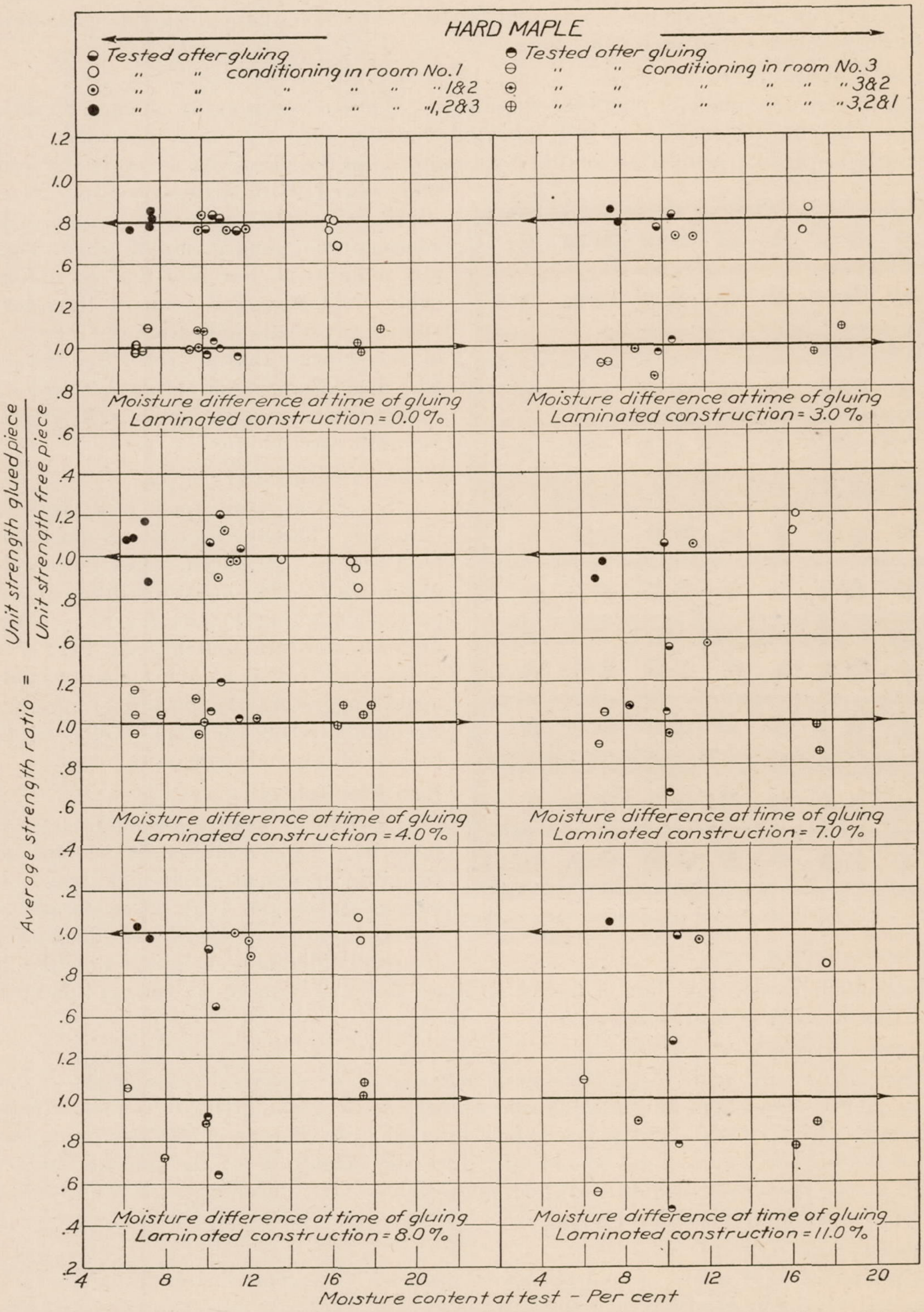

PLATE 7.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

Consequently, strength ratios were more uniform. In specimens manufactured with large moisture differences no great development of internal stress appeared when tests were made on them directly on leaving the glue room, and further conditioning brought practically all results within the strength variation for this species.

Yellow poplar (pl. 12).

Specimens were made of plain-sawed material. This species is easily affected by moisture changes. Results from other species indicated that moisutre differences of 3 per cent were practically negligible; hence this condition was omitted in this test. As shown in the series on plain-sawed and quarter-sawed specimens, the study on yellow poplar was extended over a comparatively long period of time. This was not intentional, but was due to unforeseen delays in testing. Results of tests for this species gave little indication of stress at time of test, showing that if stresses had developed, they had disappeared before test to such an extent that strength ratios fell within the strength variation for the species.

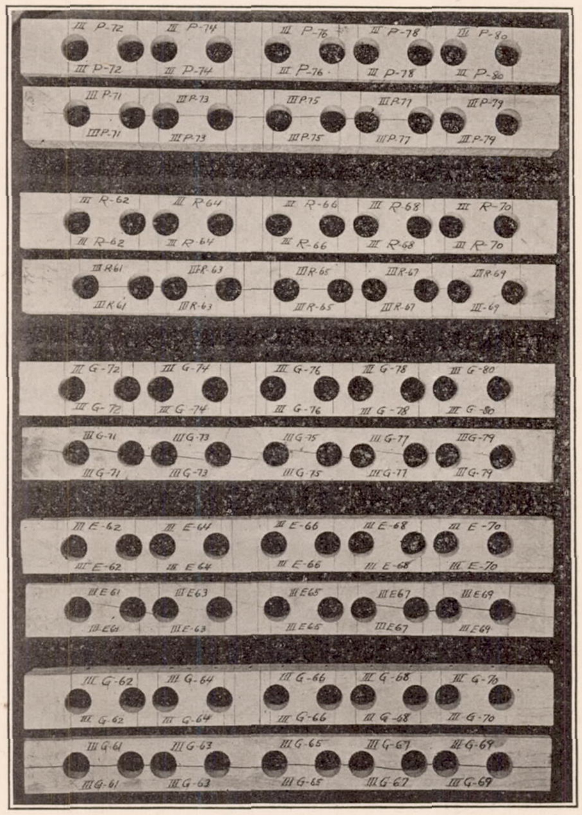

Plate 8.—Laminated maple showing tension failures due to moisture difference at time of gluing. Odd numbers indicate glued pieces. Even numbers indicate free pieces.

African mahogany (pl. 13).

Specimens were made of quarter-sawed material. This species changes moisture content readily. Strength ratios for specimens glued with large moisture differences were only slightly lower than for those glued at uniform moisture content, and were a maximum when tested at low moisture contents, again suggesting the possibility of glue-film strength affecting the ratio. Only slight indications of internal stress were found.

Red gum (pl. 14).

Specimens were made of quarter-sawed material. Tangential tensile strength across the grain is comparatively high, and moisture change takes place at a moderate rate. Strength ratios of specimens glued at large moisture differences showed as much as 20 per cent reduction in strength, but in nearly all cases this was reduced by further conditioning, indicating the dying out of stresses.

Northern white oak (pl. 15).

Specimens were made of quarter-sawed material. This species changes moisture content slowly, and possesses high tangential tensile strength across grain, giving rather small variation in strength ratios. Only slight indications of internal stress at time of test were found, and in such cases further conditioning served to reduce the magnitude of the internal stress. No doubt if the specimens had been tested immediately after reaching moisture equilibrium, greater stresses would have been found.

Northern red oak (pl. 16).

Specimens were made of quarter-sawed material. Tangential strength across grain is comparatively high, resulting in a small strength-ratio variation, and moisture changes take place slowly. Specimens were tested after conditioning in the glue room only. Indications of internal stress were slight, even for specimens manufactured with high moisture differences. This was probably due to the long conditioning period. Further conditioning served to reduce the magnitude of internal stresses until they fell within the strength variation for the species.

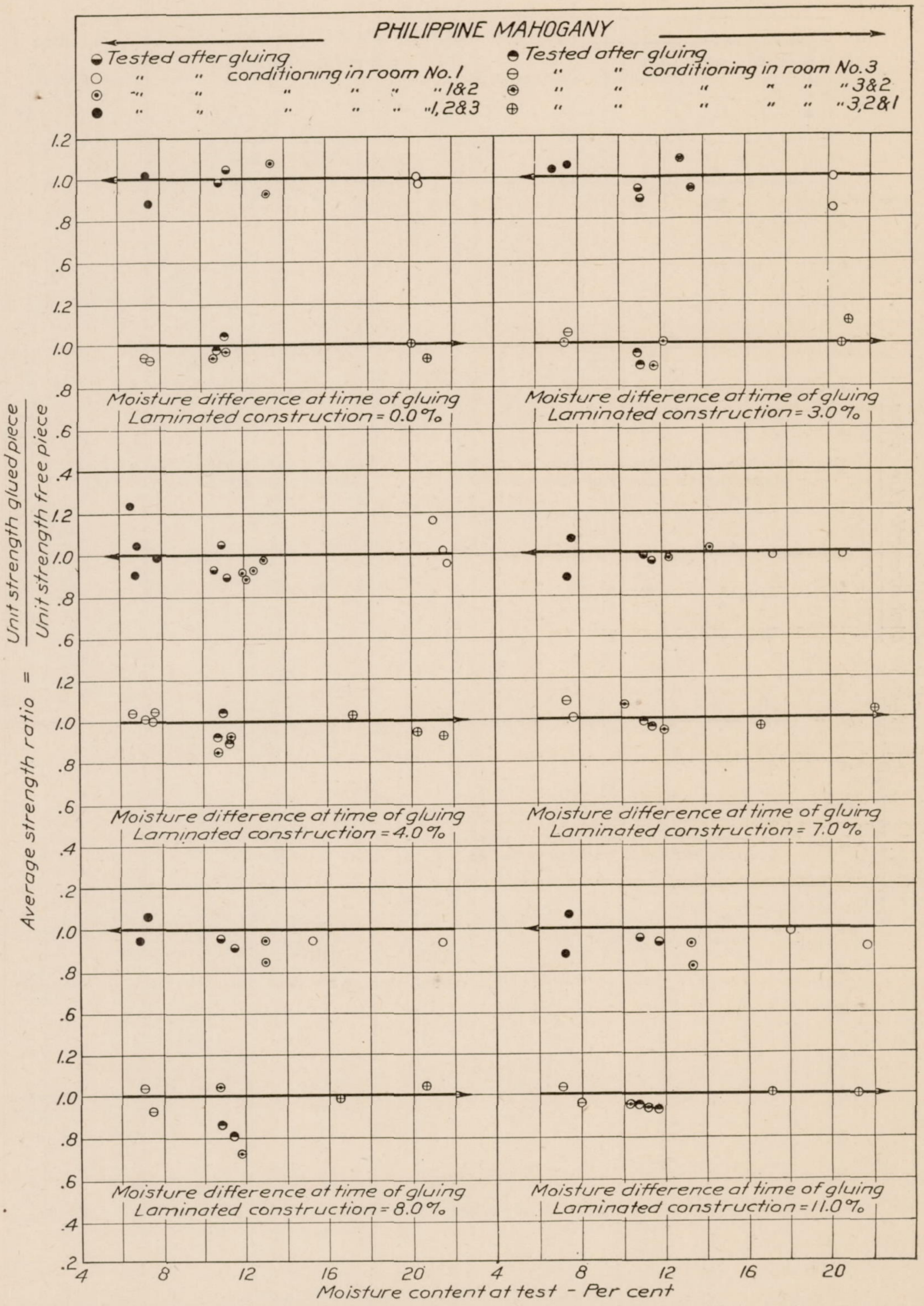

PLATE 9.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

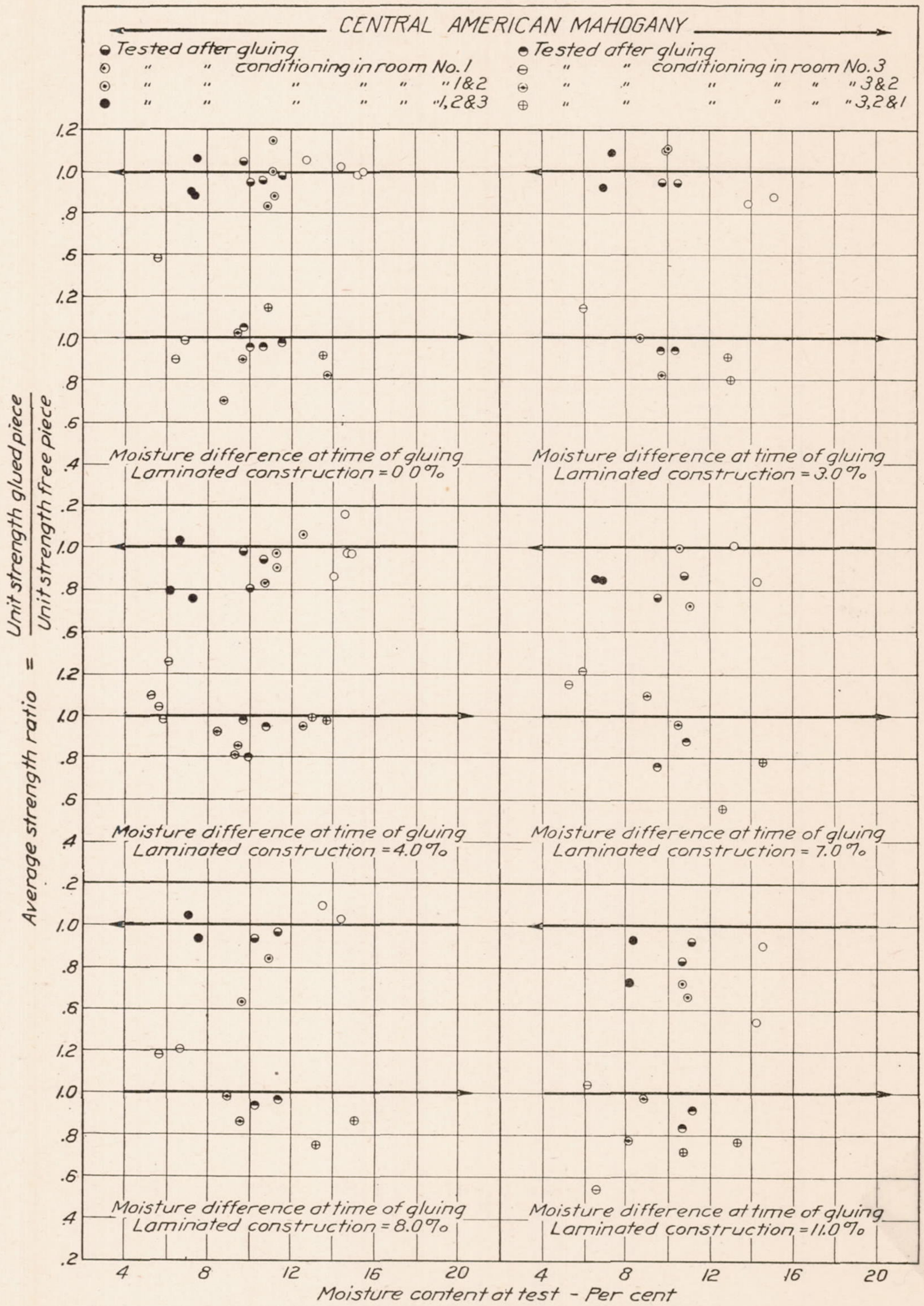

PLATE 10.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

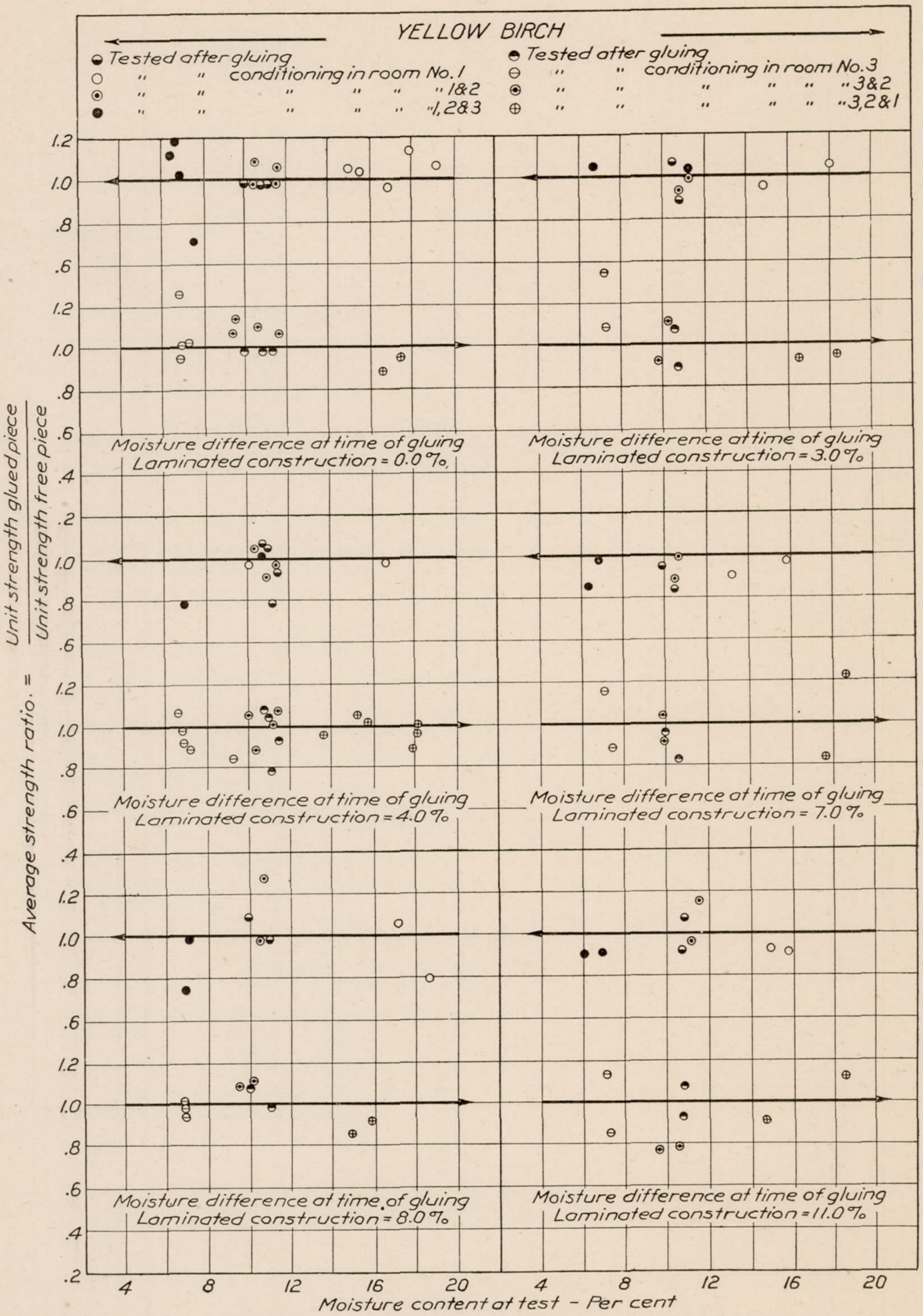

PLATE 11.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

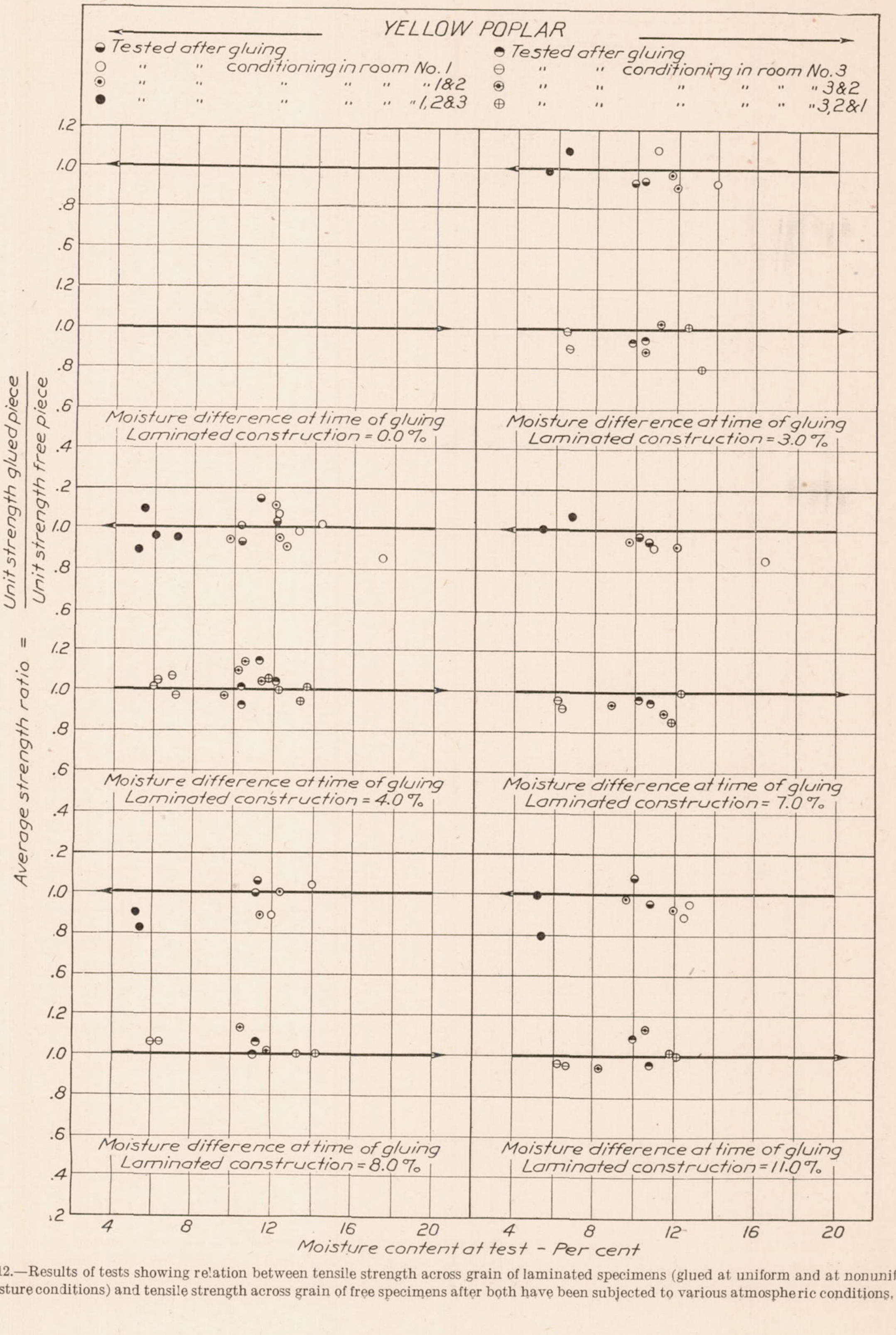

PLATE 12.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

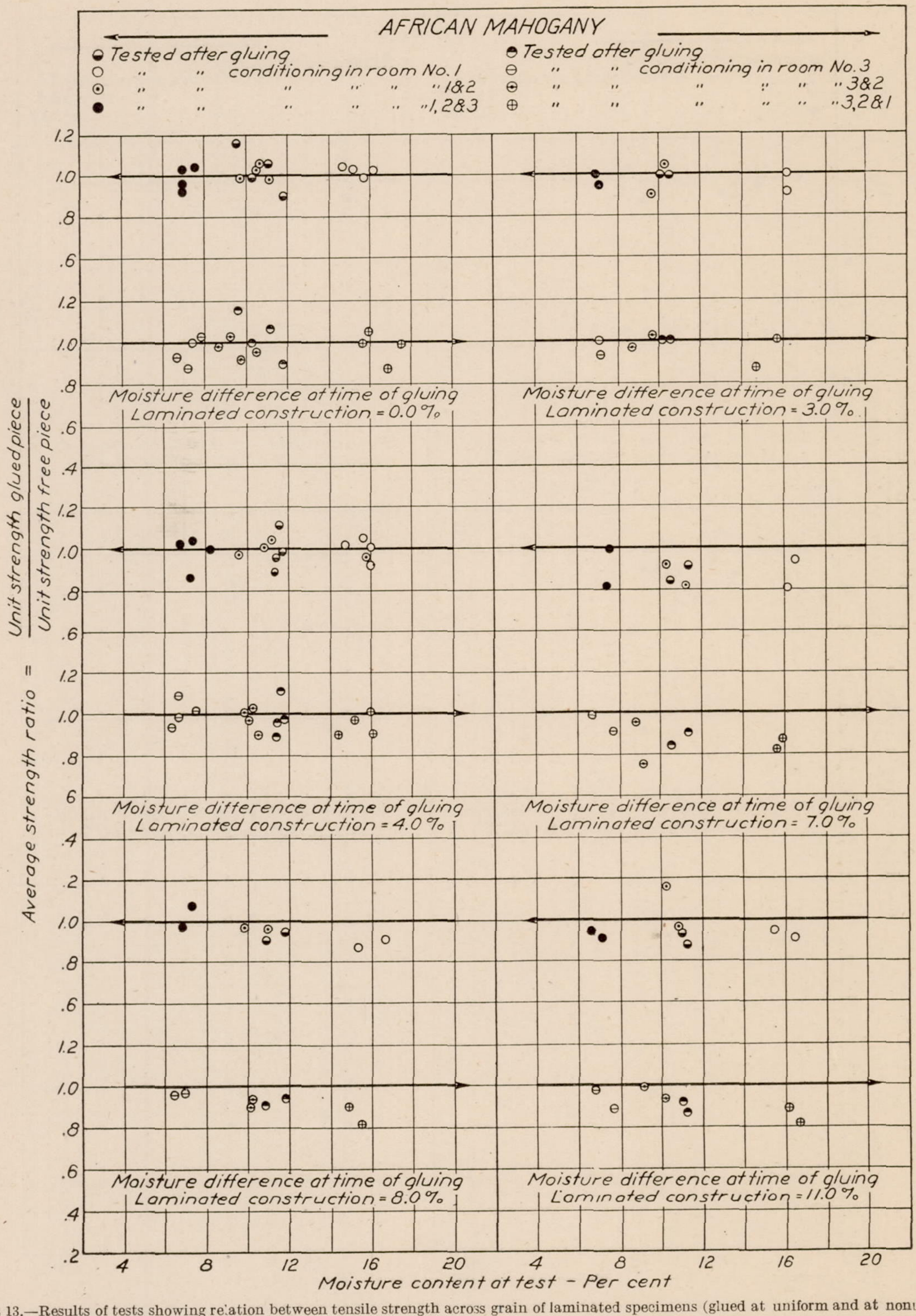

PLATE 13.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

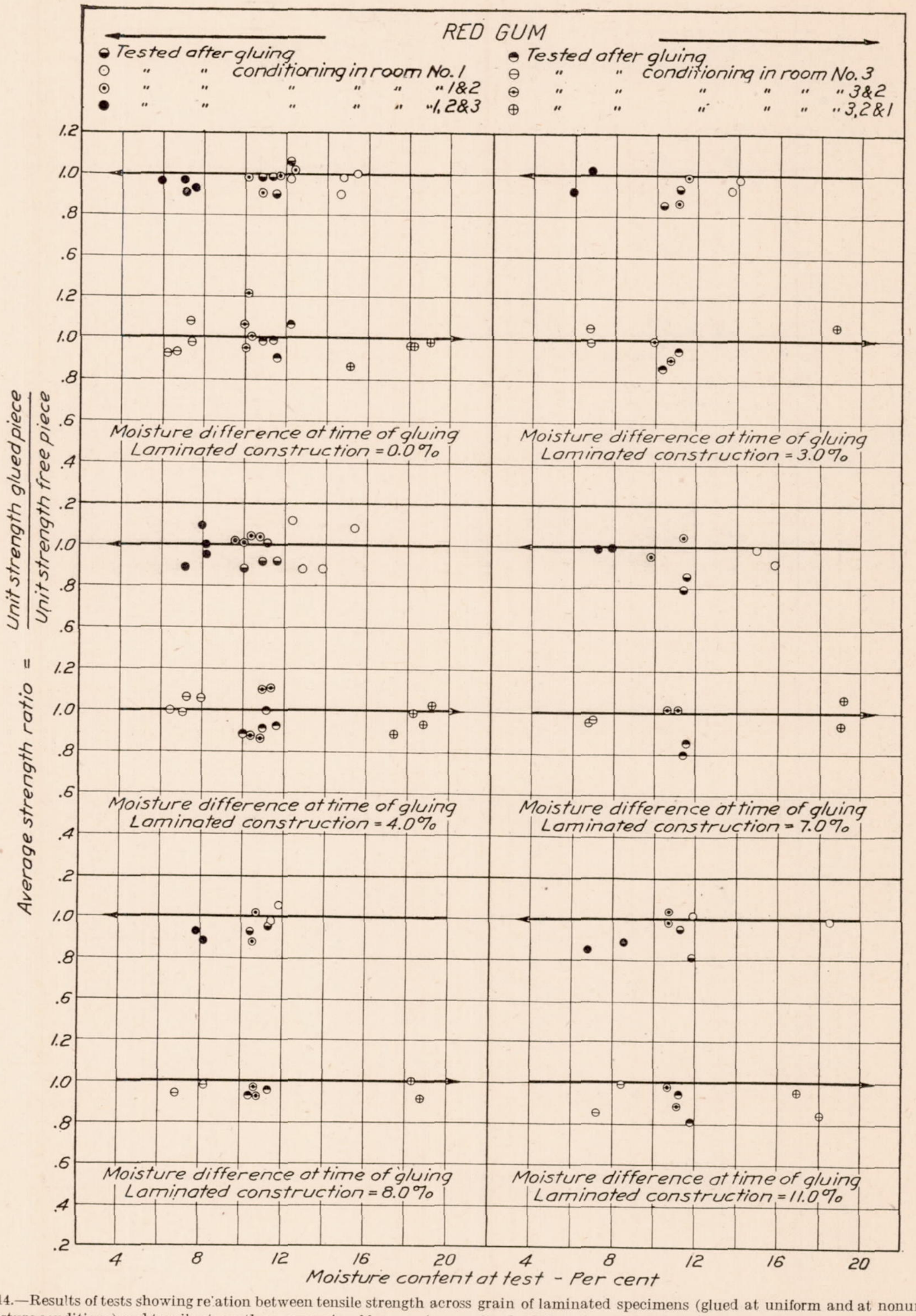

PLATE 14.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

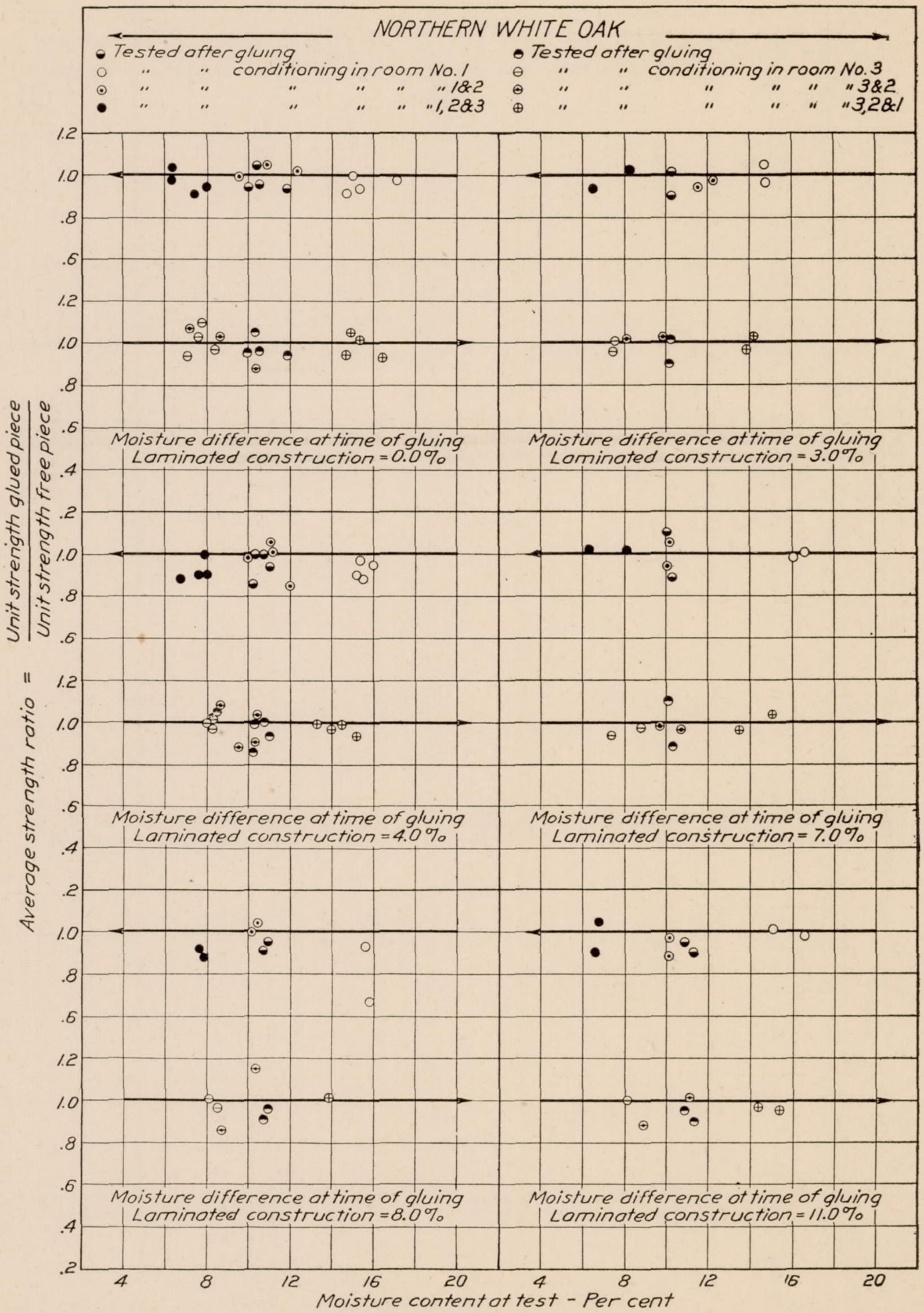

PLATE 15.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

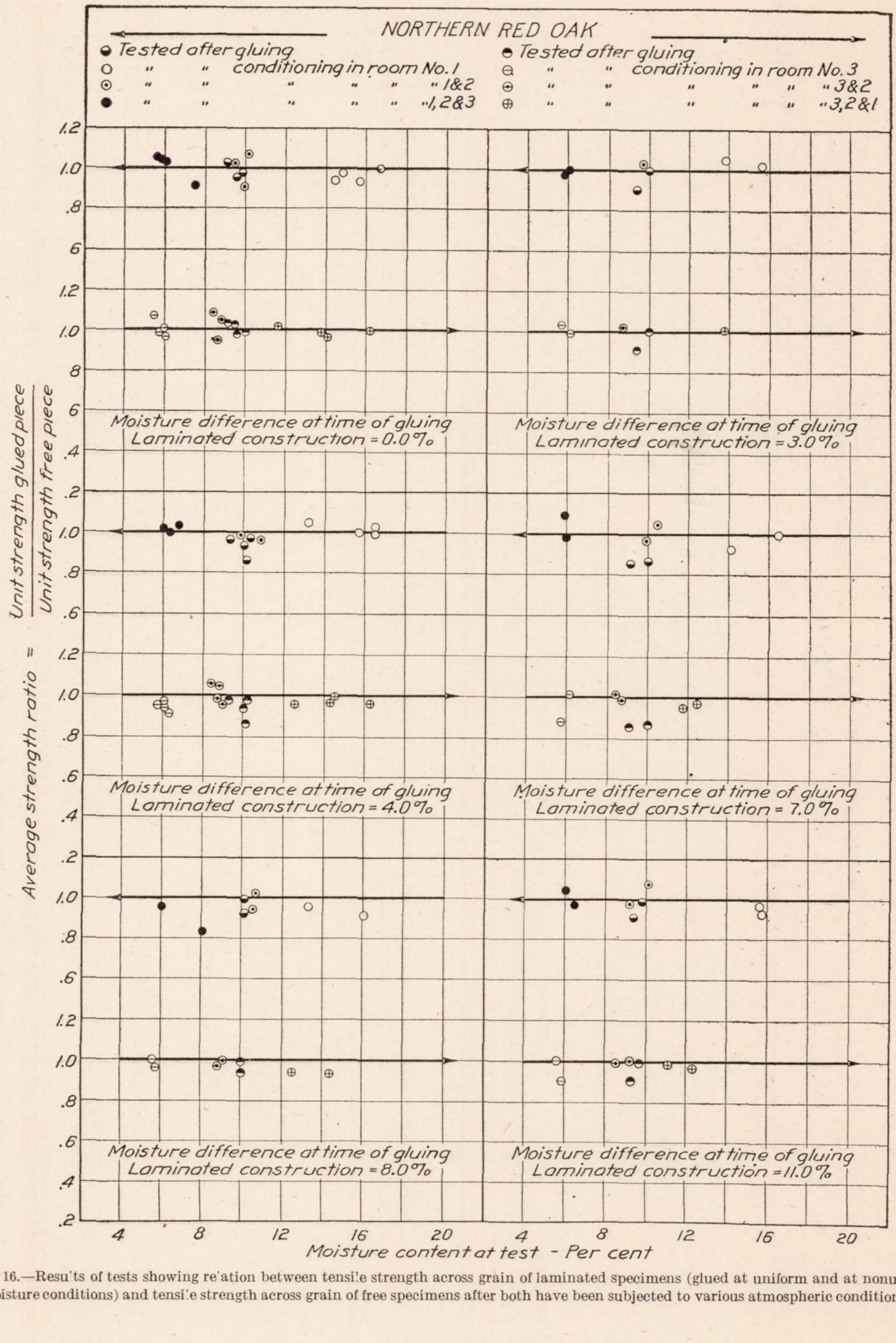

PLATE 16.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued at uniform and at nonuniform moisture conditions) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

That internal stresses of serious magnitude can be developed by gluing together material of different moisture contents is shown by the failure of maple specimens soon after manufacture. While this action occurred only in the maple specimens for which the rate of shrinkage was high, internal stresses would likewise be set up, to a lesser degree perhaps, in the other species with relatively high rates of shrinkage. The rapid regain in strength in maple specimens which did not fail immediately after gluing, shows that the internal stresses are developed to a maximum and then die out, probably at a constantly decreasing rate. The results for other species conform to the same theory and indicate that if specimens are allowed to condition for a long period of time, internal stress will completely disappear.

CONCLUSIONS FROM SERIES B TESTS.

From this series of tests the following conclusions seem warranted:

1. The gluing together of laminations of different moisture contents gives rise to internal stresses on account of the unequal swelling and shrinkage as the laminations approach a common moisture content. This results in a weakening across the grain of the structure, which may be of sufficient magnitude to cause rupture of members of the laminated structure.

2. When a laminated structure is composed of members whose moisture contents are not the same, the moisture in the wood tends to equalize, and stresses are set up in the structure through unequal shrinkage or swelling of the members. These stresses die out, leaving the structure stress-free but with changed dimensions: and, if the elastic limit of the wood has not been exceeded, the strength is not affected. If the structure is subjected to further moisture change, no stresses are induced, since all members have reached the same condition and act together.

3. Animal glue used in these tests does not set properly when the laminations are of rather high moisture content. The exact point where unsatisfactory results occur can not be determined from the data secured, but it appears to be between 15 and 18 per cent. Also, glued specimens placed under conditions tending to produce a moisture content of from 15 to 18 per cent in the wood indicate that the glue softens and permits the laminations to be easily pulled apart.

ANALYSIS OF RESULTS OF SERIES C.

THE INFLUENCE OF COMBINING HIGH-DENSITY AND LOW-DENSITY MATERIAL ON THE STRENGTH OF LAMINATED CONSTRUCTION.

Glued and free specimens were made in which faces and core differed in density. The direction of the annual rings within a species and the moisture content at gluing were made uniform.

In this series the elastic properties of the wood also affect strength ratios of the test, high-density wood usually having greater strength [7] and elasticity than low-density wood. Results of the tests are shown in plates 16 to 21, inclusive.

CENTRAL AMERICAN MAHOGANY.

This is a species of relatively low radial tensile strength across the grain. Small variations in strength result, therefore, in considerable variation of strength ratios, as seen in plate 16, where laminated specimens of uniform density gave variable results with or without moisture changes. Theoretically, these specimens developed no internal stress with moisture changes, and the strength ratios should equal unity.

In the specimens made of mixed-density material, greater variations were obtained, possibly due to variation in elastic properties, to the presence of internal stresses, or to both. Internal stresses should come, however, only with changes in moisture content, because the laminations were brought to equilibrium before being glued. Specimens in which moisture changes had taken place showed only slight reduction in strength ratio below those having no change in moisture content, indicating that if internal stresses were present, they were of small magnitude.

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[7] Bulletin No. 676, U. S. Department of Agriculture, "The Relation of the Shrinkage and Strength Properties of Wood to its Specific Gravity," by J. A. Newlin and T. R. C. Wilson.

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HARD MAPLE.

This is a species of relatively high radial tensile strength across the grain, and strength ratios (pl. 17) for specimens of uniform density were less variable than for Central American mahogany. Although greater variation of strength ratios, due probably to variation in elastic properties, is found in specimens of mixed density, average ratios remain the same for all moisture changes, indicating that only slight, if any, internal stresses were present at time of test.

PHILIPPINE MAHOGANY.

This is a species of relatively low radial tensile strength across the grain, and strength ratios for this species (pl. 18) were somewhat variable for specimens of uniform density. Specimens of mixed density gave strength ratios somewhat more variable, but with the same average over all ranges of moisture change, indicating but slight, if any, internal stresses present at the time of testing.

YELLOW POPLAR.

This is a species of medium but variable radial tensile strength across the grain, giving quite variable strength ratios, even for specimens of uniform density material (pl. 21). Specimens of mixed density material showed a similar variation in the tensile strength across grain, but indicated at the time of test no development of appreciable internal stresses due to change in moisture content.

YELLOW BIRCH.

This is a species of relatively high radial tensile strength across the grain, and strength ratios for uniform density specimens are only moderately variable (pl. 19). Specimens of mixed density gave no indication of internal stress development with moisture changes, except those having greatest density difference $\left(\frac{D}{D'}=.779-.761\right)$. The values here are so few, however, that they can not be taken to indicate serious stress conditions inconsistent with values for specimens of other densities.

AFRICAN MAHOGANY.

This species is of comparatively low tangential tensile strength, and quite variable strength ratios were obtained for specimens of uniform and of nonuniform density material. The results (pl. 18) do not indicate moisture changes causing any serious development of internal stress at time of test.

NORTHERN WHITE OAK.

This species is of comparatively high tangential tensile strength across the grain, giving uniform strength ratios (pl. 20). Specimens of mixed density gave strength ratios as great as those of uniform density, indicating that there were no internal stresses at time of test.

NORTHERN RED OAK.

This species also possesses relatively high tangential tensile strength across the grain, and the strength ratios (pl. 20) are comparable in uniformity with those of other species. No indications of internal stress at time of test were found.

RED GUM.

This species is lower in tangential tensile strength across grain than the oaks and is also more variable. Results (pl. 19) for specimens of mixed density do not indicate lower strengths than for those of uniform density, nor were internal stresses apparent at time of test.

CONCLUSIONS FROM SERIES C TESTS.

The results of these tests do not indicate that internal stresses of any serious magnitude are developed by the unequal shrinkage properties of material of rather extreme densities within the species studied. While stresses may be set up in laminated construction containing material of the various densities found within a species, they are apparently of small magnitude and within a comparatively short time become so small that they fall within the variation of the strength properties.

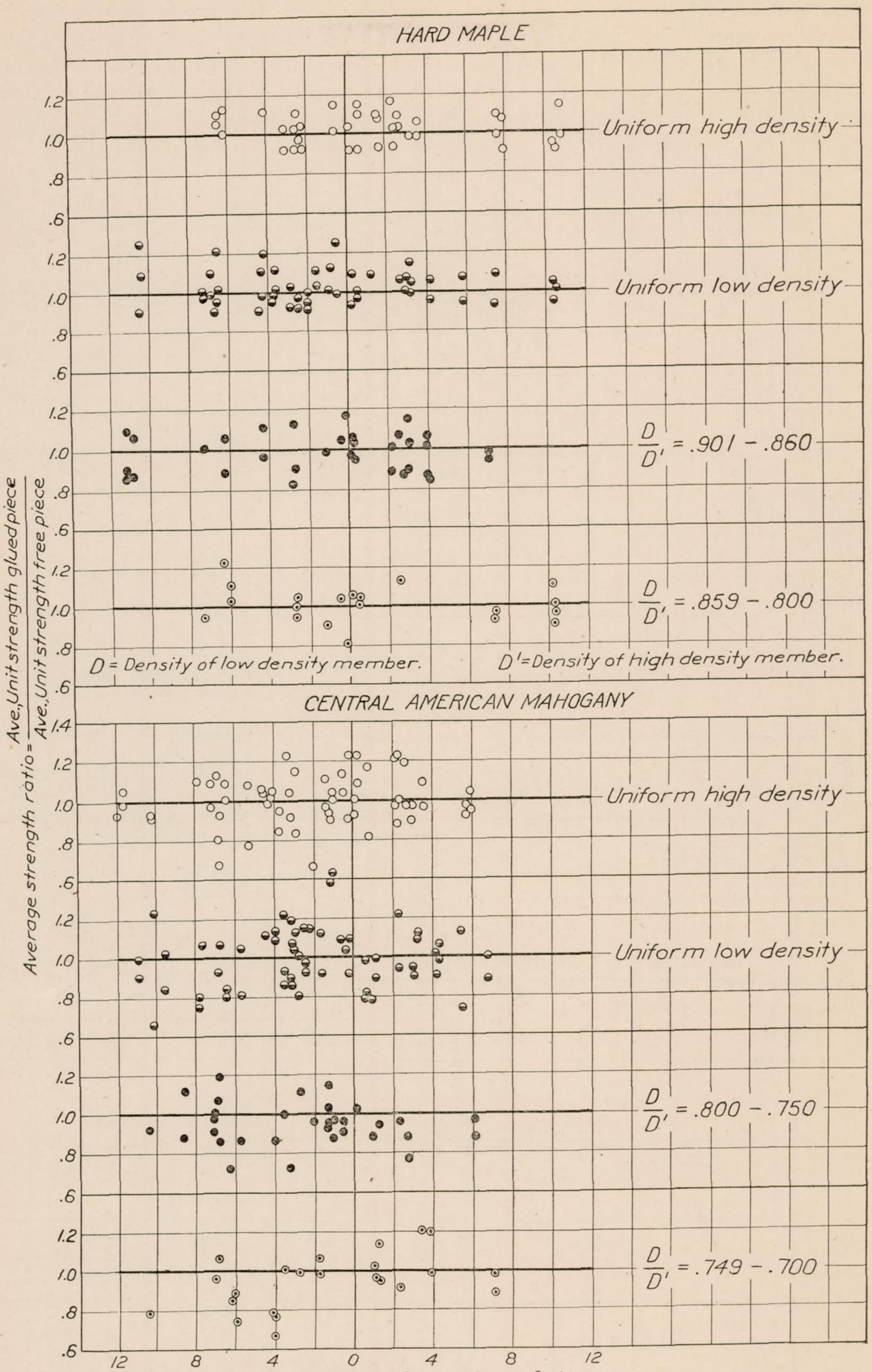

PLATE 17.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued of uniform density and of non-uniform density stock) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

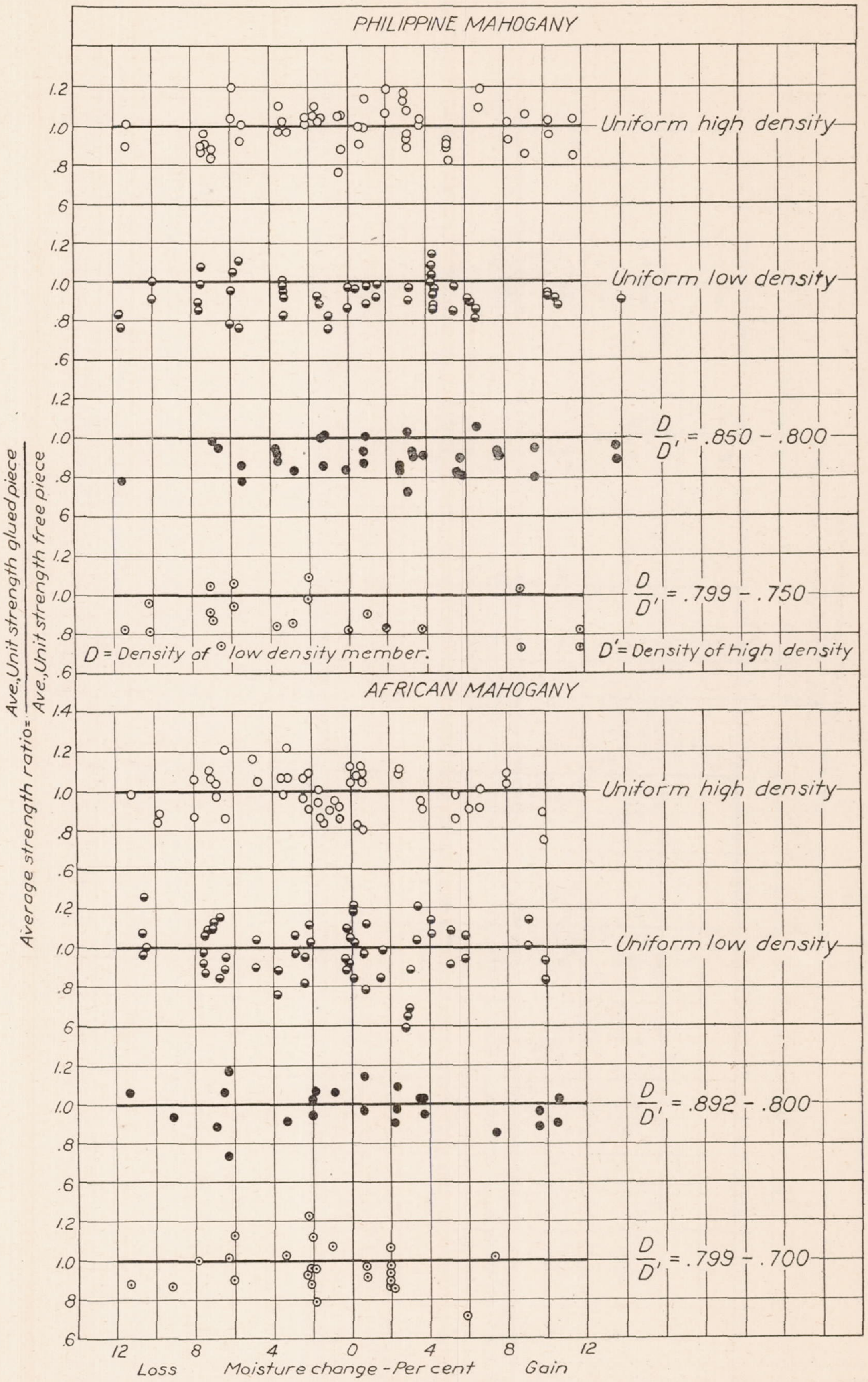

PLATE 18.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued of uniform density and of non-uniform density stock) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

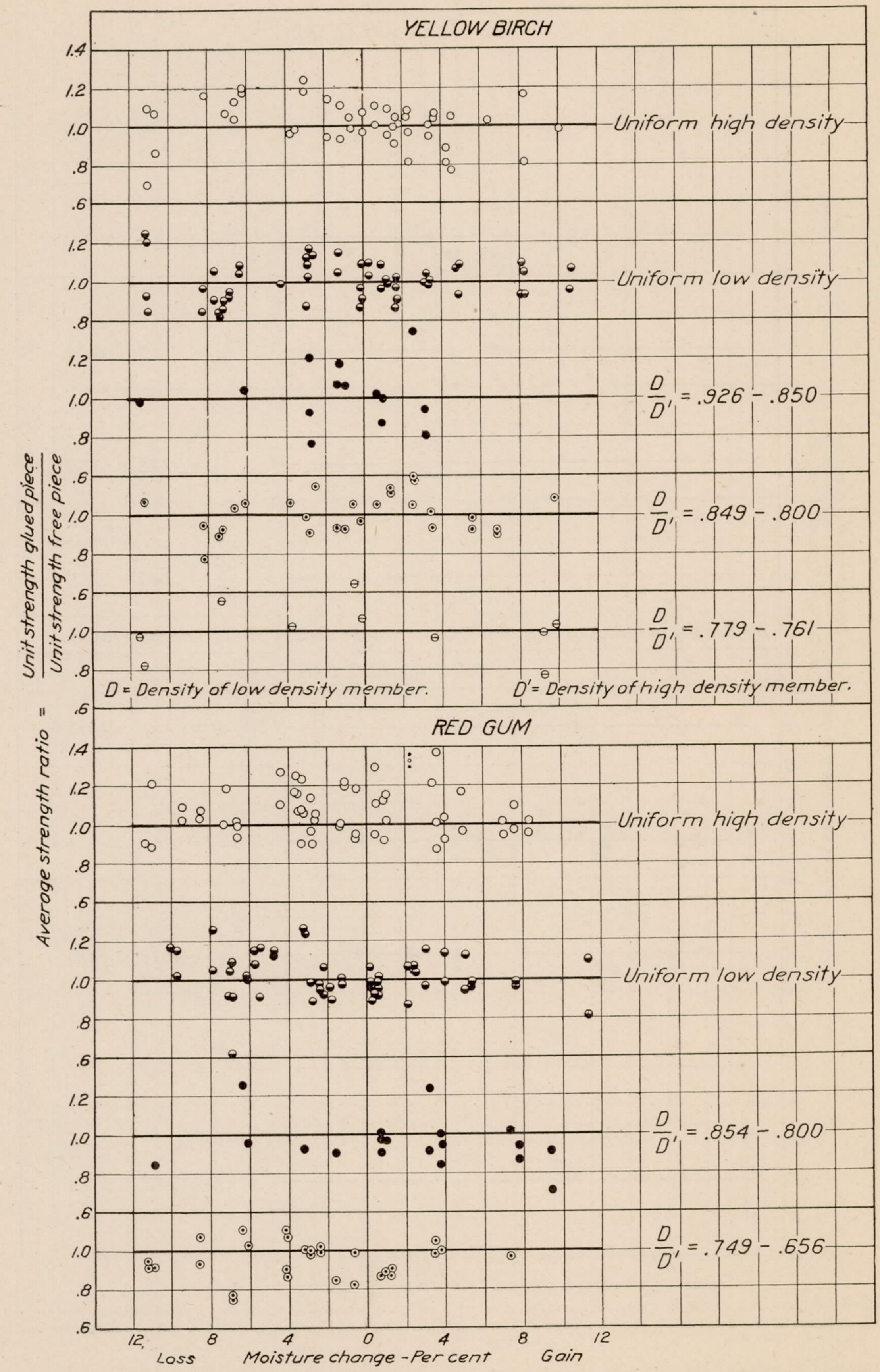

PLATE 19.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued of uniform density and of non-uniform density stock) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

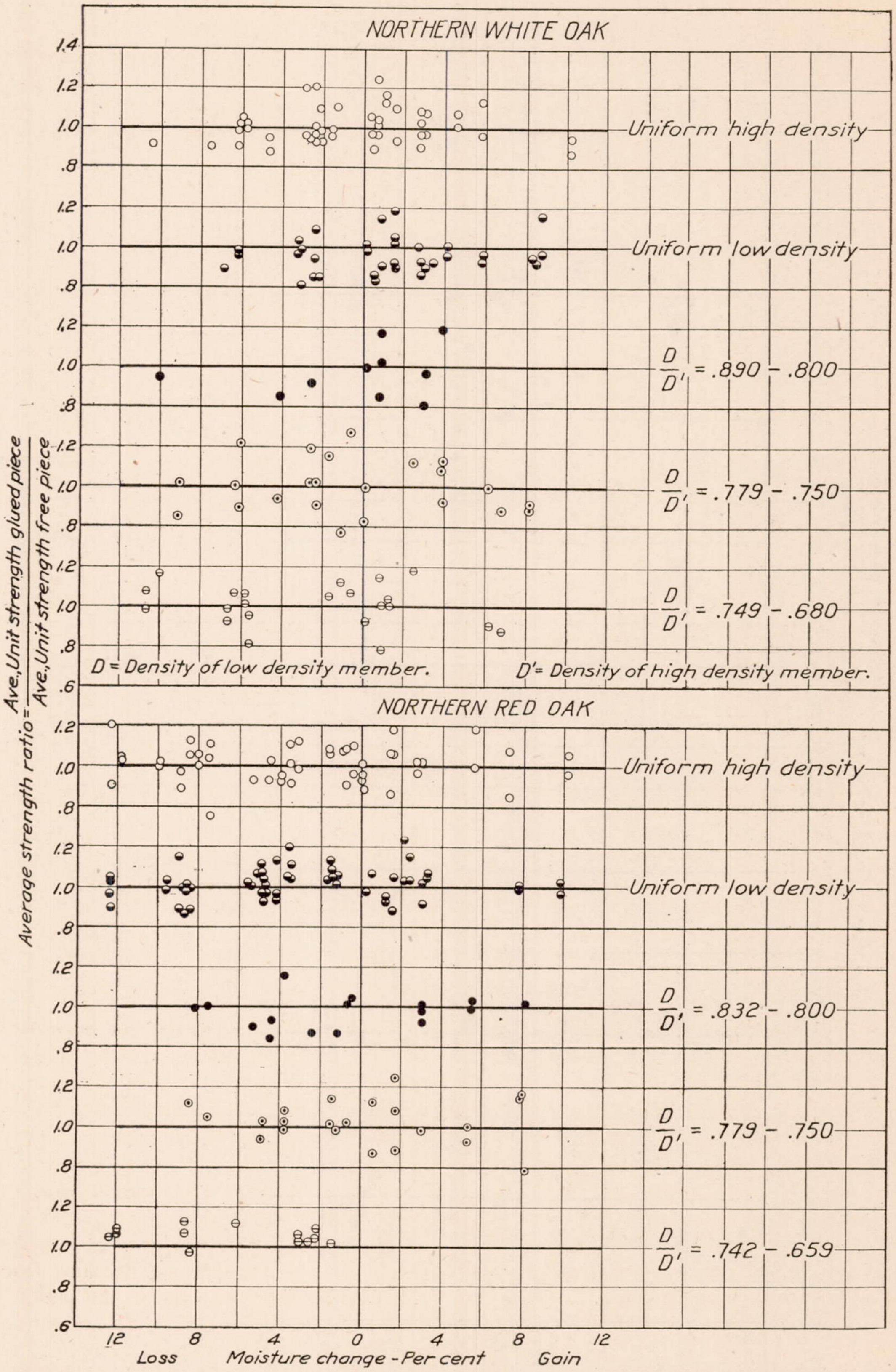

PLATE 20.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued of uniform density and of non-uniform density stock) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

From this series of tests the following conclusion appears warranted:

When laminations of very high and very low densities are combined to form a laminated structure, change of moisture content induces stresses on account of the unequal shrinkage or swelling of the members. These stresses disappear, and, if the elastic limit of the wood has not been exceeded, only a change in dimension results. Further changes in moisture content induce new stresses. Within a single species the stresses so induced are relatively small, however, and not likely to be serious except in extreme cases.

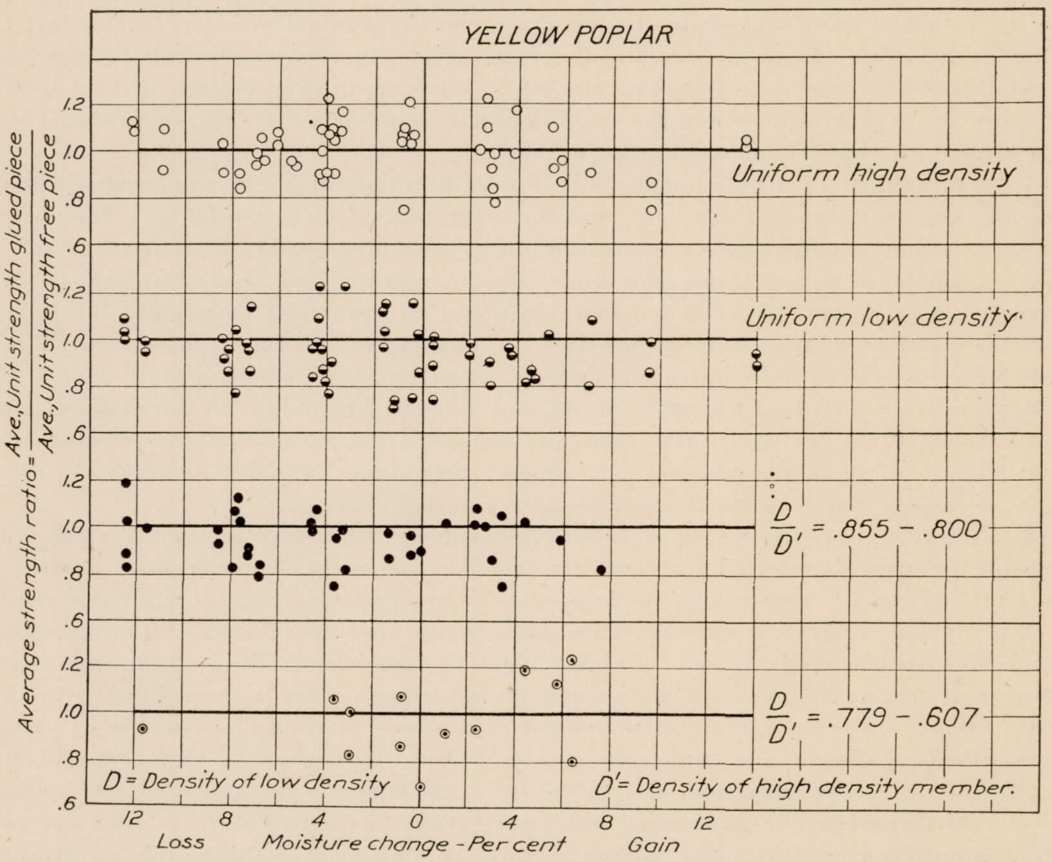

PLATE 21.—Results of tests showing relation between tensile strength across grain of laminated specimens (glued of uniform density and of non-uniform density stock) and tensile strength across grain of free specimens after both have been subjected to various atmospheric conditions.

DISCUSSION OF RESULTS.

The outstanding feature of this series of investigations is the decrease in magnitude of internal stresses with time. Although shrinkage governs the development of internal stresses, the time factor affects the permanency of these stresses. In laminated construction containing plain-sawed and quarter-sawed material, results showed internal stresses in specimens tested after a comparatively short period of conditioning, but showed absence of such stresses where specimens were conditioned for comparatively long periods before test, due consideration being given to the rate of moisture change peculiar to the species. Thus there is strong indication that internal stresses die out under constant uniform atmospheric conditions.

Evidence from the series in which material of different moisture contents was glued together showed development of internal stresses in some specimens of maple sufficient to cause rupture. In other specimens similarily made, which did not fail under internal stresses and which were allowed to condition under uniformly constant atmospheric conditions, there was evidence of a remarkable regain in strength, corroborating further the theory that internal stresses die out in time, provided atmospheric conditions remain constant. Results from the other species of this series showed the development of internal stresses to a lesser extent, and likewise showed regain in strength with continued conditioning.

The series in which variable shrinkage due to density difference was studied indicated that stresses developed from this source are much less significant than those caused by moisture differences at time of gluing, or by the combining of plain-sawed and quarter-sawed material. The results have shown that internal stress in numerous species disappears under constant atmospheric conditions, but the specimens suffered permanent deformation. This must be due to a property of the wood fiber, by virtue of which it may be deformed and develop resistant stress, but in which the stress gradually disappears, leaving the deformation permanent. Such property must be inherent in the wood itself, irrespective of the source of internal stress, and the theory explains the dying out of internal stresses in the laminated specimens of these tests. In order, however, that the strength of the wood shall not be permanently reduced, internal stresses must not have exceeded its elastic limit.

The development of internal stresses is due to unequal shrinking and swelling, and the magnitude of stress developed will vary with the magnitude of such inequality. The inequality of shrinkage within a species between wood of low density and wood of high density, for any of the species studied in this test, does not seem to be enough to cause serious internal stress with moisture changes of even 10 or 12 per cent. Stresses so developed eventually die out when a uniform moisture content is maintained. Any change in moisture content develops new stresses, which also eventually disappear under constant moisture conditions.

Between plain-sawed and quarter-sawed material the inequality of shrinkage is greater; and larger stresses are developed with moisture changes. Moisture differences between laminations at gluing can develop stresses of even greater magnitude, capable sometimes, as shown in the test, of causing failure without application of external loading.

The shrinkage properties given in Table 1 give some indication of the factor which is likely to develop the greatest internal stress in laminated construction of any species. Values from Table 1 may be used in comparing the magnitude of unequal shrinkage in laminated construction of plain and quartered material when undergoing moisture changes after manufacture, with the unequal shrinkage caused by gluing together material of different moisture contents.

Internal stresses that have once died out do not always recur with a change in moisture content. When only moisture differences exist at the time of gluing, the source of stress disappears when a common moisture content is reached. Thereafter all members will change moisture content at the same rate, and shrinking or swelling will be approximately equal.

Unequal shrinkage due to density difference, or to method of sawing, does not permanently disappear with conditioning, and each moisture change sets up new stresses, irrespective of previous moisture contents or conditioning.

The results of this test do not indicate the rate of development or disappearance, nor the magnitude to which internal stresses are developed. Failure of specimens in maple indicated that internal stresses beyond the strength of the wood may be developed. Stresses measured at test give merely the stress at that particular time and can not be taken as the maximum. The rate of development and disappearance of stress no doubt varies with the size of construction, species of wood used, and magnitude of source of stress, and can be determined only by an actual test with respect to time.

In commercial practice, the sources of stress frequently occur in combination; and each lends its influence with respect to the development of internal stresses. Plain-sawed and quarter-sawed material of different densities and at different moisture contents are frequently combined. Since gluing at different moisture contents causes the greatest development of internal stresses, elimination of this source of stress is highly desirable. This can be accomplished only by bringing the moisture content of material to the same uniform condition before the structure is glued up. Combining plain-sawed and quarter-sawed material in the same structure develops stress of somewhat lesser magnitude with moisture changes. Where maximum strength across grain, in the direction of the glue joints, is desired in built-up construction, mixing plain and quartered material should be prohibited, as it results in a weakening of the structure which may be temporary but will return with each subsequent change in moisture content.

Controlling variables to eliminate the development of internal stresses increases the difficulties of manufacture. The density of wood is difficult to determine except by actual tests, and the slight development of stresses from this source can be more easily offset by the use of somewhat lower working stresses. Moisture differences before gluing can be eliminated by proper conditioning of the material, which, although not inexpensive, is highly desirable because of the stresses thereby avoided. Matching material for uniformity in direction of annual growth rings reduces the amount of available material and increases the cost of the finished article quite appreciably. Only two courses of action can be followed to eliminate the development of serious stresses from this cause. Either the material must be selected to give uniform matching of grain—and this only serves to minimize the development of stresses with moisture changes—or the moisture content of the construction containing both plain-sawed and quarter-sawed material must be prevented from changing, an extremely difficult task to accomplish.

The effect of internal stresses in airplane propellers can be minimized by the proper control of manufacturing. Tests on airplane propellers have shown that changes in moisture content cause finished propellers to warp and become unfit for service.[8] Preventing such changes by maintaining constant moisture content would also eliminate any development of internal stress, provided moisture contents at gluing were uniform, and the maximum strength of the propeller would be retained.

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[8] "The Influence of Atmospheric and Manufacturing Conditions on Airplane Propellers." Project 233, dated July 8, 1920, by A. L. Heim and A. C. Knauss.

APPENDIX A.—WORKING PLAN.

PURPOSE OF THE INVESTIGATIONS.

Field observations and tests of timber construction involving laminations and glued joints have indicated that differences in moisture content, differences in density, the combining of quarter-sawed with plain-sawed material induce stresses due to atmospheric conditions that cause checking or opening of the glued joints, or combine with working stresses, and in this way contribute to failure.

The purpose of this investigation is to obtain information for use in the design and construction of airplane members made of laminated wood, with special reference to propellers. Conditions similar to those of field service will be maintained and controlled and the test specimens subjected to them. Rooms will be provided in which there can be maintained under control constant conditions of temperature and relative humidity. These conditions are to be such as to approximate the extreme conditions found in actual service.

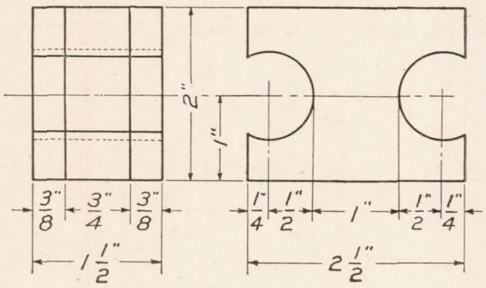

FIG. 8.—Test specimen.

The specific information sought is:

1. A comparison of the strength across the grain of laminated construction made entirely of quarter-sawed material, partly of quarter-sawed and partly of plain-sawed, and entirely of plain-sawed boards under such conditions as may take place after gluing, after the seasoning period, or in transferring the glued member from one condition to another.

2. A comparison of the strength across the grain of laminated construction made of pieces of different densities, with the view of determining the limit of density difference that may be safely had in the constituent members of laminated construction when they undergo certain atmospheric conditions.

3. A comparison of the strength across the grain of laminated construction made of pieces differing in moisture content at the time of gluing, when these are subsequently allowed to come to a uniform moisture content.

It is proposed to combine this information with data to be obtained from service failures and data taken on built-up propellers undergoing the same conditions, with a view of establishing a recommendation as to the allowable moisture and density difference and restrictions upon the use of plain-sawed, quarter-sawed, or plain-sawed combined with quarter-sawed material.

MATERIAL.

In order to accomplish the purpose of this project, laminated test pieces will be made of each of five species representing three classes of wood material used in propeller construction, and tested. Other species will be added later, if deemed advisable. A series of tests will be made for each of the following species of woods:

Central American mahogany (*Swetenia mahogani*).
African mahogany (*Khaya senegalensis*).
Northern white oak (*Quercus sp.*).
Northern red oak (*Quercus sp.*).
Yellow birch (*Betula sp.*).
Red gum (*Liquidambar styraciflua*).
Yellow poplar (*Liriodendron tulipifera*).
Hard maple (*Acer saccharum*).
Philippine mahogany (*Shorea sp.*).

All pieces used in the test specimens are to be cut from clear material free from checks. This material will be selected from kiln-dried stock on hand at this laboratory, for which complete data on other wood properties is available.

TEST SPECIMENS.

The test specimens shall have the dimensions shown in Figure 8. Each test piece is to be made of three laminations, a center, ¾ inch thick, and sides ⅜ inch thick. The laminations are to be glued together when practicable in 20-inch lengths, making blocks from each of which four standard specimens for tension across the grain are to be cut. Other test specimens are to be made up in the same manner, but not glued together. Each free specimen is to be matched to a glued-up specimen and serve as a standard of comparison for the glued-up blocks. These are to be tested in the usual manner. Laminations for the glued and free test pieces are to be matched end to end and taken as near each other as possible. Sketches will be made showing direction of the annual growth rings in each lamination of each specimen.

Sample data sheet.

Stick No.	Wet weight stick.	Wet weight disk.	Dry weight disk.	Dry volume disk.	% moisture content.	Density.	High, av., or low density.	Series assignment.	Paired with stick No.	% M. C. at gluing.	Weight at gluing.	Group assignment.
1	746	17.92	15.99	32.1	12.2	0.499	A	I	179	7.0	712	I F (1-10)
2	754	17.96	16.25	32.0	10.5	.508	A	I	180	7.0	730	I F (11-20)
3	752	18.00	16.15	31.7	11.5	.509	A	III	5	7.0	722	III A(1-10)
4	742	17.90	15.87	32.0	12.8	.496	A	I	206	7.0	703	I G (1-10)
5	747	17.62	15.89	31.6	11.0	.503	A	III	3	7.0	720	III A(1-10)
6	838	20.36	18.46	32.7	10.3	.565	H	II	7	18.0	897	II H (1-10)
7	841	20.34	18.35	32.7	10.8	.561	H	II	6	18.0	895	II H (1-10)
8	721	17.00	15.31	33.0	10.8	.464	L	II	17	14.0	742	II Y(51-60)

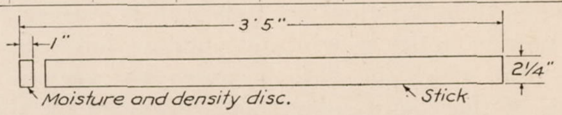

FIG. 9.—Sheet showing data used in determining physical properties of material and assignment to schedule of working plan.

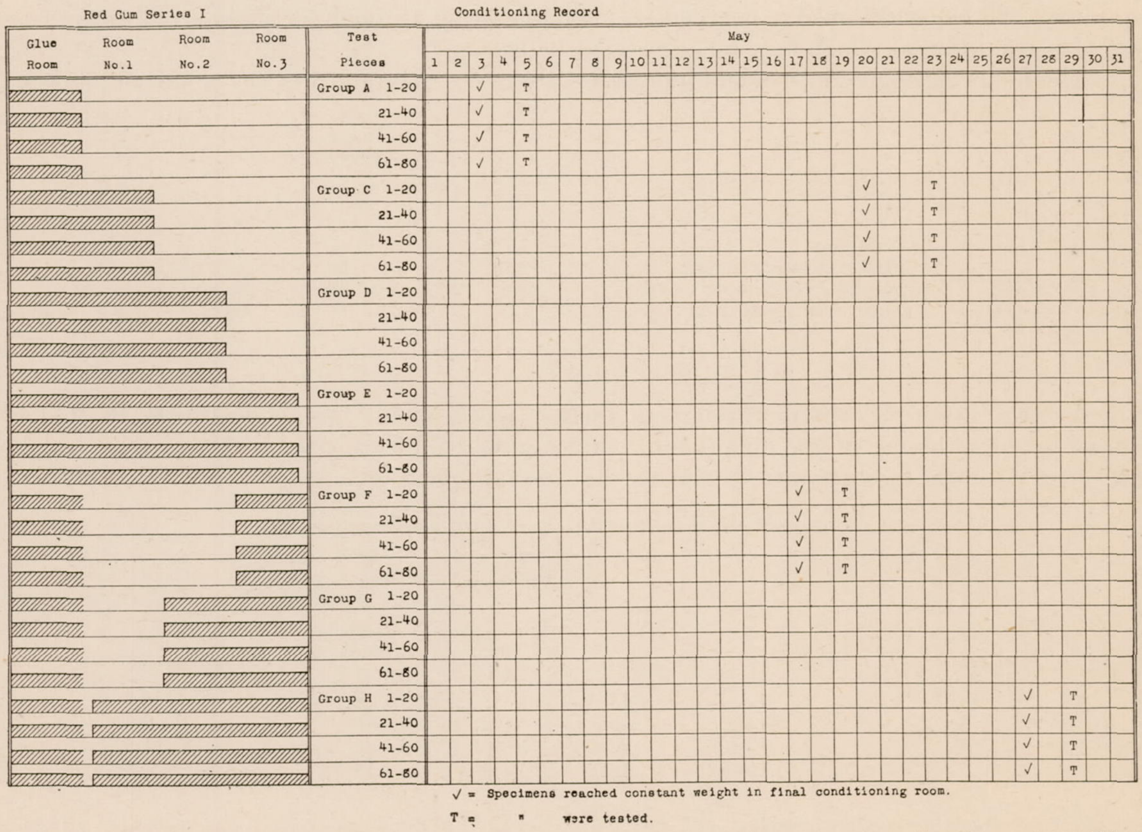

FIG. 10.—Chart showing record of conditioning of specimens. Portion of chart at left shows progress of specimens through rooms in conditioning schedule.

MOISTURE DETERMINATIONS.

Moisture determinations will be made upon each board from which the 20-inch laminations are cut. Three blocks 1 inch in length along the grain are to be cut from approximately the third points of the board. A 1-inch section is to be cut from the center of each 20-inch block at the time the block is cut into test specimens, for the purpose of determining the average moisture content of the block. Moisture determinations will also be made upon each test piece after rupture—one-half of the broken test piece is to be sawed apart and the moisture content obtained for each lamination—the average moisture content of the test piece to be obtained from the other half en masse. The test specimens will be weighed at such intervals as are necessary for obtaining information on the rate of change of moisture in laminated construction.

MARKING.

All of the information available (shipment, tree, and piece) shall be indicated in the standard way. Besides these items the test specimen is to have a mark giving the series, the group, and the number. Series are to be indicated with roman numerals, groups with capital letters, and the numbers with ordinary Arabic numerals. In such cases, when test pieces are made of the same material as the propellers outlined in working plan for project L–233 ND as regards density, moisture content, etc., the test specimen is to have a mark corresponding to the mark on the propellers.

SERIES 1.—MATCHING PLAIN SAWED WITH QUARTER SAWED.

BIRCH, OAK, AND MAHOGANY ARE TO BE TESTED.

Preparation of test pieces.—The center lamination of each test piece is to be quarter sawed and the sides plain sawed. All laminations are to be cut from clear material, free from checks. Density shall be based upon oven-dry weight and volume, and a determination shall be made upon each of the boards from which the 20-inch laminations are cut. Moisture conditions are to be obtained by means of the conditioning rooms provided for this purpose. The average moisture content will be determined by weighing the test pieces from time to time. Each test specimen will be conditioned in consecutive rooms, passing through all of the conditions preceding that condition at which the test piece is to be broken.[9]

The following temperatures and humidities are to be maintained in the conditioning rooms:

	Relative humidity.	Temperature.
	Per cent.	° *F.*
Glue room	65	90
Workshop	55	70
First conditioning room	30	80
Second conditioning room	60	80
Third conditioning room	90	80

GROUP A.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the glue room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center quarter sawed.	Sides flat sawed.
1–20	20	7	7
21–40	20	10	10
41–60	20	14	14
61–80	20	18	18

[9] See "Purpose of the Investigations," above.

GROUP B.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the workshop after conditioning in the glue room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center quarter sawed.	Sides flat sawed.
1–20	20	7	7
21–40	20	10	10
41–60	20	14	14
61–80	20	18	18

GROUP C.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the first conditioning room after conditioning in the glue room and then in the workshop. Odd numbers indicate the test specimens that are glued up; even numbers, test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center quarter sawed.	Sides flat sawed.
1–20	20	7	7
21–40	20	10	10
41–60	20	14	14
61–80	20	18	18

GROUP D.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the second conditioning room after conditioning in the glue room and the first conditioning room consecutively. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	10	10
41–60	20	14	14
61–80	20	18	18

GROUP E.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the third conditioning room after conditioning in the glue room, work shop, first and second conditioning rooms consecutively. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center.	Sides.
1-20	20	7	7
21-40	20	10	10
41-60	20	14	14
61-80	20	18	18

GROUP F.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the third conditioning room after conditioning in the glue room and then in the work shop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center.	Sides.
1-20	20	7	7
21-40	20	10	10
41-60	20	14	14
61-80	20	18	18

GROUP G.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the second conditioning room after conditioning in the glue room, work shop and third conditioning room consecutively. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center.	Sides.
1-20	20	7	7
21-40	20	10	10
41-60	20	14	14
61-80	20	18	18

GROUP H.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the first conditioning room after conditioning in the glue room, work shop, and third and second conditioning rooms consecutively.

Conditions at the time the test pieces are glued together.

No.	Number of test pieces.	Moisture per cent when glued.	
		Center.	Sides.
1-20	20	7	7
21-40	20	10	10
41-60	20	14	14
61-80	20	18	18

SERIES 2.—DENSITY DIFFERENCE.

BIRCH, OAK, AND MAHOGANY ARE TO BE TESTED.

Preparation of test pieces.—The laminations for birch and mahogany are to be cut from plain-sawed material and the laminations for oak are to be cut from quarter-sawed material. All material is to be clear and without checks. Density is to be determined upon three 1-inch sections cut from each board at approximately the third points. After the density has been determined, the boards are to be selected. Three groups are to be made consisting of boards having a comparatively high density, a comparatively low density, and a mixed density. These test pieces are to be marked with numbers corresponding to numbers on propellers built under like conditions as to species, moisture content, and density. Each test specimen will be conditioned in consecutive rooms passing through all of the conditions preceding that condition at which the test piece is to be broken.[10]

GROUP A.

All laminations to contain 7 per cent moisture at the time of gluing and be of a comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time f test.
1– 20	20	Glue room conditions.
21– 40	20	Work shop.
41– 60	20	First conditioning room.
61– 80	20	Second conditioning room.
81–100	20	Third conditioning room.

GROUP B.

All laminations to contain 10 per cent moisture at the time of gluing and be of a comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1– 20	20	Glue room conditions.
21– 40	20	Work shop.
41– 60	20	First conditioning room.
61– 80	20	Second conditioning room.
81–100	20	Third conditioning room.

GROUP C.

All laminations to contain 14 per cent moisture at the time of gluing and be of a comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1– 20	20	Glue room conditions.
21– 40	20	Work shop.
41– 60	20	First conditioning room.
61– 80	20	Second conditioning room.
81–100	20	Third conditioning room.

10 See "Purpose of the Investigations," above.

GROUP D.

All laminations to control 18 per cent moisture at the time of gluing and be of comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room conditions.
21- 40	20	Work shop.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP E.

All laminations to contain 7 per cent moisture at the time of gluing and be of a comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1-20	20	Third conditioning room.
21-40	20	Second conditioning room.
41-60	20	First conditioning room.

GROUP F.

All laminations to contain 10 per cent moisture at the time of gluing and be of a comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1-20	20	Third conditioning room.
21-40	20	Second conditioning room.
41-60	20	First conditioning room.

GROUP G.

All laminations to contain 14 per cent moisture at the time of gluing and be of a comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1-20	20	Third conditioning room.
21-40	20	Second conditioning room.
41-60	20	First conditioning room.

GROUP H.

All laminations to contain 18 per cent moisture at the time of gluing and be of a comparatively high density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1-20	20	Third conditioning room.
21-40	20	Second conditioning room.
41-60	20	First conditioning room.

GROUP J.

All laminations to contain 7 per cent moisture at the time of gluing and be of a comparatively low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room condition.
21- 40	20	Work shop condition.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP K.

All laminations to contain 10 per cent moisture at the time of gluing and be of comparatively low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room condition.
21- 40	20	Work shop condition.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP L.

All laminations to contain 14 per cent moisture at the time of gluing and be of low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room condition.
21- 40	20	Work shop condition.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP M.

All laminations to contain 18 per cent moisture at the time of gluing and be of low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room condition.
21- 40	20	Work shop condition.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP N.

All laminations to contain 7 per cent moisture at the time of gluing and be of comparatively low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1–20	20	Third conditioning room.
21–40	20	Second conditioning room.
41–60	20	First conditioning room.

GROUP O.

All laminations to contain 10 per cent moisture at the time of gluing and be of comparatively low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1–20	20	Third conditioning room.
21–40	20	Second conditioning room.
41–60	20	First conditioning room.

GROUP P.

All laminations to contain 14 per cent moisture at the time of gluing and be of a comparatively low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1–20	20	Third conditioning room.
21–40	20	Second conditioning room.
41–60	20	First conditioning room.

GROUP R.

All laminations to contain 18 per cent moisture at the time of gluing and be of comparatively low density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1–20	20	Third conditioning room.
21–40	20	Second conditioning room.
41–60	20	First conditioning room.

GROUP S.

All laminations to contain 7 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1– 20	20	Glue room conditions.
21– 40	20	Workshop conditions.
41– 60	20	First conditioning room.
61– 80	20	Second conditioning room.
81–100	20	Third conditioning room.

GROUP T.

All laminations to contain 10 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room conditions.
21- 40	20	Workshop conditions.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP U.

All laminations to contain 14 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room conditions.
21- 40	20	Workshop conditions.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP V.

All laminations to contain 18 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1- 20	20	Glue room conditions.
21- 40	20	Workshop conditions.
41- 60	20	First conditioning room.
61- 80	20	Second conditioning room.
81-100	20	Third conditioning room.

GROUP W.

All laminations to contain 7 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1-20	20	Third conditioning room.
21-40	20	Second conditioning room.
41-60	20	First conditioning room.

GROUP X.

All laminations to contain 10 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1–20	20	Third conditioning room.
21–40	20	Second conditioning room.
41–60	20	First conditioning room.

GROUP Y.

All laminations to contain 14 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1–20	20	Third conditioning room.
21–40	20	Second conditioning room.
41–60	20	First conditioning room.

GROUP Z.

All laminations to contain 18 per cent moisture at the time of gluing and be of a mixed density. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

No.	Number of test pieces.	Average moisture content at time of test.
1–20	20	Third conditioning room.
21–40	20	Second conditioning room.
41–60	20	First conditioning room.

SERIES 3.—VARIATION IN MOISTURE CONTENT.

BIRCH, OAK, AND MAHOGANY ARE TO BE TESTED.

Preparation of test pieces.—The laminations of any one test piece are to be all plain sawed or all quarter sawed and of the same density and rate of growth. The variations in moisture content are to be obtained either by drying (under conditions slightly more severe than air drying) in the laboratory or by placing the specimen in one of the conditioning rooms, providing temperature and moisture conditions as required. Each test specimen will be conditioned in consecutive rooms, passing through all of the conditions preceding that condition at which the test piece is to be broken.

GROUP A.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the glue room. Odd numbers indicate test pieces that are glued up; even numbers indicate test pieces that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP B.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the workshop. Odd numbers indicate test pieces that are glued up; even numbers indicate test pieces that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP C.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the first conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP D.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in second conditioning room after conditioning in the workshop and the required period of time in the first conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP E.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in third conditioning room after conditioning in the workshop and the required period of time in the first and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP F.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the third conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP G.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the second conditioning room after conditioning in the workshop and the required period of time in the third conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP H.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the first conditioning room after conditioning in the workshop and the required period of time in the third and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	7	7
21–40	20	7	10
41–60	20	7	14
61–80	20	7	18

GROUP J.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the glue room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP K.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP L.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in first conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP M.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in second conditioning room after conditioning in the workshop and the required period of time in the first conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP N.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in third conditioning room after conditioning in the workshop and the required periods of time in the first and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP P.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the third conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP R.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the second conditioning room after conditioning in the workshop and the required period of time in the third conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP S.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the first conditioning room after conditioning in the workshop and the required period of time in the third and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	10	7
21–40	20	10	10
41–60	20	10	14
61–80	20	10	18

GROUP T.

Average moisture content throughout the test pieces at the time of testing to be that produced by conditioning in the glue room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP U.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP W.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the first conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP X.

Average moisture throughout the test pieces at the time of testing to be that produced by final conditioning in the second conditioning room after conditioning in the workshop and the required period of time in the first conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP Y.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the third conditioning room after conditioning in the workshop and the required period of time in the first and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP Z.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in third conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP AA.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in second conditioning room after conditioning in the workshop and the required period of time in the third conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP BB.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in first conditioning room after conditioning in the workshop and the required periods of time in the third and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center,	Sides.
1–20	20	14	7
21–40	20	14	10
41–60	20	14	14
61–80	20	14	18

GROUP CC.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the glue room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

GROUP DD.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

GROUP EE.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the first conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

GROUP FF.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the second conditioning room after conditioning in the workshop and the required period of time in the first conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

GROUP GG.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in the third conditioning room after conditioning in the workshop and the required period of time in the first and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

GROUP HH.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in third conditioning room after conditioning in the workshop. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

GROUP KK.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in second conditioning room after conditioning in the workshop and the required period of time in third conditioning room. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

GROUP MM.

Average moisture content throughout the test pieces at the time of testing to be that produced by final conditioning in first conditioning room after conditioning in the workshop and the required periods of time in the third and second conditioning rooms. Odd numbers indicate test specimens that are glued up; even numbers indicate test specimens that are not glued up.

Conditions at the time the test pieces are glued together.

No.	Number of pieces.	Moisture per cent when glued.	
		Center.	Sides.
1–20	20	18	7
21–40	20	18	10
41–60	20	18	14
61–80	20	18	18

APPENDIX B.—SAMPLES OF RECORD FORMS.

SERIES 1.—MATCHING PLAIN AND QUARTER SAWED.

Specimens are to be conditioned or brought to constant weight in each of the various rooms in the order given below, then taken out and tested, e. g., Group E will be conditioned in the glue room, workshop, first, second, and third conditioning rooms and then tested.

	Group.
Glue room	A.
Workshop	B.
First conditioning room	C.
Second conditioning room	D.
Third conditioning room	E.
Glue room.	
Workshop.	
Third conditioning room	F.
Second conditioning room	G.
First conditioning room	H.

SERIES 2.—DENSITY DIFFERENCE.

Specimens are to be conditioned or brought to constant weight in each of the various rooms in the order given below until they reach constant weight in the room opposite which their numbers appear. They will then be tested.

Groups A, B, C, D.	Groups J, K, L, M.	Groups S, T, U, V.	Specimen numbers.
Glue room			1- 20
Workshop			21- 40
First conditioning room			41- 60
Second conditioning room			61- 80
Third conditioning room			81–100

Groups E, F, G, H.[1]	Groups N, O, P, R.[2]	Groups W, X, Y, Z.[3]	Specimen numbers.
Glue room			
Workshop			
Third conditioning room			1–20
Second conditioning room			21–40
First conditioning room			41–60

[1] Comparatively high density. [2] Comparatively low density. [3] Mixed density.

SERIES 3.—VARIATION IN MOISTURE CONTENT.

Specimens are to be conditioned or brought to constant weight in each of the various rooms in the order given below, then taken out and tested, e. g., Groups E, N, Y, and GG will be conditioned in the glue room, workshop, first, second, and third conditioning rooms and then tested.

	Groups.
Glue room	A, J, T, CC.
Workshop	B, K, U, DD.
First conditioning room	C, L, W, EE.
Second conditioning room	D, M, X, FF.
Third conditioning room	E, N, Y, GG.
Glue room.	
Workshop.	
Third conditioning room	F, P, Z, HH.
Second conditioning room	G, R, AA, KK.
First conditioning room	H, S, BB, MM.

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