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DIRECTIONAL PROPERTIES OF GLASS-FABRIC-BASE PLASTIC LAMINATE PANELS OF SIZES THAT DO NOT BUCKLE



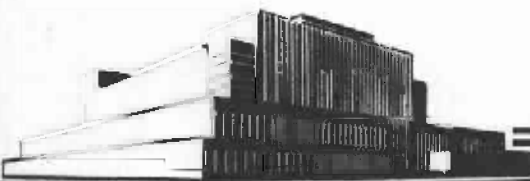
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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE

In Cooperation with the University of Wisconsin

DIRECTIONAL PROPERTIES OF GLASS-FIBER-BASE PLASTIC
LAMINATE PANELS OF SIZES THAT DO NOT BUCKLE¹

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Summary and Conclusions

It has been suggested that glass-fabric laminates might be treated as an orthotropic material, and that the general elastic equations and interaction formula applicable to plywood might similarly be used for this material. This report is a study of the elastic and strength properties of glass-fabric laminates, at various angles to the grain, on specimens so proportioned as to preclude buckling or failure because of elastic instability. Comparisons between the experimental and theoretical values in tension, compression, and shear are presented.

Also included in the report are data showing the effect of grain direction upon the bearing, edgewise-shear, and interlaminar-shear properties of the material.

Except for the panel-shear-test values, the correlation between the experimental and theoretical values is good.

¹-The work covered by this report was done under Army Air Force No. (33-038) 47-359, 47-2902E, and 48-11E. Original report published April 1949.

²-Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

From the analysis, the following conclusions are drawn:

- (1) The stress-strain curve of glass-fabric laminate in tension, particularly when θ is 0° or 90° ; exhibits two straight-line sections (referred to as initial and secondary); therefore, an initial and secondary value of modulus of elasticity and stress at proportional limit is obtained.
- (2) The modulus of elasticity and stress at proportional limit from tension tests, based on initial straight line, are in good agreement with the theory. Modulus of elasticity from the secondary line shows considerable variation from the theoretical values when θ is 15° or 75° . Stress at proportional limit, based on the secondary line, is in good agreement with the theory.
- (3) There is very good agreement between experimental and theoretical values of ultimate stress in tension.
- (4) Modulus of elasticity, stress in proportional limit, and ultimate stress from compression tests are in good agreement with the theoretical values.
- (5) The ultimate stress of a compression specimen, except when θ is 0° or 90° , is influenced considerably by the degree of end restraint.
- (6) For panel shear tests, there is reasonable agreement between experimental and theoretical values of modulus of elasticity and stress at proportional limit except when θ is -45° or $+45^\circ$.
- (7) Ultimate shear stress was not obtained in the panel shear tests when θ was -45° or $+45^\circ$. Experimental values at θ equal to -30° and $+30^\circ$ were about 15 percent lower than the theoretical values. It may be that the theoretical values are more accurate than the experimental ones.
- (8) The bearing stress is approximately the same at 0° , 45° , and 90° to the direction of warp of the laminations.
- (9) The Johnson shear test cannot, from these data, be recommended as reliable for tests of this material.
- (10) The interlaminar shear strength of this material is approximately the same when the angle of loading, θ , is 0° , 45° , or 90° .

Introduction

The proper structural application of glass-fabric laminates, particularly for aircraft, requires a knowledge of their mechanical properties at various angles to the direction of the glass fibers. A theoretical analysis, substantiated by empirical data, will enable the designer to apply this material properly for structural uses.

In the studies of the behavior of plywood, the Forest Products Laboratory has made extensive use of the mathematical theory of elasticity as applied to orthotropic materials; that is, materials having three mutually perpendicular planes of symmetry. The general elastic equations, summarized and verified in Forest Products Laboratory Report No. 1328,³ can be used in the design of plywood where tensile, compressive, and shear stresses are applied in the plane of the plywood. The report also suggests and verifies an interaction formula of the second power for the strength of plywood with stresses applied at various angles to the face grain. If glass-fabric laminates may be considered to be orthotropic materials, the above formulas should be applicable to the material. It is the purpose of this report, in part, to verify these formulas by the results of tests in which tension, compression, and shear stresses are applied in the plane of the laminate.

A few supplementary tests in bearing, edgewise shear, and interlaminar shear were made, and the results are included in this report.

Description of Material

Five glass-fabric-laminate panels, approximately 1/4 by 36 by 36 inches, of 181-114 satin-weave fabric, and of 25 plies each, were furnished to the Laboratory by the sponsor of the test program. The fabric was parallel-laminated with a high-temperature-setting, low viscosity, laminating resin of the alkyd-styrene type polyester. The resin was catalyzed by 1.6 percent by weight of a mixture of tricresyl phosphate and benzoyl peroxide, (each 50 percent by weight of the mixture), containing 3.30

³-Norris, C. B. "Compression, Tension, and Shear Tests on Yellow-poplar Plywood Panels of Sizes that do not Buckle with Tests Made at Various Angles to the Face Grain." January 1946.

percent active oxygen. The lay-up was made between cellophane-covered glass plates. Immediately after impregnation and lay-up, the panel was cured at a pressure of 13 pounds per square inch for 2 hours in an oven at 265° F. Pressure was applied by an air inflated rubber diaphragm located on the bottom plate of the press. The resin content and specific gravity of each panel was as follows:

<u>Panel No.</u>	<u>Percent resin by weight</u>	<u>Specific gravity</u>
1	36.5	1.85
2	36.0	1.87
3	38.0	1.84
4	35.8	1.85
5	36.8	1.82

Each of the first four panels was cut to provide specimens for all of the types of tests conducted in this program. A sketch of the panel lay-out or cutting diagram is shown in figure 1. Panel 5 had slightly different characteristics than the others and was used for exploratory tests. The specimens were rough-cut from the panels with a metal-cutting band saw and finished by other methods, as described below.

Tensile specimens were finished to the desired curvature by use of an emery wheel mounted on a shaper head. The compression, bearing, edgewise shear, and interlaminar shear specimens were carefully finished by means of a surface grinder to insure flatness of the edges.

The specimen number indicates the classification within which each specimen falls. For example, the numbering of specimen C1B-15-2 designates:

- C1 Compression specimen of 1-inch width
- B Type of glass fabric (181-114 satin weave)
- 15 Angle in degrees between applied stress and warp direction of
 laminates
- 2 Specimen from panel 2

The meanings of the various letters employed to designate the types of tests are given in figure 1.

Testing

Tension Tests

The tensile specimens used in these tests were of the boiler-plate type, 16 inches long, and of the thickness of the laminate. The maximum sections at the ends were 1-1/2 inches wide and 2-7/8 inches long. The minimum section at the center was 0.8 inch wide and 2-1/2 inches long. The maximum and minimum sections were connected by circular arcs of 20-inch radius tangent to the minimum section. This type of specimen was selected to avoid stress concentrations and the influence of end restraint.

Tests to determine values of Poisson's ratio were made on three specimens in which the stress was applied in the direction of the warp of the laminates (TB-0-2, 3, and 4) and on three specimens perpendicular to the warp (TB-90-2, 3, and 4). A Tuckerman strain gage of 2-inch-gage length was placed parallel to the applied load on each face at the center of the specimen. Load was applied slowly, and readings were taken in small increments up to some stress well below the proportional limit. This procedure was repeated three or four times. Then a Tuckerman strain gage of 1/2-inch-gage length was mounted perpendicular to the applied load on each face at the center of the specimen, and the same procedure followed. Load-strain curves were plotted for each type of test. The ratios of the slopes of the curves were used in calculating Poisson's ratios.

All of the tension specimens were tested in a 100,000-pound-capacity hydraulic testing machine using templin tension grips (fig. 2). Load was applied at a head speed of 0.035 inch per minute, and load-deformation readings were taken to failure. The strains were measured parallel to the applied load across a 2-inch-gage length with a pair of Martens' mirrors reading to 0.00001 inch, except that strains of specimens TB-0-1 and TB-90-1 were measured with 1-inch Tuckerman gages. The specimens failed suddenly when the maximum load was reached. The tension failure was sometimes accompanied by interlaminar shear failure.

Compression Tests

The specimens used in these tests were 1 inch wide, 4 inches long, and the thickness of the laminate. Two types of tests were employed. In

the first type, the specimen was loaded at its ends and restrained from buckling by means of the apparatus illustrated in figure 3, which is described elsewhere.⁴ In the second type, the specimen was loaded at its edges as illustrated in figure 4.

The specimens were tested in a hydraulic testing machine, employing a spherical head, at a head speed of 0.012 and 0.003 inch per minute for the two types of specimens, respectively. Strains were measured by means of a pair of Martens' mirrors reading to 0.00001 inch, mounted on opposite faces, of 2-inch and 1/2-inch-gage length, respectively. The load increased steadily to a maximum value, and then the specimen failed suddenly. The type of failure was substantially the same for all specimens; that is, a crushing of fibers combined with a transverse shear failure followed by some delamination of the specimen. A typical failure is shown in figure 5.

Panel Shear Tests

Exploratory tests on specimens cut from panel 5 showed that the panel shear apparatus used at the Laboratory for testing plywood could not be used successfully for this material. The stresses at the bond between the metal plates of the apparatus and the "arms" of the specimen caused a delamination of resin from the outer layer of glass cloth. It was necessary to design a new apparatus that supplied a greater bond area in the "arms" of the specimen. In addition, machine bolts were used with each pair of plates to provide clamping action, which supplemented the strength of the cement.

The specimen was cut to the shape of a sort of Formee cross, the outline of which is that of figure 6. The part of the specimen common to the four arms of the cross is 3 inches square. Four pairs of machined steel plates (fig. 7) having the shape of the arms of the cross, excluding the 3-inch square at the center, are cemented to the arms, one plate on each side of each arm. Each plate is alined to its mate, during the cementing process, by two pins. Upon completion of cementing, seven machine bolts are added. Thus when the bolts are tightened the specimen is clamped between two plates. A specimen to which the plates have been cemented and bolted is shown in figure 6, with the rollers and roller pins in place.

⁴A. S. T. M. Designation: D805-45T "Tentative Methods of Testing Plywood, Veneer, and Other Wood and Wood-base Materials." 1945.

The load is applied to the rollers through triangular steel pieces that direct the load along the edges of the 3-inch-square central section of the specimen. Thus a condition of approximately pure shear stress is obtained in this section. The apparatus is shown, set up ready for test, in figure 8.

The load was applied at a head speed of approximately 0.01 inch per minute. Load and compressive strain readings were taken at regular intervals of load. Strain measurements were made with a 1-inch-gage-length dial compressometer reading to 0.0001 inch. (Note that figs. 6 and 8 show metaelectric strain gages attached to the panel shear specimen. This is a specimen from panel 5, used for exploratory tests.)

The failures of these specimens were less pronounced than those of the tensile or compression specimens. Failure usually became visible shortly after the maximum load was reached. When the specimen was cut from the laminate so that the direction of the warp of the laminations was at 0° to one of the edges of the central square of the specimen, diagonal compression and shear failures predominated, while at -30° or +30°, diagonal tension and shear failure were most evident. At -45° or +45°, the failure of the specimen occurred within the arms of the cross. This type of failure was not satisfactory because it is doubtful whether the maximum shear stress of the central part of the specimen was attained. Greater shear area should be provided in the arms of the specimen. This might be accomplished by providing an especially made specimen with the arms split on their central planes thus doubling the glue area.

Bearing Tests

Exploratory tests in bearing conducted according to Federal Specifications⁵ were not satisfactory because the apparatus allows no room for expansion of the thickness of the specimen in the neighborhood of the hole, and thus increases the measured load by an amount due to friction between the specimen and the apparatus. This difficulty was overcome by using the apparatus described in Forest Products Laboratory Report No. 1523-C⁶

⁵-Federal Specifications for Plastics, Organic; General Specifications (Methods of Test) L-P-406a. January 1944.

⁶-A. M. McLeod. "Bolt Bearing Strength of Wood and Modified Wood," November 1946.

and illustrated in figure 9. Bearing tests were made in compression in which the load was applied at angles of 0°, 45°, and 90° to the direction of the warp of the laminations. The specimen was 2 inches wide and 4 inches long, with a centrally located drilled and reamed hole 0.250 inch in diameter. Bearing load was applied to the hole by a 0.250-inch hardened-steel pin. In computing stresses the bearing area was considered to be the product of the diameter of the hole and the thickness of the specimen.

The load was applied at a head speed of 0.008 inch per minute by means of a hydraulic testing machine. Load-deformation readings were taken at regular increments of load until the maximum load was reached. The load held momentarily at this level under increased deformation, and then the specimen failed suddenly. The failures were all a combination of crushing and delamination of the specimen under the pin.

Johnson Shear

A few edgewise-shear tests, employing the Johnson shear tool,⁵ were made to compare the shear strength by this method with the shear strength as obtained from the panel shear test. The shearing force was exerted at 0° or 45° to the direction of the warp of the laminations.

For each test four 3-inch strips were cut from the 1/4-inch thick panel (fig. 10a) and carefully machined to a width of 0.125 inch. The adjacent strips were laid side by side in the shear tool to form a specimen approximately 1 inch in effective width, as shown in figure 10b, and tested as shown in figure 10c. The apparatus and test methods conformed to those outlined in Federal Specifications.⁵ The specimens were tested (fig. 11) in a mechanical testing machine at a head speed of 0.017 inch per minute. The load increased steadily until the maximum load was reached, and then the specimen failed suddenly.

Interlaminar Shear Tests

An apparatus designed for testing the shear strength of glue joints⁴ in blocks of wood was used in this test. The test specimen is shown in figure 10d, and the test method is indicated by figure 10e. The apparatus is illustrated in figure 12. The specimens were carefully machined to insure flat and parallel bearing edges.

Interlaminar shear tests were made at angles of 0° , 45° , and 90° to the direction of the warp of the laminations of the specimens. The nominal shear area of the specimen was $1/2$ by 2 inches.

Presentation of Data

Experimental values obtained from the tests are presented in the appropriate tables. Typical stress-strain curves for various angles of loading are shown for tension, compression, shear, and bearing. The comparison between theoretical and experimental values for stresses applied at various angles to the direction of the warp of the laminations are shown for tension, compression, and panel shear specimens. The theoretical values are represented by curves that, in each case, bear the number of the equation from which the curve was obtained.

Table 1 presents the results of tension and compression tests with the stress applied at an angle θ (0° , 15° , 45° , 75° , or 90°) to the direction of the warp of the laminations. Values of modulus of elasticity, stress at proportional limit, 0.2 percent offset yield stress, and ultimate stress are given for the specimens. In the tension series, two values of modulus of elasticity and stress at proportional limit are given. The initial value is based on the initial straight-line portion of the load-deformation curve, and the secondary value on the second straight-line portion. The 0.2 percent offset yield stress is the stress at the point where the strain first deviates 0.2 percent of the gage length from the initial straight line of the load-deformation curve. The compression values given are for specimens 1 by 4 inches, with one group loaded on the 1-inch end and the other group loaded on the 4-inch edge.

Table 1 also presents the results of panel shear tests with the direction of the warp of the laminations at an angle θ ($+45^\circ$, $+30^\circ$, 0° , -30° , and -45°) to the applied shear stress.

Table 2 presents the results of bearing-test loads at 0° , 45° , or 90° to the direction of the warp of the laminations. The stress and deformation at bearing strength, proportional limit, and ultimate loads are given. Stress at 2 percent of the hole diameter offset from the initial straight line is, in all cases, equal to the ultimate stress.

Table 3 presents the ultimate shear stress as obtained from the Johnson and interlaminar shear tests, with load applied at angles of 0° and 45°

and of 0° , 45° , and 90° , respectively, to the direction of the warp of the laminations.

Figures 1 through 12 include line drawings and photographs to show the selection of and type of specimens as well as the various types of test apparatus employed.

Figures 13 through 16 show typical stress-strain curves at various angles of applied load for tension, compression, shear, and bearing specimens.

Figures 17 and 18 are typical load-deformation curves for tensile specimens, with stress applied parallel to the direction of warp of the laminations.

The load-deformation curves for four panel shear specimens when θ is 0° are shown in figure 19.

Figures 20, 21, and 22 show the relationship between tangent modulus and stress in tension, compression, and shear for the typical specimens illustrated by the stress-strain curves of figures 13, 14, and 15.

The agreement between theoretical and experimental values of modulus of elasticity, proportional limit, and ultimate stress in tension, compression, and shear is shown in figures 23 through 26. Theoretical values are computed from the equations presented in "Analysis of Data" of this report. The number of the equation used in obtaining values for the theoretical curve is, in each instance, shown adjacent to the curve.

Figure 27 shows the effect of width of specimen upon the ultimate stress in compression. Theoretical curves are plotted representing a condition of no end restraint and complete end restraint, and experimental values are plotted for narrow and wide specimens.

Analysis of Data

General

A general observation of the results reported herein indicates considerable variation within a group in many of the strength properties of glass-fabric-laminate material. Even though the over-all physical properties, such as resin content, are similar, there is undoubtedly appreciable

variation within the individual panels. For example, it was observed that the variation in thickness of a single panel was as much as 0.015 inch. It was also observed that the directions of the warp in the individual plies making up a panel were not always parallel to each other. From the nature of the material and the methods used in laying up such a panel, it is extremely difficult to obtain exact uniformity. A few random tests have shown that, in addition to the aforementioned variables, the percent of resin content may vary ± 3 percent within a panel.

Under the above circumstances, testing a single specimen from each of the four panels cannot be expected to give an exact average value for the material and, therefore, variation between experimental and calculated values must be expected. It is apparent from the curves, for example, that a few degrees of error in the direction of the applied load will greatly affect some of the strength properties.

Stress-strain Curves

Typical stress-strain curves in tension, compression, shear, and bearing have been drawn in figures 13 through 16. These curves show the effect of applying stress at various angles to the direction of warp of the laminations. It will be noted that, with the exception of bearing, the mechanical properties are considerably affected by the angle of loading.

Attention is called to the very low proportional limit of the tension specimens, particularly when loaded at 0° or 90° to the warp direction of the laminates. The initial straight-line portion is in effect to about 20 percent of the maximum load, at which point the curve assumes another straight-line portion. These two lines have been called the initial and secondary straight-line portions of the curve, from which initial and secondary values for modulus of elasticity and stress at proportional limit are obtained. This phenomenon is described by Lamb and Axilrod⁷ and was found by them to be common to the six laminates they tested but most marked in the glass-fabric laminate. It is shown more clearly by the curves in figures 17 and 18, which are plotted to a larger deformation scale than those in figure 13. The data shown in figure 17 were taken from a tension test in which the specimen was loaded parallel to the warp direction of the laminate and the strains were measured by means of a Marten's mirror extensometer. Figure 18 shows data taken from a similar test in which metaelectric strain gages were used. Transverse

⁷"Tensile Stress-strain Relationships of Laminated Plastics for Small Strains," J. J. Lamb and B. M. Axilrod, ASTM Bul. No. 151, March 1948.

strains are also shown in this figure. These strains increase in decreasing increments beyond the initial proportional limit and later reverse slightly. Specimens tested with warp direction at intermediate angles to the applied load exhibit the same phenomenon but it is less clearly defined. Tests by Marin⁸ in which plastic laminates, including glass-fabric laminate, were loaded to two-thirds of the ultimate stress 100 times and then tested to failure indicate that stresses in excess of the initial proportional limit do not sensibly damage the laminate.

In some investigations of glass-cloth laminates this initial straight line has not been recognized. In those cases, the secondary straight-line portion of the stress-strain curve formed the basis of the results reported. It will be seen from table 1 that the initial tensile values of modulus of elasticity agree reasonably well with those from the 1-inch wide compression specimens. Such an agreement between values from tension and compression specimens is to be expected.

Typical stress-strain curves in compression (fig. 14) show that at intermediate angles there is more strain per unit of stress, especially at 45° than at 0° or 90° to the warp direction. The effect at these intermediate angles is not nearly as marked, however, as in tension tests. Further, there is no evidence of an initial and of a secondary straight-line portion as in tension tests, and therefore there is only one value of modulus of elasticity and stress at proportional limit for each specimen.

The effect of the direction of the warp of the laminations with respect to the applied stress is very noticeable from the panel shear stress -- strain curves (fig. 15). A loaded shear panel is subjected to shear stresses that resolve into planes of maximum tensile and compressive stresses. When the angle θ is -45° or 45° , the tensile and compressive stresses act either parallel or perpendicular to the warp of the laminations, and the shear stresses at an angle of 45° to the warp direction. Under these conditions the greatest resistance to strain is expected and was obtained. When θ is 0° , the opposite condition holds true and the least resistance to strain is obtained. Considering further the condition when the angle θ is 0° , it is obvious that the resin would offer by far the greatest resistance to shear. When the resin crazes a condition exists that, in part, resolves itself to adjacent threads sliding parallel to each other. Examination of the load-deformation curves for the four 0° specimens (fig. 19)

⁸"Static and Dynamic Creep Properties of Laminated Plastics for Various Types of Stress," Joseph Marin, NACA Tech. Note No. 1105, Feb. 1947.

shows that there is a clearly defined straight-line portion for only one of the specimens. Thus a value of modulus of elasticity and stress at proportional limit can be computed from only one of these curves.

It is apparent from the bearing curves (fig. 16) that there is no appreciable difference in the bearing properties at various angles to the direction of warp of the laminations.

Tangent Modulus Versus Stress Curves

For each typical stress-strain curve (figs. 13, 14, and 15), the tangent modulus is considered as a constant to the proportional limit stress (figs. 20, 21, and 22). In tension, therefore, the initial and secondary moduli are drawn to both the initial and secondary proportional limit stresses. The tangent modulus values beyond the proportional limit are based on the stress-strain curve drawn through the plotted values.

An examination of the tangent modulus versus stress curves shows considerable irregularity. In compression particularly the curves are plotted as a series of straight lines, except when θ is 45° . This should not be interpreted to mean that the tangent modulus and stress vary exactly in this manner, but it is merely to show the general tendency of variation between the two values. A special study, using more sensitive strain gages, would show a more regular relationship between the tangent modulus and stress. However, these curves are based on stress-strain data taken and plotted by ordinary laboratory methods and are an indication of the variation.

Mathematical Equations

Since a complete summary of the general elastic equations and interaction formula is found in a previous report,³ a repetition of the development is not required here. The appropriate equation in each instance will be repeated, however, in the following discussions with an explanation of what values were used. In all cases, θ is the angle between the applied stress and the direction of the warp of the laminates.

Great reliance cannot be placed in the results of the panel shear tests. Although the shear test used is the best which could be devised it is known² that the stress distribution in the test specimen is easily disturbed by small variations in the strain distribution at the boundaries of the specimen, particularly for values of θ not near 0° . The low proportional limit

of the laminate in tension, previously described, may possibly cause shear stress concentrations in the specimens, leading to measured values of properties in shear that are too low. It is likely that the computed values of these properties are more nearly correct than those measured by the shear tests. For this reason a value of the shear strength (F_{ab}) for substitution in the various equations was obtained from values of tensile tests at θ equal 0° , 45° , and 90° , by use of equation (15), rather than from the shear tests. Similarly, a value of the proportional limit stress in shear (p_{ab}) was obtained from the tensile tests at θ equals 45° by use of the last of equations (11).

Tension Tests

Previous experience with tension specimens has shown that the type of specimens selected for these tests is very nearly free from end restraints. Therefore, if the material can be considered as orthotropic, the no-restraint formulas given below should apply. If the lengths of the specimens had not been great compared to their widths they could be considered to be restrained. For a condition of complete end restraint, the equations for restrained compression would be used.

Modulus of elasticity, E_x

$$\frac{e_{xx}}{t_{xx}} = \frac{1}{E_x} = \frac{1}{E_a} \cos^4 \theta + \frac{1}{E_b} \sin^4 \theta + \left[\frac{1}{\mu_{ab}} - 2 \frac{\sigma_{ab}}{E_a} \right] \sin^2 \theta \cos^2 \theta \quad (7)$$

E_a and E_b , initial or secondary, are averages from tension tests for $\theta = 0^\circ$ and $\theta = 90^\circ$, taken from table 1. σ_{ab} is Poisson's ratio as obtained from tension tests and is equal to 0.16. μ_{ab} is the modulus of rigidity at $\theta = 0^\circ$ taken from the panel shear tests. It should be repeated here that the value of μ_{ab} is based on one satisfactory value from the panel shear tests, with the other panels showing no definite straight-line on the load-deformation curve (fig. 19). The value is near the expected value, however, and is considered reliable.

Values of Poisson's ratio were computed by use of tensile specimens. The values obtained are considered satisfactory in that there was no end restraint that might appreciably influence the strain distribution in the specimen. With load applied parallel to the direction of the warp of the laminations, values of σ_{ab} obtained were 0.17, 0.14, and 0.16, or an average of 0.16. With load applied perpendicular to the direction of the

warp of the laminations, values of σ_{ba} obtained were 0.16, 0.17, and 0.20, or an average of 0.18. These values apply to strains below the initial proportional limit but are considered to be sufficiently accurate because they do not enter the mathematical equations in a significant manner.

From the above equation, the theoretical and experimental values must be in exact agreement at $\theta = 0^\circ$ and $\theta = 90^\circ$, as shown in figure 23. At other angles, the initial experimental values are in good agreement with the initial theoretical curve. At $\theta = 15^\circ$ and $\theta = 75^\circ$, however, the agreement between the secondary theoretical and experimental values is only fair, but the theoretical values are conservative.

Proportional limit, p_x

Since it is assumed that the proportional limit at any angle, p_x , will be reached when any of the components in tension, compression, or shear reaches its proportional limit, the applicable component is the one that gives the least value. For no restraint,

$$\begin{aligned} p_x &= \frac{p_a}{\cos^2 \theta} \\ p_x &= \frac{p_b}{\sin^2 \theta} \\ p_x &= \frac{-p_{ab}}{\sin \theta \cos \theta} \end{aligned} \tag{11}$$

p_a and p_b are taken, either initial or secondary, as average tensile values from table 1. Because there is no clearly defined proportional limit in shear when $\theta = 0^\circ$, as mentioned above, p_{ab} in this and subsequent equations is taken as one-half the initial proportional limit in tension when $\theta = 45^\circ$. This is permissible because within the elastic range at that angle, this relationship is true. In this and subsequent equations the proper sign must be applied to the value of p_{ab} , since p_{ab} is numerically equal to $-p_{ab}$.

Theoretical and experimental values are identical when θ is 0° , 45° , or 90° , so that no comparison between the two values can be made at these angles. There is also reasonable agreement between theoretical and experimental values, when θ is 15° or 75° , for both initial and secondary values (fig. 23).

Maximum stress, F_x

For no restraint, the maximum computed stress, F_x , is

$$\frac{1}{F_x^2} = \frac{\cos^4 \theta}{F_a^2} + \frac{\sin^4 \theta}{F_b^2} + \frac{\sin^2 \theta \cos^2 \theta}{F_{ab}^2} \quad (15)$$

F_a and F_b are average values from tension tests for $\theta = 0^\circ$ and $\theta = 90^\circ$, taken from table 1. Experience has shown that values obtained from tension tests are more reliable than those obtained from panel shear tests. Therefore, instead of using the average maximum stress at $\theta = 0^\circ$ from panel shear tests, F_{ab} was calculated from equation (15) by inserting experimental values of F_a , F_b , and $F_x = F_{45}$. If the value of F_{ab} obtained from the shear tests was used the lowest point of the curve would be raised about 18 percent.

From the above, it is seen that the theoretical and experimental values must coincide when θ is 0° , 45° , and 90° . The proof of the equation lies in the results of tests at other angles. It can be seen from figure 23 that the agreement between theoretical and experimental values at 15° and 75° is very good.

Compression Tests

The Laboratory has previously shown³ that the difference in properties obtained from wide and narrow specimens is due to lateral restraints upon the ends of the specimen imposed by the testing machine. Therefore, a wide compression specimen would be expected to exhibit properties approaching a condition of complete end restraint; and a narrow specimen, properties approaching a condition of no restraint.

The strength values obtained from the accepted "pack" test have been used in the theoretical calculations from two main reasons: (1) It is difficult to apply uniform stress across a wide compression specimen, whereas the "pack" test proposes no special difficulty; and (2) the strains of the 4-inch wide specimen were measured over a 1/2-inch-gage length, which means that the gage points were one-quarter inch from the loaded edge. Strain measurements made in this way must be expected to be influenced by the loaded edges. This is verified by a comparison of modulus of elasticity to stress at proportional limit, when θ is 0° or 90° , obtained from the two types of compression tests (table 1). It may be

noted that the values of modulus of elasticity obtained from the compression "pack" test are in reasonable agreement with the modulus of elasticity obtained from the corresponding tension test.

In view of the above discussion, the experimental values of modulus of elasticity, stress at proportional limit, and ultimate stress would be expected to fall somewhere between the theoretical values of no restraint and complete restraint. In the following discussion of compression, it will therefore be necessary to consider both of the extremes in end conditions in calculating the theoretical values.

Modulus of elasticity, E_x

The modulus of elasticity, E_x , at an angle θ , is calculated as follows:

For no restraint:

$$\frac{e_{xx}}{t_{xx}} = \frac{1}{E_x} = \frac{1}{E_a} \cos^4 \theta + \frac{1}{E_b} \sin^4 \theta + \left[\frac{1}{\mu_{ab}} - 2 \frac{\sigma_{ab}}{E_a} \right] \sin^2 \theta \cos^2 \theta \quad (7)$$

For complete restraint:

$$\lambda \frac{t_{xx}}{e_{xx}} = \lambda E_x = E_a \cos^4 \theta + E_b \sin^4 \theta + (4\lambda \mu_{ab} + 2E_a \sigma_{ba}) \sin^2 \theta \cos^2 \theta \quad (8)$$

E_a and E_b are average values from the 1-inch wide compression specimens for $\theta = 0^\circ$ and $\theta = 90^\circ$, taken from table 1. Values of σ_{ab} , σ_{ba} , and μ_{ab} are as mentioned in the discussion of tension tests above.

$$\lambda = 1 - \sigma_{ab} \sigma_{ba}$$

A comparison of the theoretical and experimental values is shown in figure 24. Values of E_a and E_b are selected so that the no-restraint theoretical and experimental values are equal. This was done because the 1-inch wide specimen would be expected to approach most nearly a condition of no-restraint. The agreement between theoretical and experimental values is good for the 45° and 75° specimens, but the experimental value for the 15° specimen is slightly higher than expected.

Proportional limit, p_x

The proportional limit at any angle, p_x , is assumed to be reached when any of the components in tension, compression, or shear reaches its proportional limit. Therefore, the applicable component is the one that gives the least value.

For no restraint:

$$\begin{aligned}
 P_x &= \frac{P_a}{\cos^2 \theta} \\
 P_x &= \frac{P_b}{\sin^2 \theta} \\
 P_x &= \frac{-P_{ab}}{\sin \theta \cos \theta}
 \end{aligned} \tag{11}$$

For complete restraint:

$$\begin{aligned}
 P_x &= \frac{P_a \lambda E_x}{E_a (\cos^2 \theta + \sigma_{ba} \sin^2 \theta)} \\
 P_x &= \frac{P_b \lambda E_x}{E_b (\sin^2 \theta + \sigma_{ab} \cos^2 \theta)} \\
 P_x &= \frac{-P_{ab} E_x}{2\mu_{ab} \sin \theta \cos \theta}
 \end{aligned} \tag{12}$$

p_a and p_b are average values for the 1-inch wide compression specimens for $\theta = 0^\circ$ and $\theta = 90^\circ$, taken from table 1. E_x is the value calculated for the corresponding group by equations (7) or (8). Values of p_{ab} , λ , σ_{ab} , σ_{ba} , and μ_{ab} are as given above in the discussion of tension and compression tests.

A comparison of theoretical and experimental values in figure 24 shows that the agreement between the two values is good. When θ is 0° or 90° , the computed and observed values must coincide because of the equations used, but a comparison at other angles shows good agreement with the theory.

Maximum stress, F_x

The maximum stress, F_x , is dependent upon the degree of end restraint, except when θ is 0° or 90° . For no restraint:

$$\frac{1}{F_x^2} = \frac{\cos^4 \theta}{F_a^2} + \frac{\sin^4 \theta}{F_b^2} + \frac{\sin^2 \theta \cos^2 \theta}{F_{ab}^2} \tag{15}$$

For complete restraint:

$$F_x^2 = F_a^2 \cos^4\theta + F_b^2 \sin^4\theta + 4F_{ab}^2 \sin^2\theta \cos^2\theta \quad (16)$$

F_a and F_b are average values for the 1-inch wide compression specimens for $\theta = 0^\circ$ and $\theta = 90^\circ$, taken from table 1. The value of F_{ab} is taken as discussed above under tension tests.

In using equations (15) and (16), theoretical and experimental values must be identical when θ is 0° or 90° . The proof of the equations lies in the results of tests at other angles. From figure 24 it can be seen that the agreement between theoretical and experimental values is good. As is expected, the plotted points fall close to the no-restraint theoretical curve.

It has been mentioned previously that wide specimens in compression may be expected to have different properties than narrow specimens because of the degree of end restraint. If there is an appreciable effect on maximum stress, this should be noticeable from the tests of the 1-inch wide and 4-inch wide compression specimens. This is verified by a comparison of the average maximum stresses of the two types of specimens as given in table 1, and by the plotted data of figure 27. For the theoretical curve, the value of F_a used in the formula was an average of the maximum stresses for the 1-inch and 4-inch wide specimens, when θ is 0° . F_b was the average of the maximum stresses for the 1- and 4-inch wide specimens at $\theta = 90^\circ$. Therefore, the theoretical curve when θ is 0° or 90° must pass midway between these points. F_{ab} was taken as for the other theoretical compression values. An examination of figure 27 shows that at all intermediate angles the observed maximum stresses of the wide specimens exhibit higher values than the narrow specimens. This shows clearly that the degree of end restraint is an important factor in the maximum load attained.

Panel Shear Tests

Previous experience with plywood³ has shown that when the shear forces are transmitted directly along the free edge of the panel, as was done for these specimens, the observed values are in good agreement with the theory. The results obtained from panel shear tests of glass-fabric laminate do not check the theory nearly as well. The reason for these discrepancies may be due to the low initial proportional limit in tension. Its effect may cause a complicated redistribution of stress, and it is

difficult to analyze exactly what happens under these conditions. It seems logical that the theoretical values for modulus of elasticity and stress at proportional limit should be calculated on the basis of the initial tension curves. This has been done in the curves of figure 25. The question may be raised, however, as to what sort of comparison would result if the curves had been based on the secondary values from the tension curves. This comparison between theoretical and experimental values is shown in figure 26.

The experimental values obtained from panel shear tests are, as in compression, dependent in part upon the degree of end restraint. For an orthotropic material, the experimental values would be expected to fall somewhere between theoretical values of complete restraint and no restraint. It will be seen, however, that the agreement between theoretical and experimental values is not very good, especially when θ is -45° or 45° .

Modulus of rigidity, μ_{xy}

For no restraint:

$$\frac{e_{xy}}{t_{xy}} = \frac{1}{\mu_{xy}} = \frac{1}{\mu_{ab}} \cos^2 2\theta + \left[\frac{1}{E_a} + \frac{1}{E_b} + 2 \frac{\sigma_{ab}}{E_a} \right] \sin^2 2\theta \quad (9)$$

For complete restraint:

$$\frac{t_{xy}}{e_{xy}} = \mu_{xy} = \mu_{ab} \cos^2 2\theta + \frac{1}{4\lambda} (E_a + E_b - 2E_a \sigma_{ba}) \sin^2 2\theta \quad (10)$$

When the angle θ is negative, the values of E_a and E_b are average values from tests in compression parallel and tension perpendicular to the warp direction of the laminations, respectively, taken from table 1. When the angle θ is positive, E_a and E_b are average values from tests in tension parallel and compression perpendicular to the warp direction of the laminations, respectively, taken from table 1. Values of μ_{ab} , σ_{ab} , σ_{ba} , and λ are as described above in the analysis of tension and compression tests.

The correlation between theoretical and experimental values (fig. 25) is fair. When θ is 0° , the values are necessarily identical, but at the other angles, particularly -45° and 45° , the experimental values are higher than the theoretical values. If secondary values in tension are used, the agreement is worse, as shown in figure 26.

Proportional limit, p_{xy}

It is assumed that the proportional limit at any angle in shear, p_{xy} , will be reached when any of the components in tension, compression, or shear reaches its proportional limit. The applicable component is the one that gives the least value.

For no restraint:

$$\begin{aligned} p_{xy} &= \frac{P_a}{2 \sin \theta \cos \theta} \\ p_{xy} &= \frac{-P_b}{2 \sin \theta \cos \theta} \\ p_{xy} &= \frac{P_{ab}}{\cos^2 \theta - \sin^2 \theta} \end{aligned} \tag{13}$$

For complete restraint:

$$\begin{aligned} p_{xy} &= \frac{P_a \lambda \mu_{xy}}{E_a (1 - \sigma_{ba}) \sin \theta \cos \theta} \\ p_{xy} &= \frac{-P_b \lambda \mu_{xy}}{E_b (1 - \sigma_{ab}) \sin \theta \cos \theta} \\ p_{xy} &= \frac{P_{ab} \mu_{xy}}{\mu_{ab} (\cos^2 \theta - \sin^2 \theta)} \end{aligned} \tag{14}$$

E_a and E_b and the corresponding values of p_a and p_b are chosen as for the calculations of modulus of rigidity above. μ_{xy} is the appropriate value calculated from equations (9) and (10). Values of λ , σ_{ab} , σ_{ba} , P_{ab} , and μ_{ab} are as described above in analysis of tension and compression tests.

There is reasonable agreement between the theoretical and experimental values (fig. 25) except when θ is -45° or 45° , where the experimental values are too high. If secondary values in tension are used (fig. 26), the agreement is similarly good except when θ is -45° or 45° , where the experimental values are too low.

Maximum stress, F_{xy}

For no restraint:

$$\frac{1}{F_{xy}^2} = \frac{1}{F_{ab}^2} \cos^2 2\theta + \left[\frac{1}{F_a^2} + \frac{1}{F_b^2} \right] \sin^2 2\theta \quad (17)$$

For complete restraint:

$$F_{xy}^2 = F_{ab}^2 \cos^2 2\theta + \frac{1}{4} (F_a^2 + F_b^2) \sin^2 2\theta \quad (18)$$

When the angle θ is negative, the values of F_a and F_b are average values from tests in compression parallel and tension perpendicular to the warp direction of the laminations, respectively, taken from table 1. When the angle θ is positive, the values of F_a and F_b are average values from tests in tension parallel and compression perpendicular to the warp direction of the laminations, respectively, taken from table 1. F_{ab} is computed from tension test values, as mentioned in the discussion following equation (15). If the value of F_{ab} obtained from the shear tests is used the theoretical curve would pass through the lowest experimental point.

The agreement between theoretical and experimental values of maximum stress F_{xy} is shown in figure 25 (and duplicated in fig. 26). Except when the angle θ is 0° , the experimental values fall below the theoretical curves. Failure of specimens when θ is -30° , 0° , or 30° was diagonal tension or shear failure, as expected. It is possible, however, that full shear strength was not developed in the -45° and 45° specimens because the specimens generally failed between the steel plates in the arms of the specimens by a combination of interlaminar shear and tension failures.

Bearing Tests

The results of bearing tests on glass-fabric laminates (table 2) show that the direction of the applied bearing load with respect to the direction of the warp of the laminations has little effect on the bearing properties. The average properties when θ is 45° are only slightly lower than when θ is 0° or 90° . A comparison of typical stress-deformation curves in bearing when θ is 0° , 45° and 90° , is shown in figure 16. The curves are approximately the same and are typical of bearing curves of other materials.

It may be noted that the stress at 2 percent offset from the initial straight line is equal to the ultimate stress.

The bearing values tabulated in table 2 are calculated as the applied load divided by the bearing area, where bearing area is the product of the hole diameter and thickness of the specimen. It must be remembered that these values are based on compressive loading and may be higher than similar tests under tensile loading in which edge and end distance ratios and notch sensitivity might affect the values. Therefore, caution should be exercised in the use of the values given in table 2.

Johnson Shear Tests

The stress distribution imposed by the Johnson shear method of test is known to be far from uniform. Nevertheless, it is a convenient method of making shear tests, and it is desirable to know how well the values of ultimate stress check with those obtained from theoretical considerations.

Specimens sheared parallel to the warp direction of the laminations ($\theta = 0^\circ$) correspond to panel shear specimens when θ is 0° . At this condition, the values of ultimate shear stress obtained with the Johnson shear tool are more than twice the theoretical values. When θ is 45° , the values from the Johnson shear test are about 16 percent lower than the theoretical values.

A comparison of the ultimate shear stress at 0° and 45° , as obtained from the Johnson shear tool, shows that the strength at 45° is only about 15 percent higher than the strength at 0° . From a theoretical consideration, and from observed values from panel shear tests, this increase is considerably less than would be expected. Further, it is known that the shear strength of a parallel laminated panel may be different when θ is -45° or $+45^\circ$; yet the Johnson shear test cannot show this difference.

The Johnson shear test, therefore, cannot be recommended from these limited data as reliable for tests of glass-fabric laminates.

Interlaminar Shear Tests

Although there is no approved method of making interlaminar shear tests on thin materials, the method employed in these tests is considered reasonably satisfactory. The apparatus minimizes the bending effects that

are a considerable factor in some shear tests of this type. It is realized that this test does not subject the specimen to a condition of pure shear but it is a practical method of obtaining an indication of the interlaminar shear strength. The results obtained may depend upon the size and shape of specimen, but this study does not include an investigation of this matter.

The results of the tests show that the interlaminar shear strength is not affected appreciably by the angle of loading; that is, specimens loaded at 0° , 45° , or 90° to the direction of the warp of the lamination, show about the same resistance to shear (table 3).

Table 1.—Series of tests of steel-plate-plate concrete specimens with stresses applied at various angles (θ) to the axis of the limitations

Specimen No.	Tension		Compression (1 inch wide)										Compression (4 inches wide)										Panel shear			
	Proportional limit		Specimen No.		Ultimate stress		Specimen No.		Ultimate stress		Specimen No.		Ultimate stress		Specimen No.		Ultimate stress		Specimen No.		Ultimate stress		Modulus of rigidity		0.2 percent offset stress	
	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress	Initial stress	Final stress
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
$\theta = 0^\circ$																										
CP-O-1	1,415	2,470	9,420	21,000	24,670	48,400	CP-O-1	1,66	2,621	29,280	48,020	48,020	48,020	1,85	4,110	28,990	45,920	45,920	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	22,150	22,150
2	1,566	2,634	7,970	33,720	24,790	38,770	2	1,84	2,759	27,150	40,160	40,160	40,160	1,85	4,102	18,990	35,960	35,960	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	22,150	22,150
3	1,633	2,661	8,420	34,680	30,880	47,060	3	1,79	2,723	34,040	40,280	40,280	40,280	1,79	4,375	33,850	36,370	36,370	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	22,150	22,150
4	1,433	2,574	7,070	35,900	28,240	47,660	4	1,83	2,594	34,500	47,370	47,370	47,370	1,80	4,375	31,840	37,470	37,470	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	22,150	22,150
Average	1,428	2,466	8,470	31,160	27,140	45,460	Average	1,83	2,562	33,390	43,960	43,960	43,960	1,82	4,318	18,910	37,960	37,960	Average	1,500	15,500	15,500	1,000	10,000	22,150	22,150
$\theta = 15^\circ$																										
CP-15-1	1,109	2,037	7,150	9,180	14,100	CP-15-1	1,85	1,024	16,300	16,300	16,300	16,300	16,300	1,85	3,233	12,150	12,150	12,150	TP-(30)-1	1,500	15,500	15,500	1,000	10,000	17,760	17,760
2	1,636	2,636	6,870	8,810	11,700	25,800	2	1,83	1,038	19,380	16,180	16,180	16,180	1,83	3,276	10,750	10,750	10,750	TP-(30)-1	1,500	15,500	15,500	1,000	10,000	17,760	17,760
3	1,633	2,507	6,460	9,230	11,770	28,700	3	1,80	2,048	16,570	16,570	16,570	16,570	1,79	3,676	10,070	10,070	10,070	TP-(30)-1	1,500	15,500	15,500	1,000	10,000	17,760	17,760
4	1,131	2,597	5,380	9,680	14,030	30,000	4	1,83	3,112	17,530	16,590	16,590	16,590	1,83	3,405	10,620	10,620	10,620	TP-(30)-1	1,500	15,500	15,500	1,000	10,000	17,760	17,760
Average	1,268	2,462	6,490	9,230	14,180	32,150	Average	1,83	2,086	17,420	16,310	16,310	16,310	1,82	3,540	10,570	10,570	10,570	Average	1,500	15,500	15,500	1,000	10,000	17,760	17,760
$\theta = 30^\circ$																										
CP-30-1	1,094	1,847	3,780	4,620	7,280	CP-30-1	1,86	2,134	7,440	7,440	7,440	7,440	7,440	1,86	2,921	15,000	15,000	15,000	TP-(10)-1	1,500	15,500	15,500	1,000	10,000	13,140	13,140
2	1,094	1,847	3,780	4,620	7,280	20,100	2	1,84	1,899	6,570	6,570	6,570	6,570	1,82	2,913	10,750	10,750	10,750	TP-(10)-1	1,500	15,500	15,500	1,000	10,000	13,140	13,140
3	1,173	1,900	3,870	5,120	8,230	20,810	3	1,83	1,786	7,130	6,280	6,280	6,280	1,83	2,928	8,740	8,740	8,740	TP-(10)-1	1,500	15,500	15,500	1,000	10,000	13,140	13,140
Average	1,116	1,894	3,820	4,920	7,780	19,770	Average	1,86	1,992	6,820	6,820	6,820	6,820	1,82	2,956	11,560	11,560	11,560	Average	1,500	15,500	15,500	1,000	10,000	13,140	13,140
$\theta = 45^\circ$																										
CP-45-1	1,067	2,789	5,480	9,470	12,950	39,080	CP-45-1	1,84	1,259	17,810	17,810	17,810	17,810	1,84	1,182	22,000	22,000	22,000	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	18,730	18,730
2	1,308	2,656	2,480	7,440	12,400	28,180	2	1,84	1,090	17,770	17,770	17,770	17,770	1,83	1,312	9,440	9,440	9,440	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	18,730	18,730
3	1,259	2,684	2,100	6,950	10,200	25,310	3	1,81	2,021	10,500	10,500	10,500	10,500	1,78	1,312	8,740	8,740	8,740	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	18,730	18,730
4	1,688	2,593	2,870	5,840	8,230	29,060	4	1,83	2,023	9,460	9,460	9,460	9,460	1,81	1,368	13,560	13,560	13,560	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	18,730	18,730
Average	1,290	2,629	4,410	7,420	11,440	30,550	Average	1,83	1,923	13,680	13,680	13,680	13,680	1,81	1,370	13,460	13,460	13,460	Average	1,500	15,500	15,500	1,000	10,000	18,730	18,730
$\theta = 90^\circ$																										
CP-90-1	1,483	2,079	9,020	24,130	24,130	50,800	CP-90-1	1,82	1,108	19,080	19,080	19,080	19,080	1,82	1,096	13,230	13,230	13,230	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	21,660	21,660
2	1,564	2,042	8,270	24,910	24,910	54,140	2	1,86	1,127	19,340	19,340	19,340	19,340	1,86	1,108	12,150	12,150	12,150	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	21,660	21,660
3	1,313	2,053	7,410	23,660	24,090	38,800	3	1,82	1,071	17,550	17,550	17,550	17,550	1,80	1,096	10,750	10,750	10,750	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	21,660	21,660
4	1,556	2,052	5,790	21,130	23,060	67,430	4	1,86	1,013	10,760	10,760	10,760	10,760	1,83	1,175	22,310	22,310	22,310	TP-(45)-1	1,500	15,500	15,500	1,000	10,000	21,660	21,660
Average	1,424	2,049	8,190	23,560	26,590	45,160	Average	1,84	1,096	16,680	16,680	16,680	16,680	1,84	1,065	15,450	15,450	15,450	Average	1,500	15,500	15,500	1,000	10,000	21,660	21,660

Values based on initial straight portion of stress-strain curve.

Values based on second straight portion of stress-strain curve.

Value at 0.2 percent offset from initial straight line of stress-strain curve.

Table 2.--Results of bearing tests of glass-fabric laminate with
load applied by a 1/4-inch pin, compressive loading

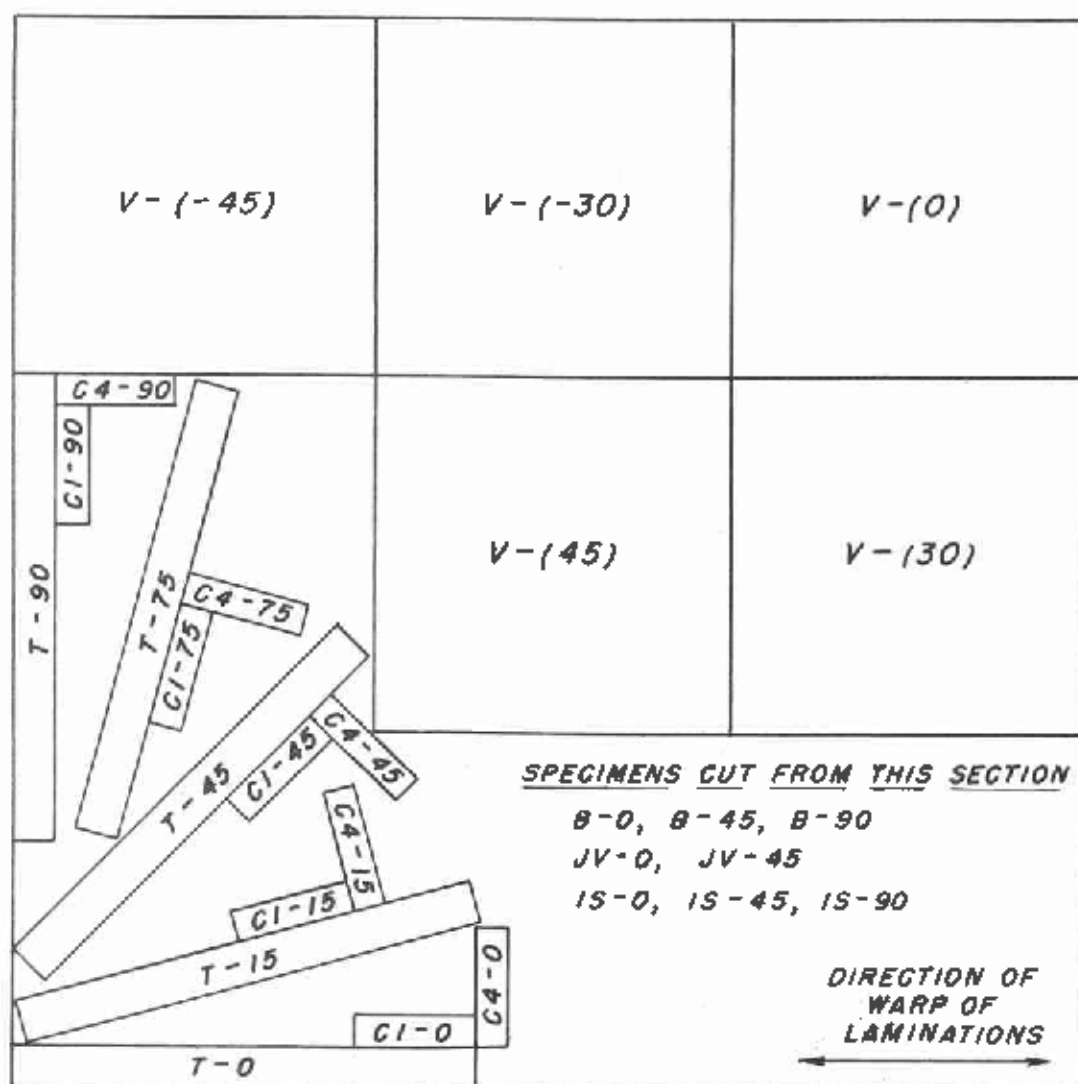
Specimen No.	Thickness	Bearing values ¹					
		Bearing strength ²		Proportional limit		Ultimate	
		Stress	Deformation	Stress	Deformation	Stress	Deformation
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Inch	P.s.i.	Inch	P.s.i.	Inch	P.s.i.	Inch
$\theta = 0^\circ$							
BB-0-2a	.0248	40,640	0.01	41,940	0.0098	60,480	0.0211
2b	.250	33,760	.01	33,600	.0084	60,000	.0330
3a	.266	34,290	.01	36,090	.0096	58,270	.0325
3b	.269	34,500	.01	35,690	.0088	58,740	.0298
4a	.254	34,330	.01	47,240	.0124	61,570	.0308
4b	.258	31,010	.01	37,210	.0093	57,360	.0308
Average.....		34,760	.01	38,630	.0097	59,400	.0297
$\theta = 45^\circ$							
BB-45-2a	.250	32,640	.01	38,400	.0108	56,800	.0230
2b	.254	35,430	.01	29,920	.0073	57,320	.0330
3a	.268	31,340	.01	35,820	.0098	58,800	.0253
3b	.272	31,910	.01	29,410	.0078	58,090	.0243
4a	.256	31,880	.01	34,380	.0096	57,810	.0232
4b	.259	31,350	.01	33,980	.0097	56,370	.0222
Average.....		32,420	.01	33,650	.0092	57,530	.0252
$\theta = 90^\circ$							
BB-90-2a	.246	36,580	.01	35,770	.0083	58,940	.0193
2b	.242	36,300	.01	46,280	.0120	56,860	.0250
3a	.265	33,960	.01	39,240	.0107	60,380	.0217
3b	.265	34,720	.01	42,260	.0114	59,470	.0250
4a	.249	34,060	.01	43,370	.0112	59,440	.0212
4b	.251	37,930	.01	44,620	.0117	59,760	.0226
Average.....		35,580	.01	41,920	.0109	59,140	.0225

¹Stress at 2 percent of the hole diameter offset from the initial straight line is equal to the ultimate stress. See figure 16.

²Values at 4 percent deformation of hole diameter.

Table 3.--Ultimate shear stress of glass-fabric laminate from Johnson and inter-laminar shear tests

Johnson shear test		Interlaminar shear test	
Specimen No.	Ultimate shear stress	Specimen No.	Ultimate shear stress
(1)	(2)	(3)	(4)
	P.s.i.		P.s.i.
$\theta = 0^\circ$		$\theta = 0^\circ$	
JVB- 0-1a	23,010	ISB- 0-2a	4,730
1b	23,530	2b	3,800
1c	22,370	ISB- 0-3a	4,350
JVB- 0-2a	25,130	3b	4,200
2b	22,620	ISB- 0-4a	4,680
2c	20,360	4b	3,990
JVB- 0-3a	22,390	-----	
3b	22,510	Average....	4,290
3c	20,540		
JVB- 0-4a	23,620	$\theta = 45^\circ$	
4b	22,480	ISB-45-2a	4,940
4c	24,060	2b	4,070
Average.....	22,720	ISB-45-3a	4,590
		3b	4,920
$\theta = 45^\circ$		ISB-45-4a	4,220
JVB-45-1a	25,290	4b	3,680
1b	23,280	-----	
1c	22,930	Average....	4,400
JVB-45-2a	28,710		
2b	24,370	$\theta = 90^\circ$	
2c	29,460	ISB-90-2a	5,060
JVB-45-3a	25,850	2b	4,160
3b	25,240	ISB-90-3a	4,830
3c	25,980	3b	4,450
JVB-45-4a	27,670	ISB-90-4a	4,460
4b	26,410	4b	4,250
4c	27,720	-----	
Average.....	26,080	Average....	4,550



SPECIMEN IDENTIFICATION

T - TENSION
 C1 - COMPRESSION (1-INCH WIDTH)
 C4 - COMPRESSION (4-INCH WIDTH)
 V - PANEL SHEAR
 B - BEARING
 JV - JOHNSON SHEAR
 IS - INTERLAMINAR SHEAR

Figure 1.--Cutting diagram for glass-fabric-laminate specimens from 1/4- by 36- by 36-inch panels.

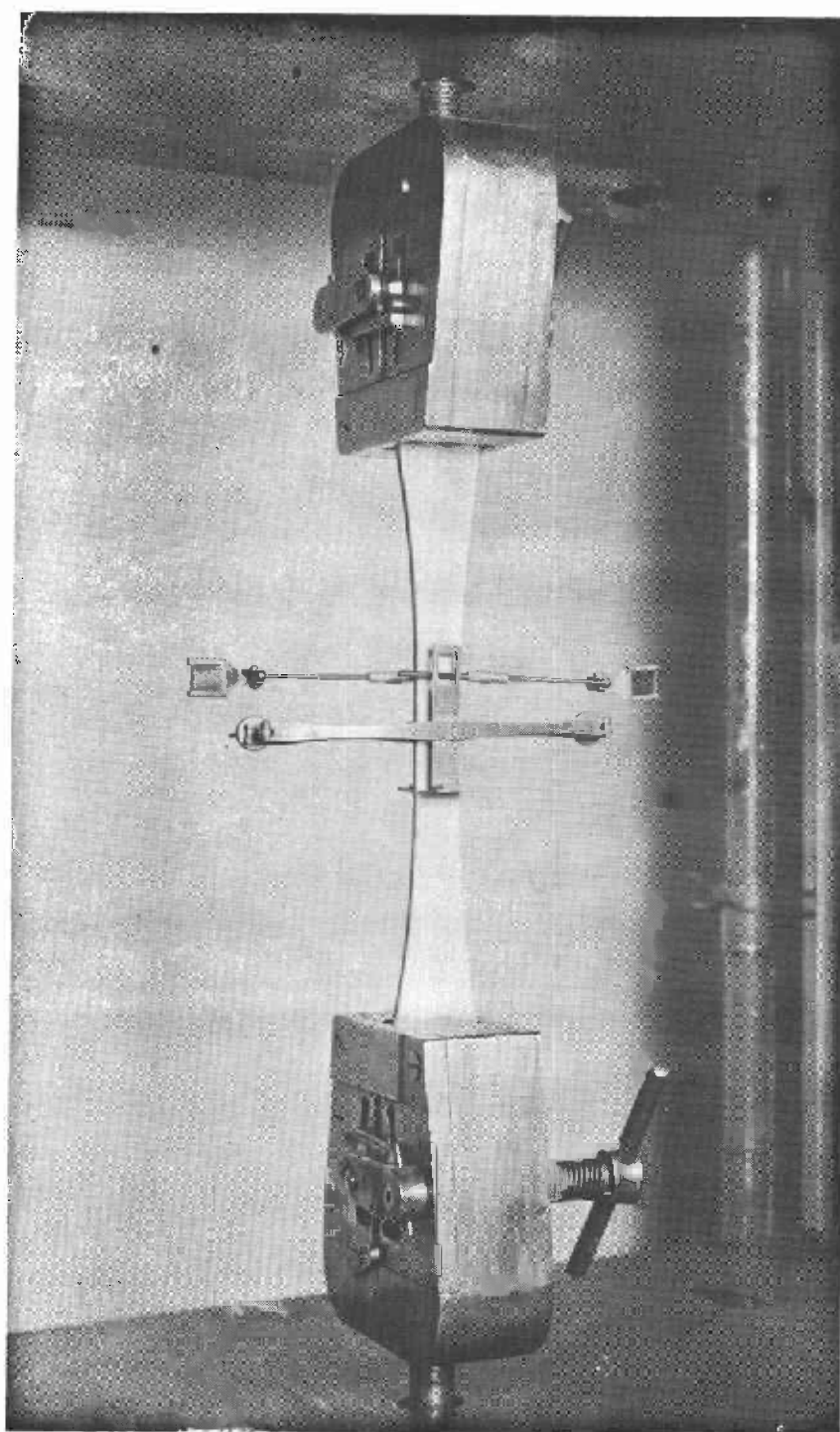


Figure 2.--Tensile test used in testing glass-fabric-laminate specimens.
Z M 80078 F

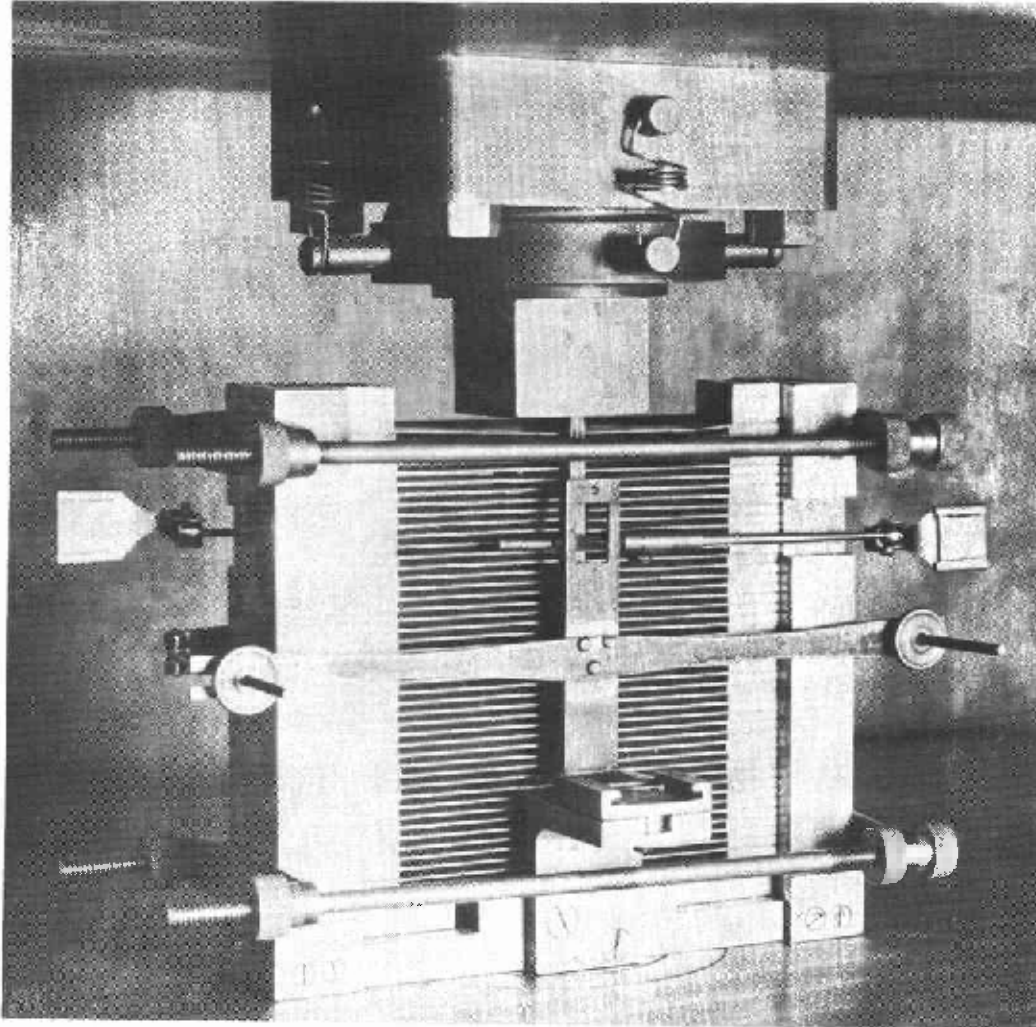


Figure 3.--Compression pack test used in testing glass-fabric-laminate specimens.

Z M 80079 F

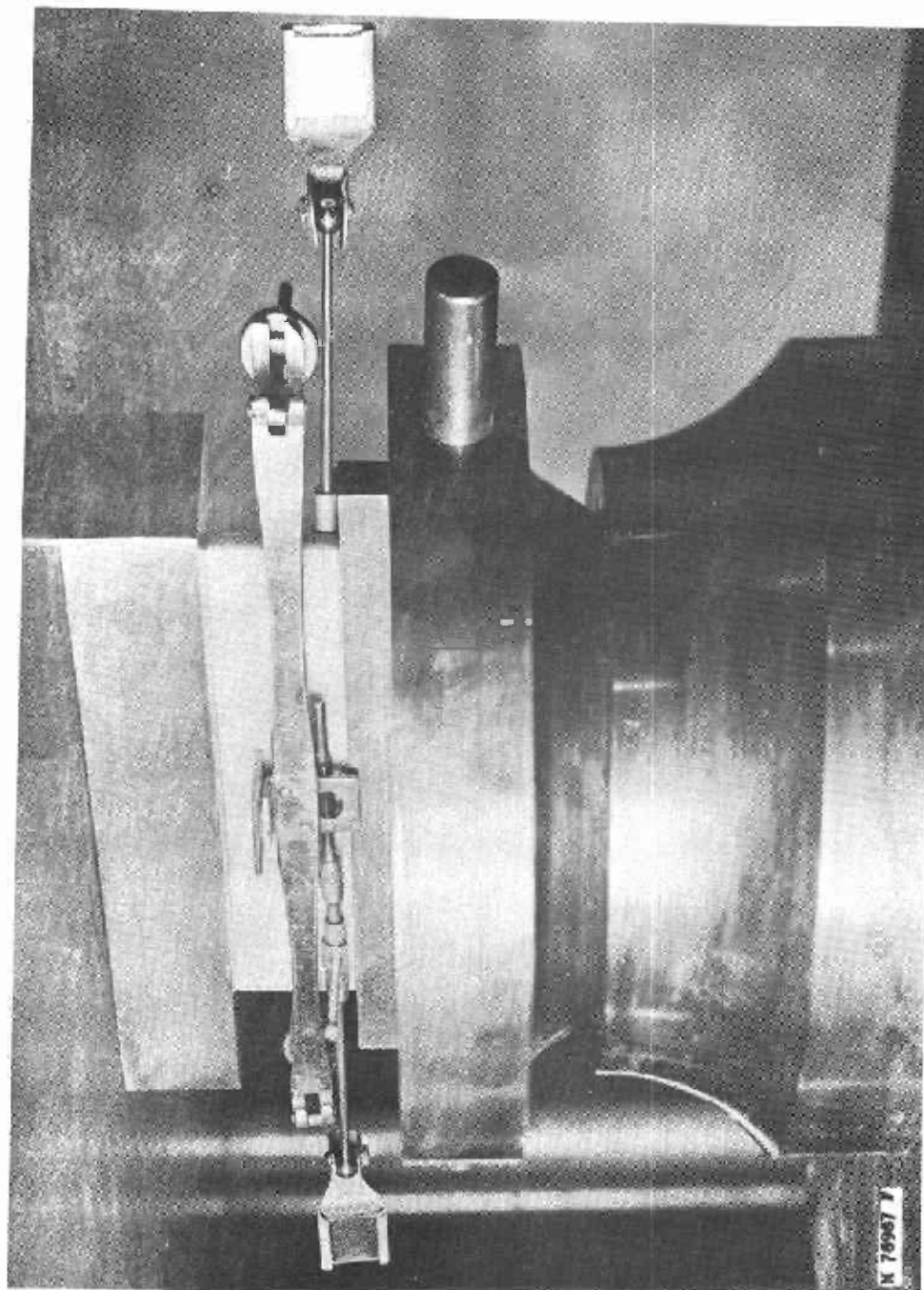


Figure 4.--Compression test of glass-fabric-laminate specimens, loaded on 4-inch edge.
Z M 50080 F



Figure 5.--Typical failure of glass-fabric-laminate compression specimen.
Z N 50081 F

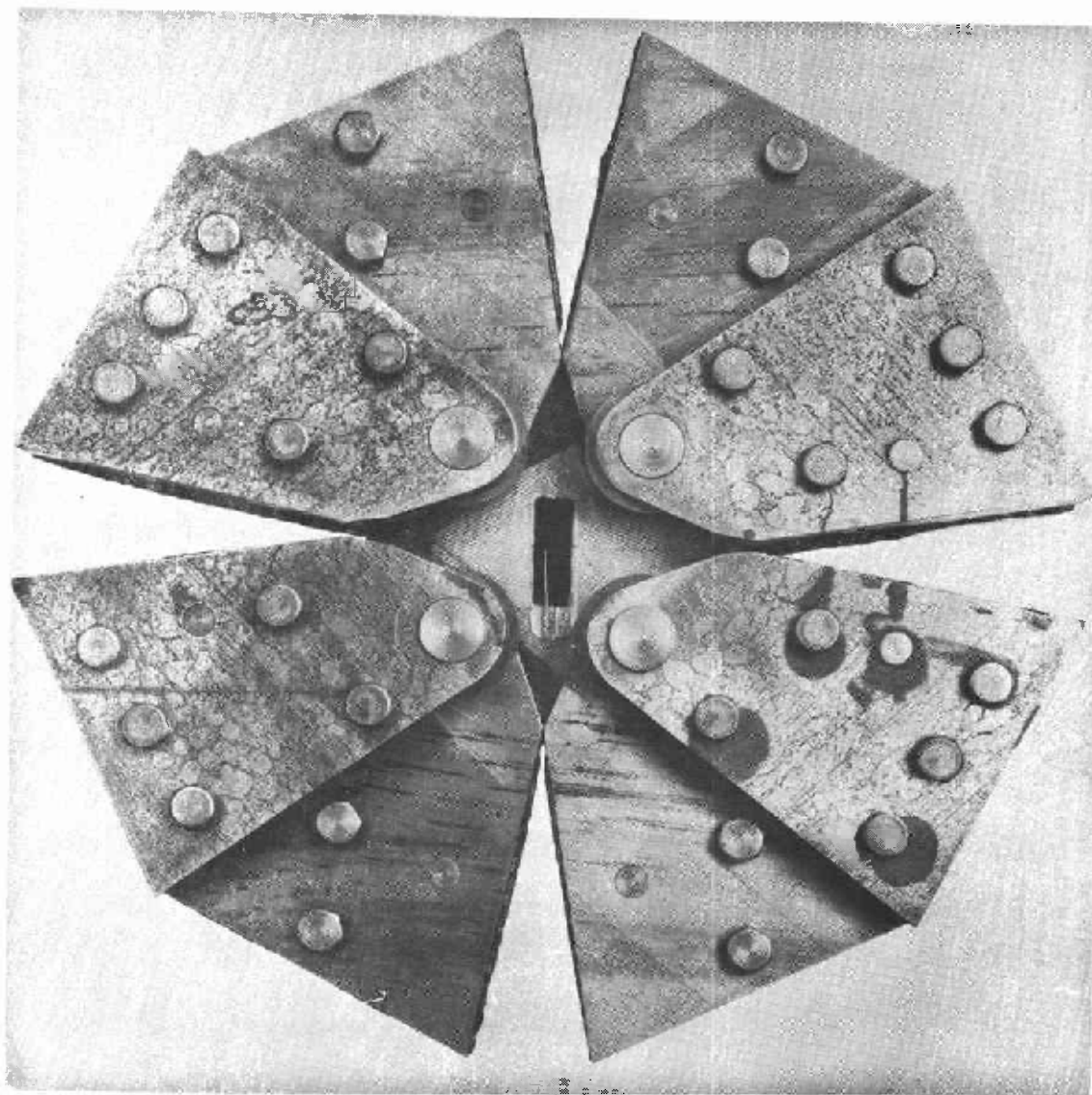


Figure 6.--Panel shear apparatus used in testing glass-fabric-laminate specimens.

Z M 80082 F

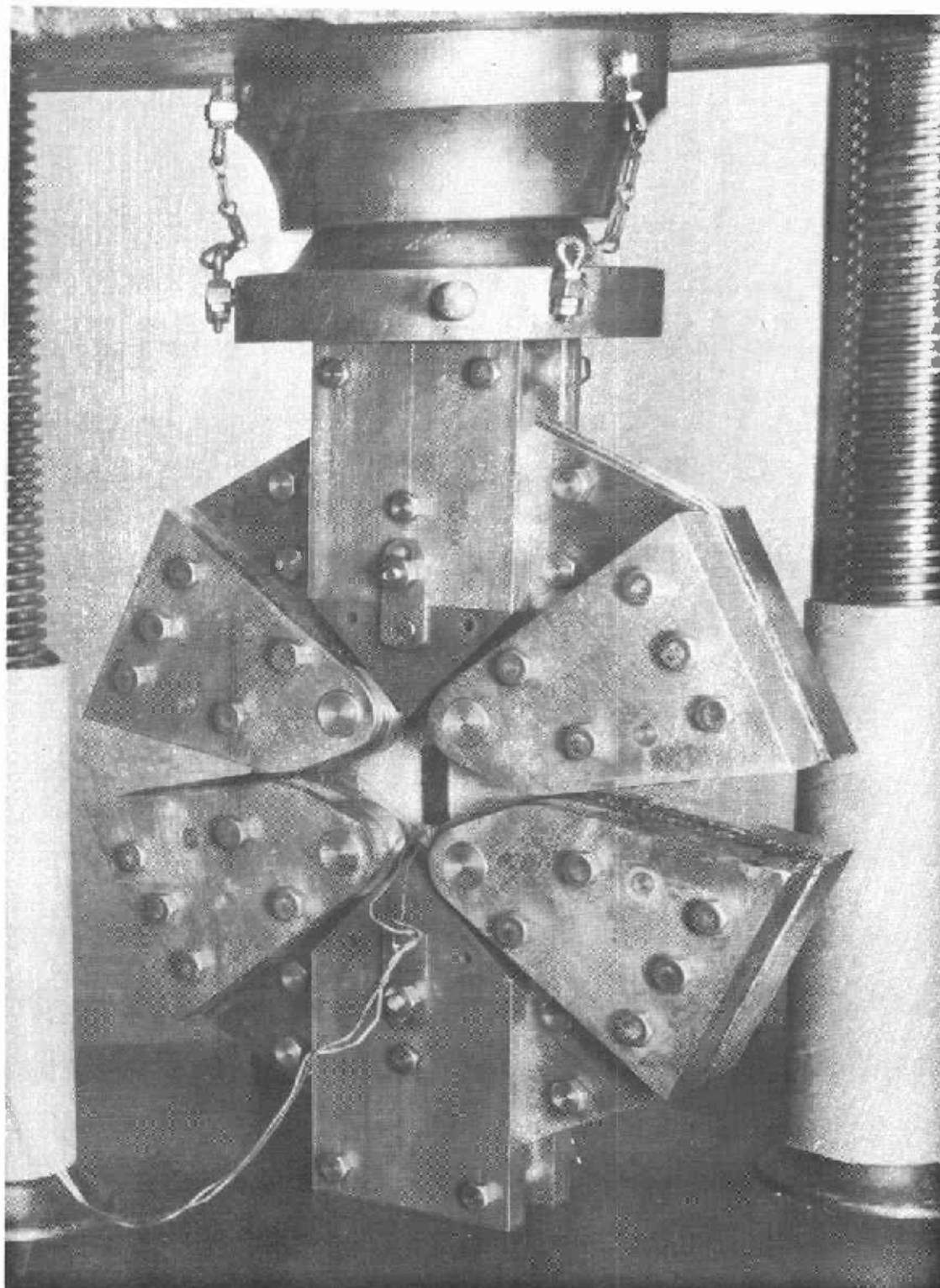


Figure 8.--Method of testing panel shear specimens of glass-fabric laminate. Strain measurements can be made with metaelectric gages (shown) or with mechanical gages employing dials.

Z M 50053 F

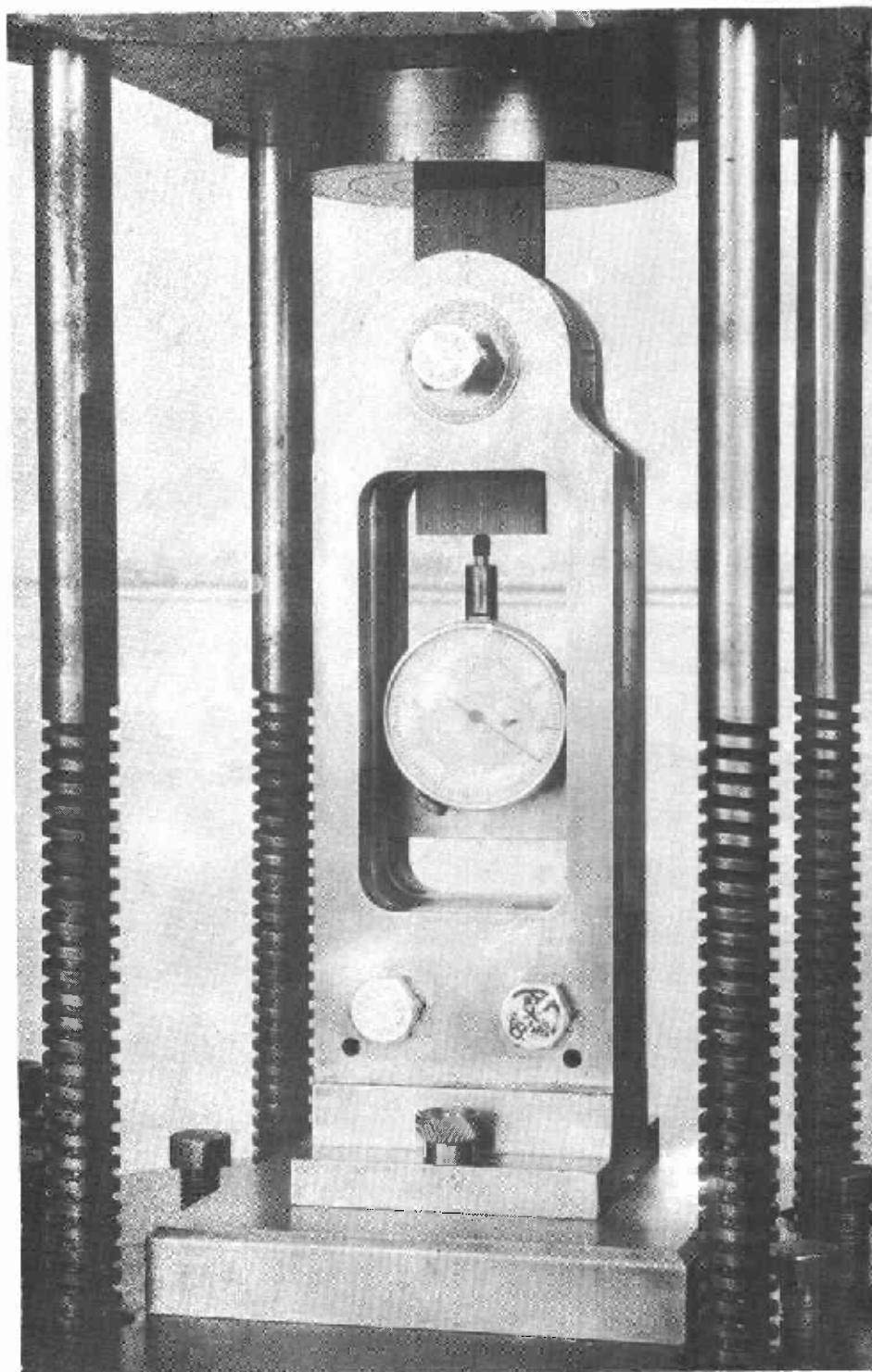


Figure 9.--Apparatus employed for bearing tests of glass-fabric-laminate specimens.

Z M 69876 P

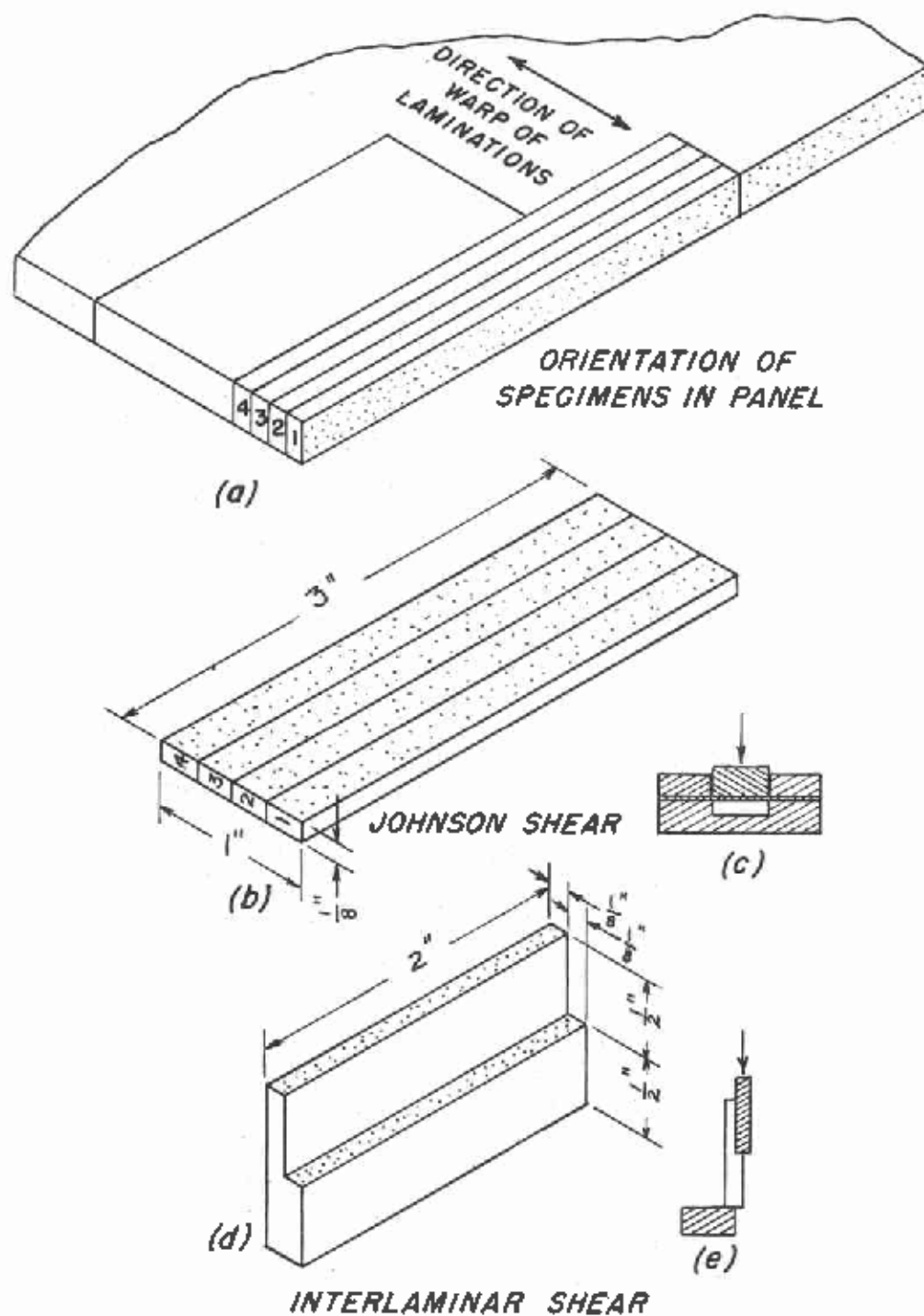


Figure 10.--Johnson and interlaminar shear specimens of glass-fabric laminate, showing methods of cutting and testing 0° specimens.

2 M 80099 P

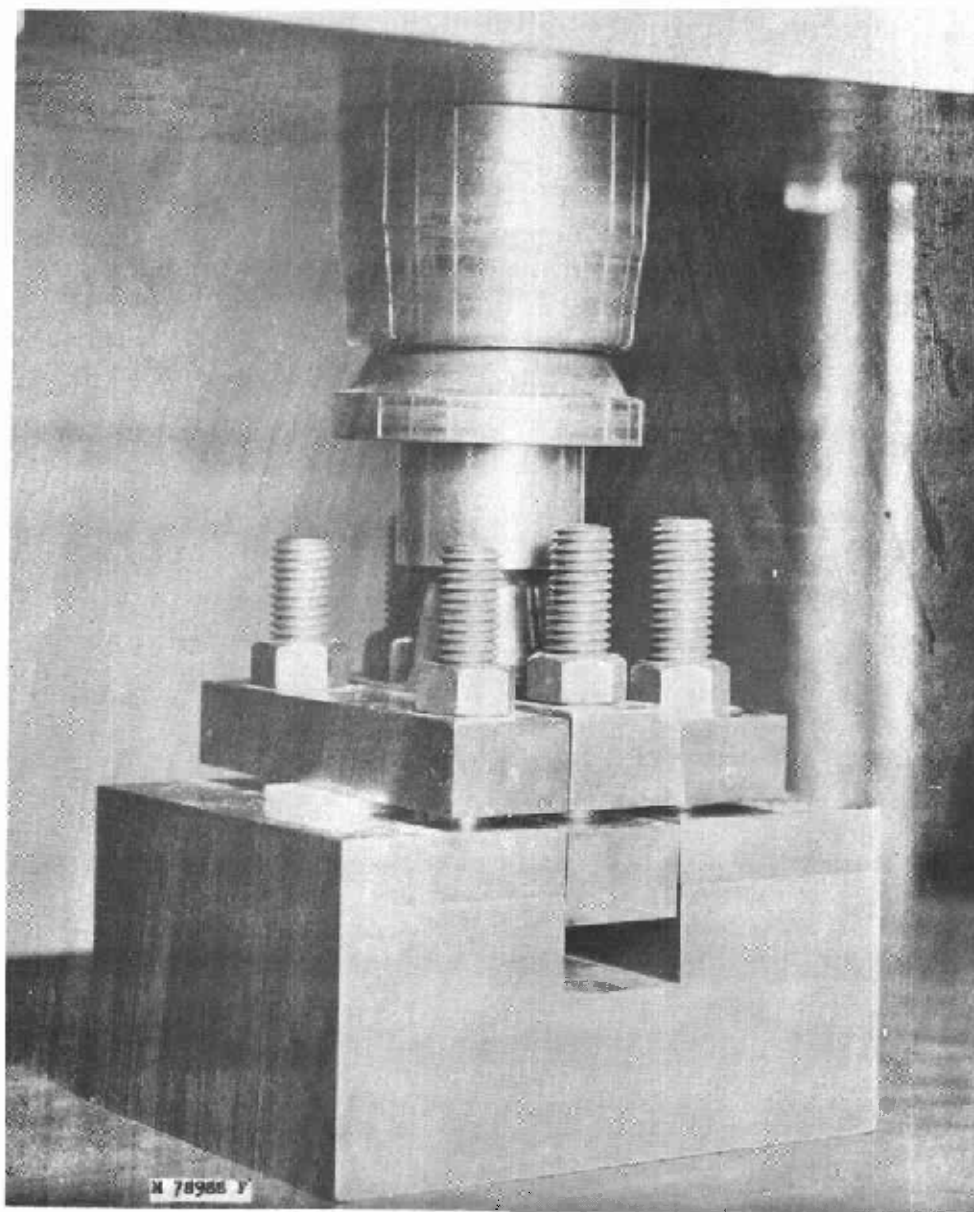


Figure 11.--Edgewise shear test of glass-fabric-laminate specimen
employing Johnson shear tool.
Z M 80084 F

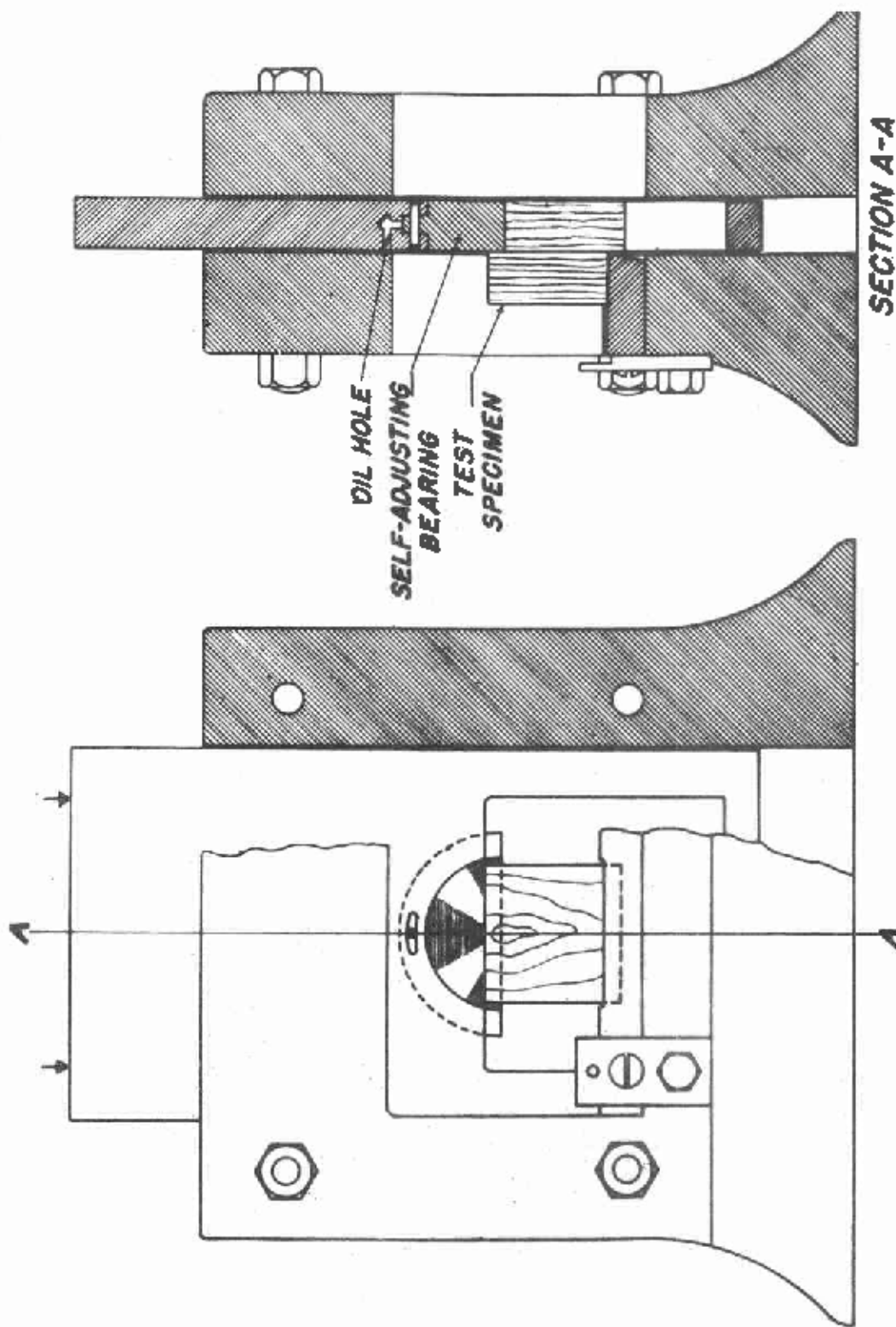


Figure 12.--Blue-line shear apparatus employed in making interlaminar shear tests of glass-fabric-laminate specimen. Type of specimen is shown in figure 8d.

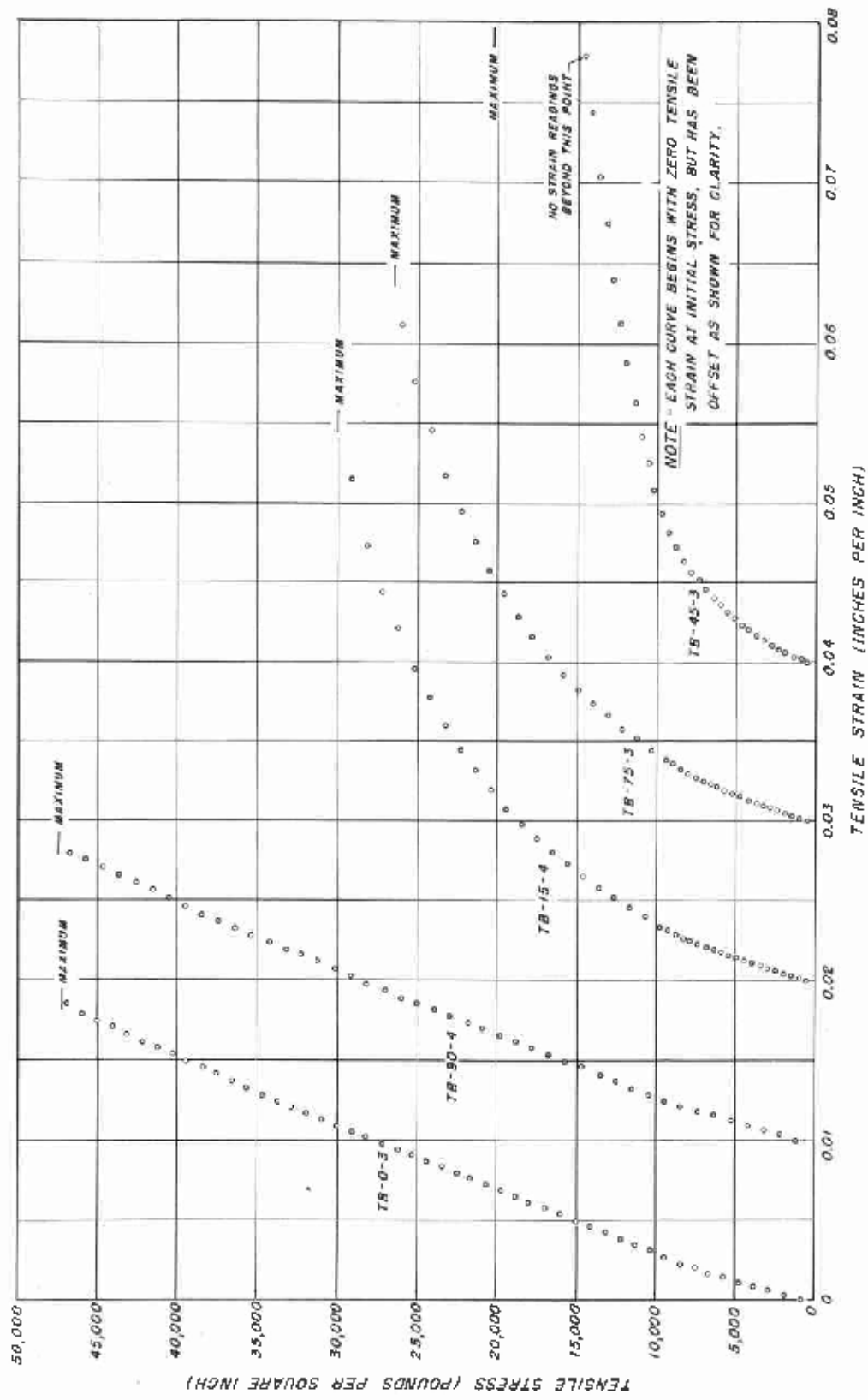


Figure 13.--Typical stress-strain curves for parallel-laminated glass-fabric-laminate tension specimens, tested at 0, 30, 45, 60, 75, and 90 degrees to the warp of the fabric.

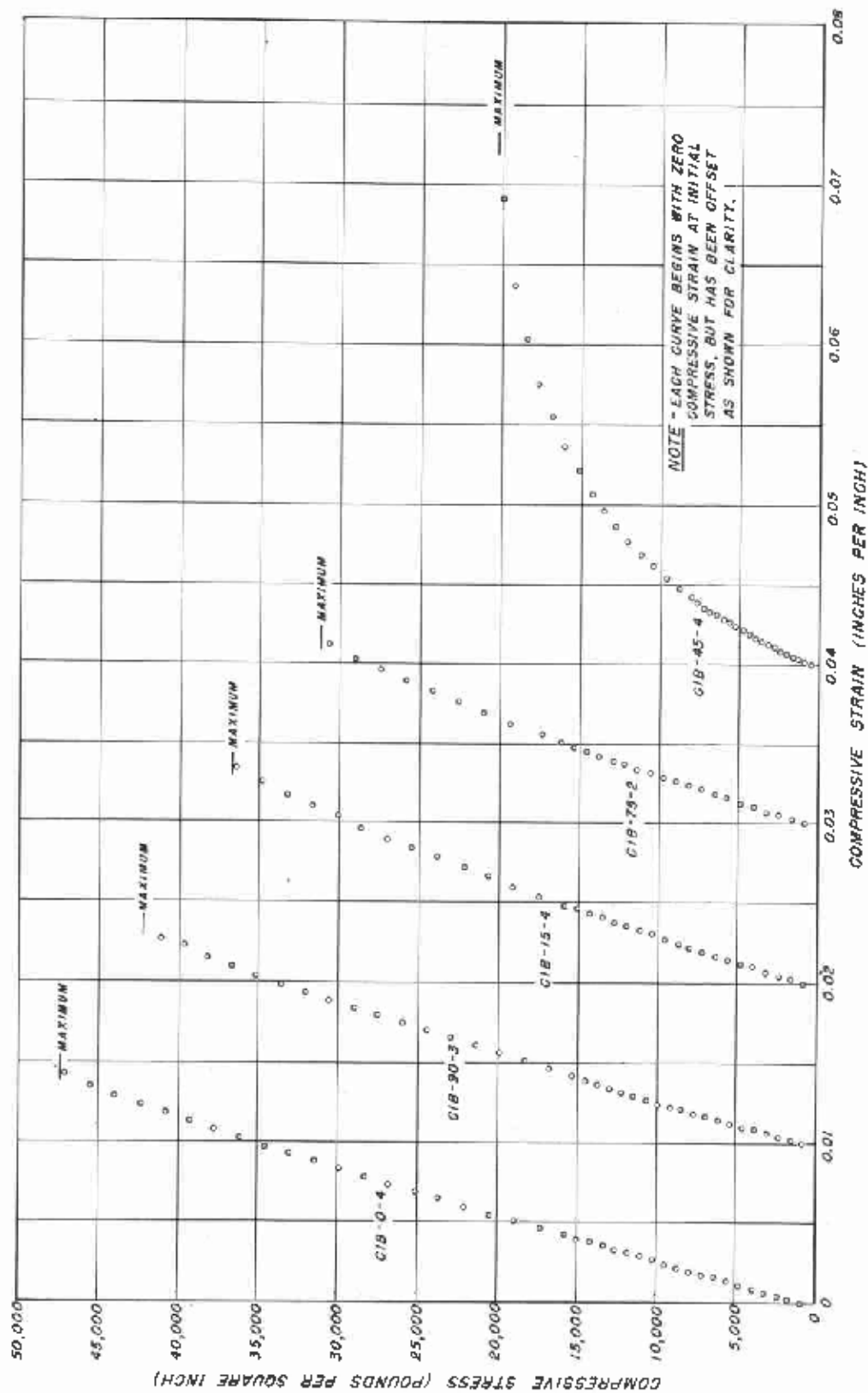


Figure 11.—Typical stress-strain curves for parallel-laminated glass-fabric-laminate compression specimens, tested at 0, 30, 45, 75, and 90 degrees to the warp of the fabric.

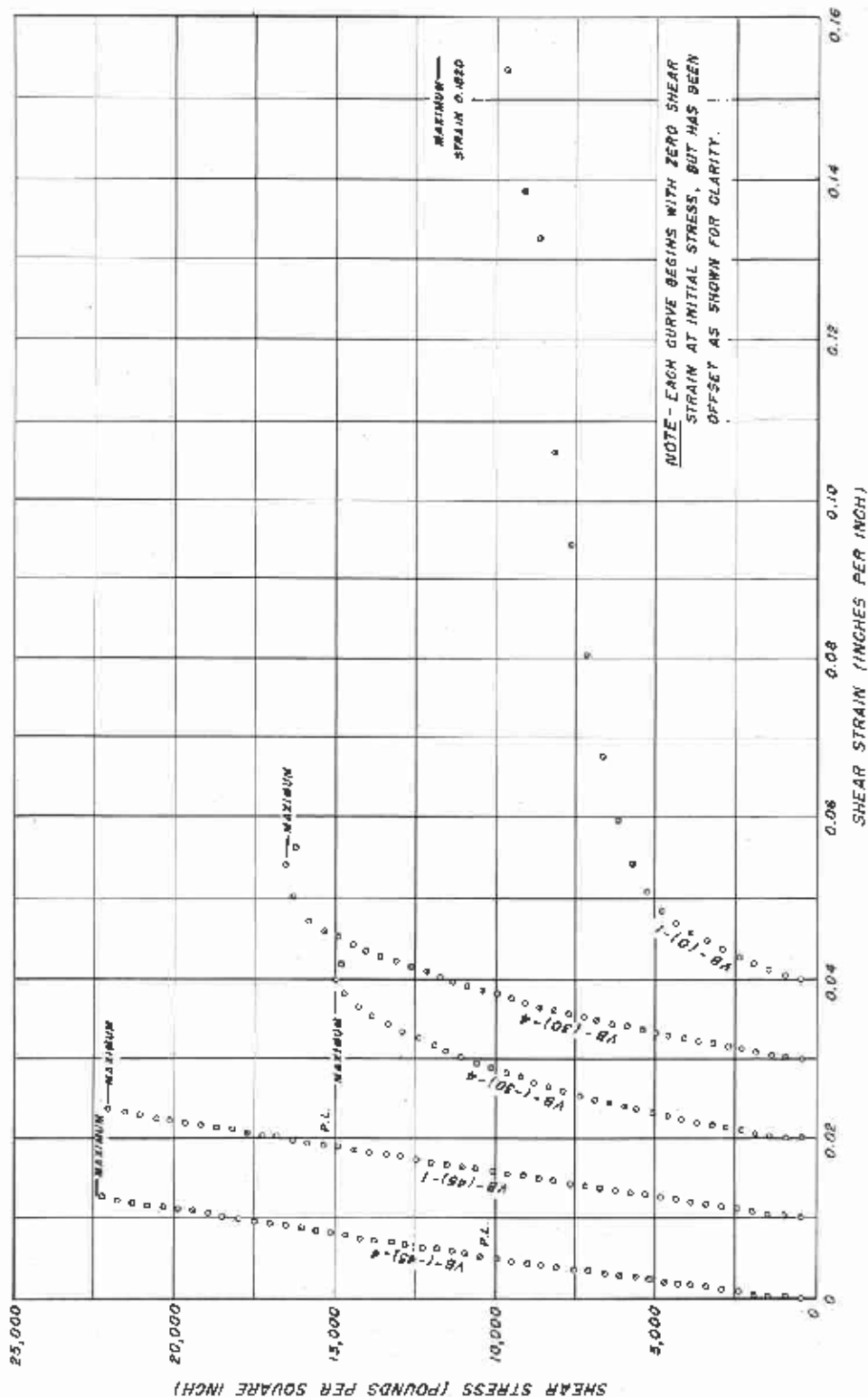


Figure 15.--Typical stress-strain curves for parallel-laminated glass-fabric-laminate shear specimens, tested at -45, 45, -30, 30, and 0 degrees to the warp of the fabric.

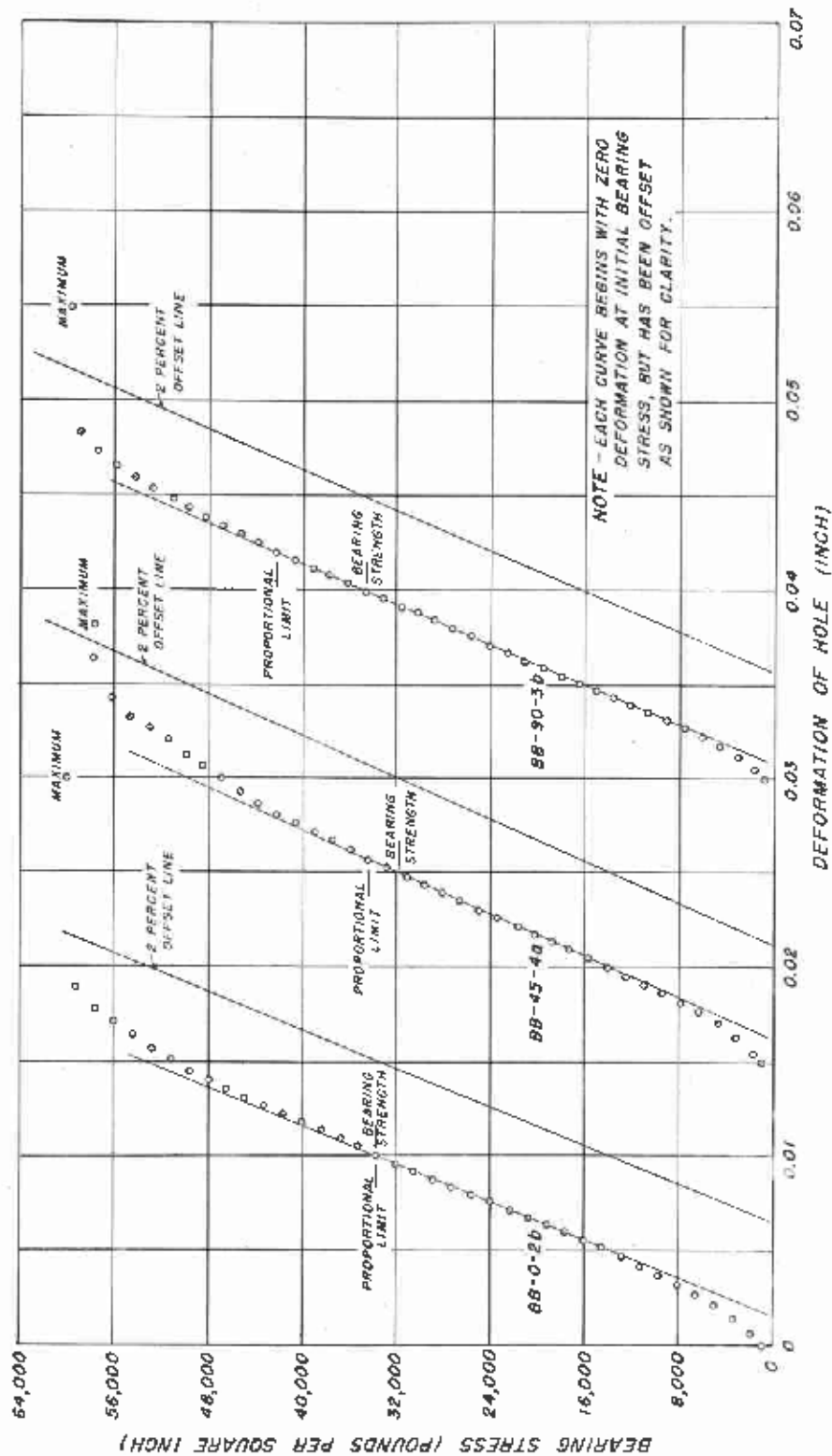


Figure 16.--Typical stress-deformation curves for glass-fabric-laminate bearing specimens.

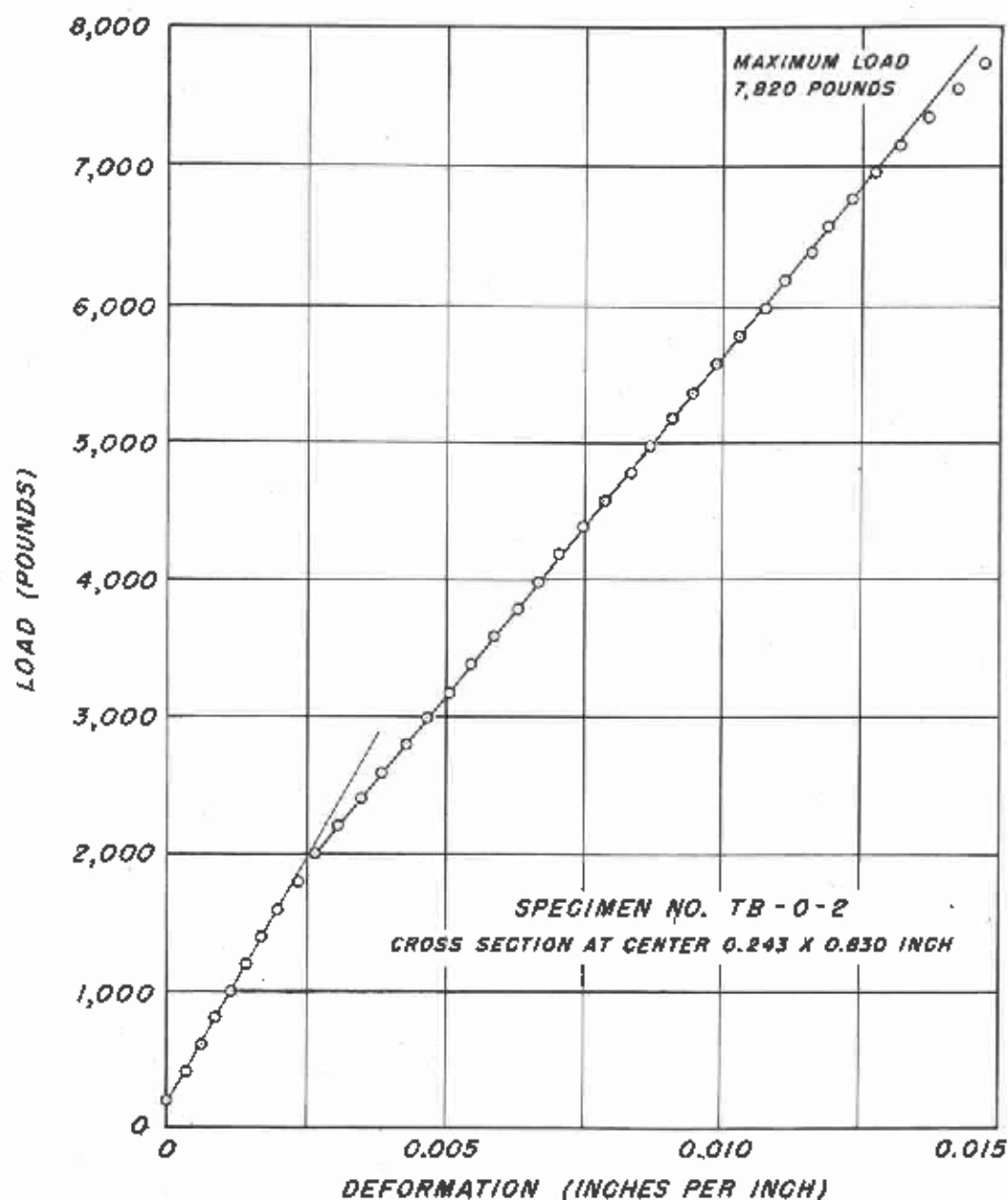


Figure 17.--Load-deformation curve for glass-fabric-laminate tensile specimen. Strains measured by Marten's mirrors.

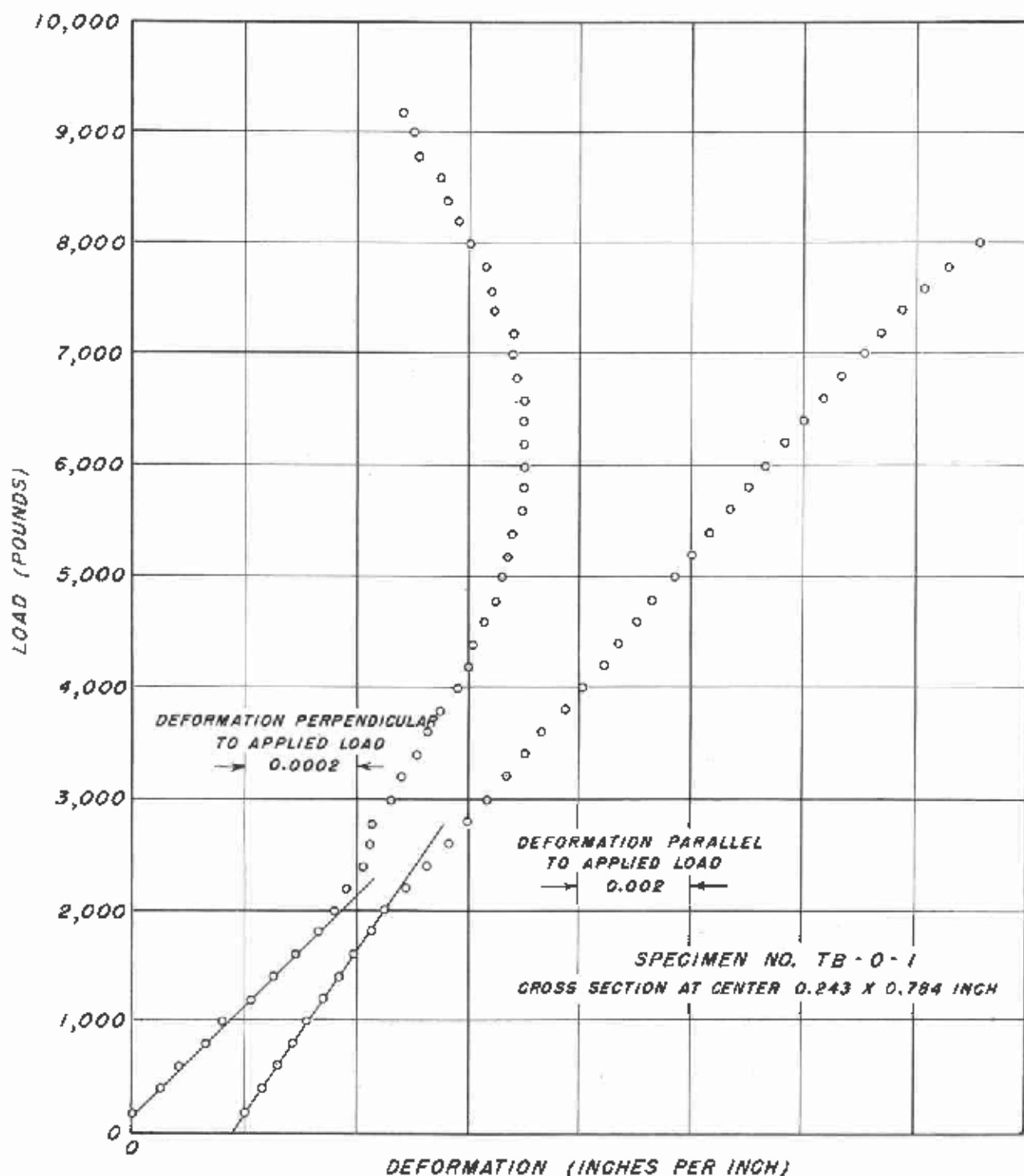


Figure 18.--Load-deformation curves for glass-fabric-laminate tensile specimen. Strains measured by 1/4-inch-gage-length metaelectric strain gages.

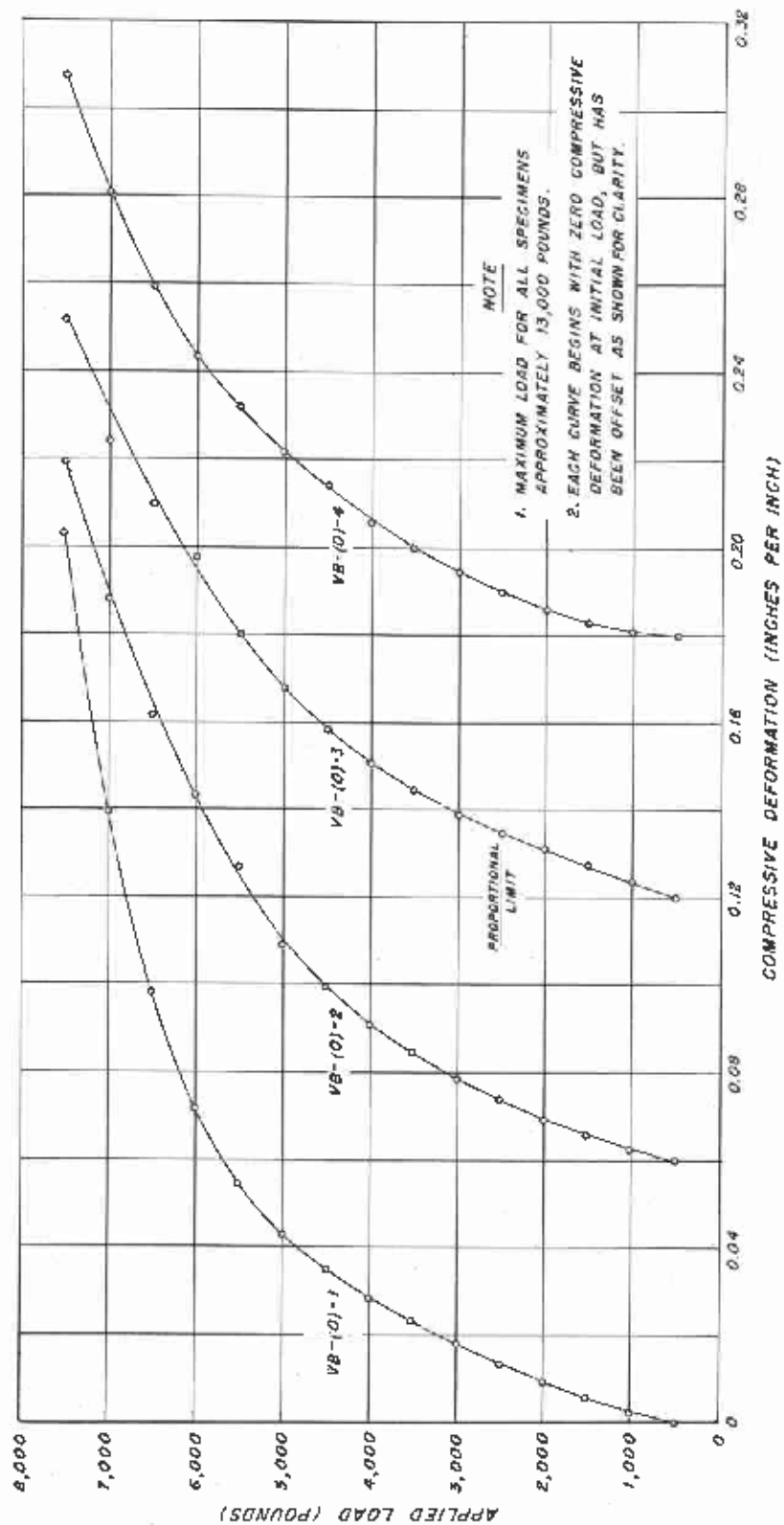


Figure 19.--Initial load-deformation curves for parallel-laminated glass-fabric laminate shear specimens, loaded at 0 and 90 degrees to the warp of the fabric. Deformation measured in plane of maximum compressive strain.

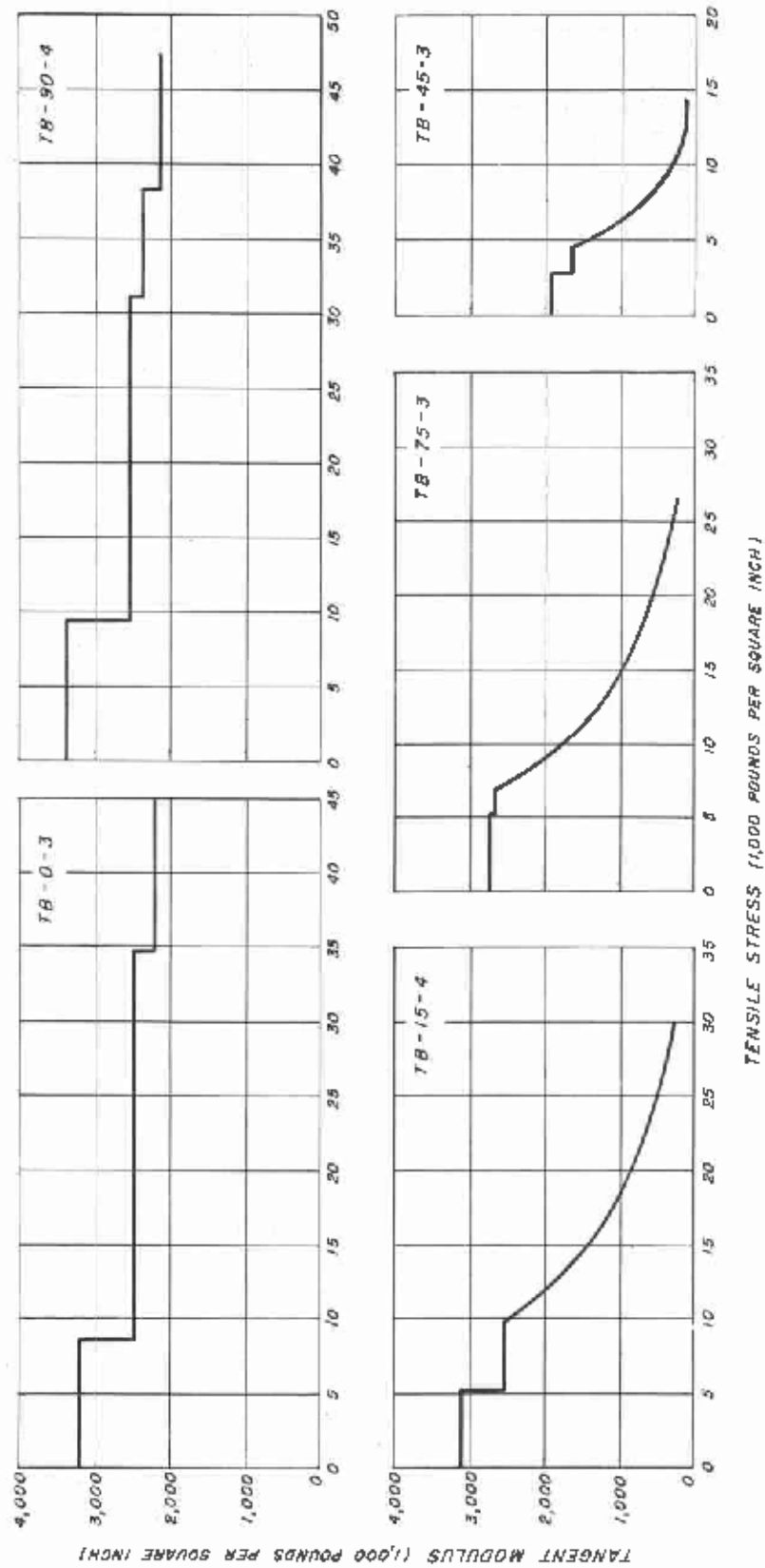


Figure 20.---Relationship between tangent modulus and tensile stress for typical glass-fabric-laminate tension specimens, based on curves of figure 13.

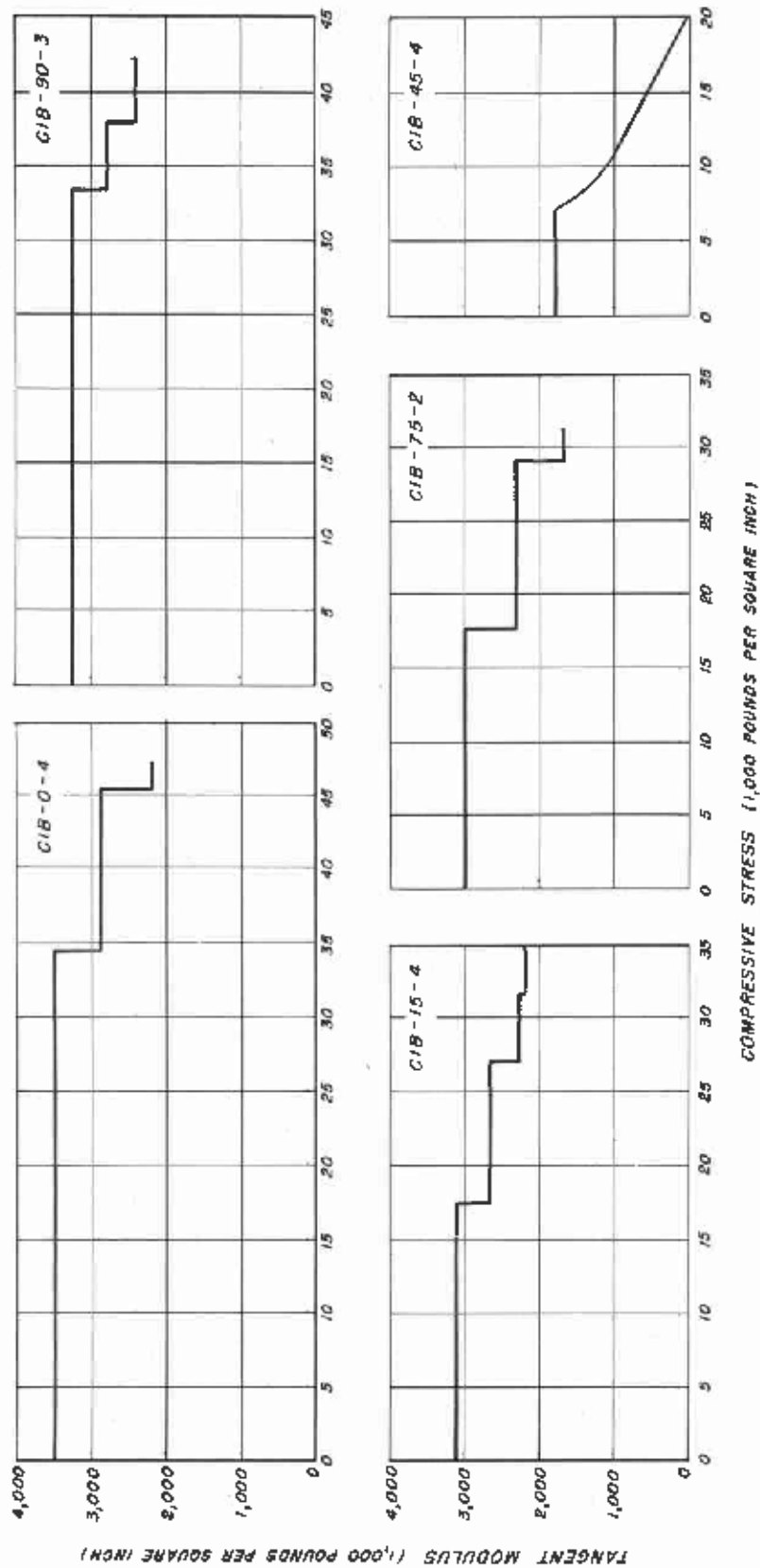


Figure 21.---relationship between tangent modulus and compressive stress for typical glass-fabric laminate compression specimens, based on curves of figure 14.

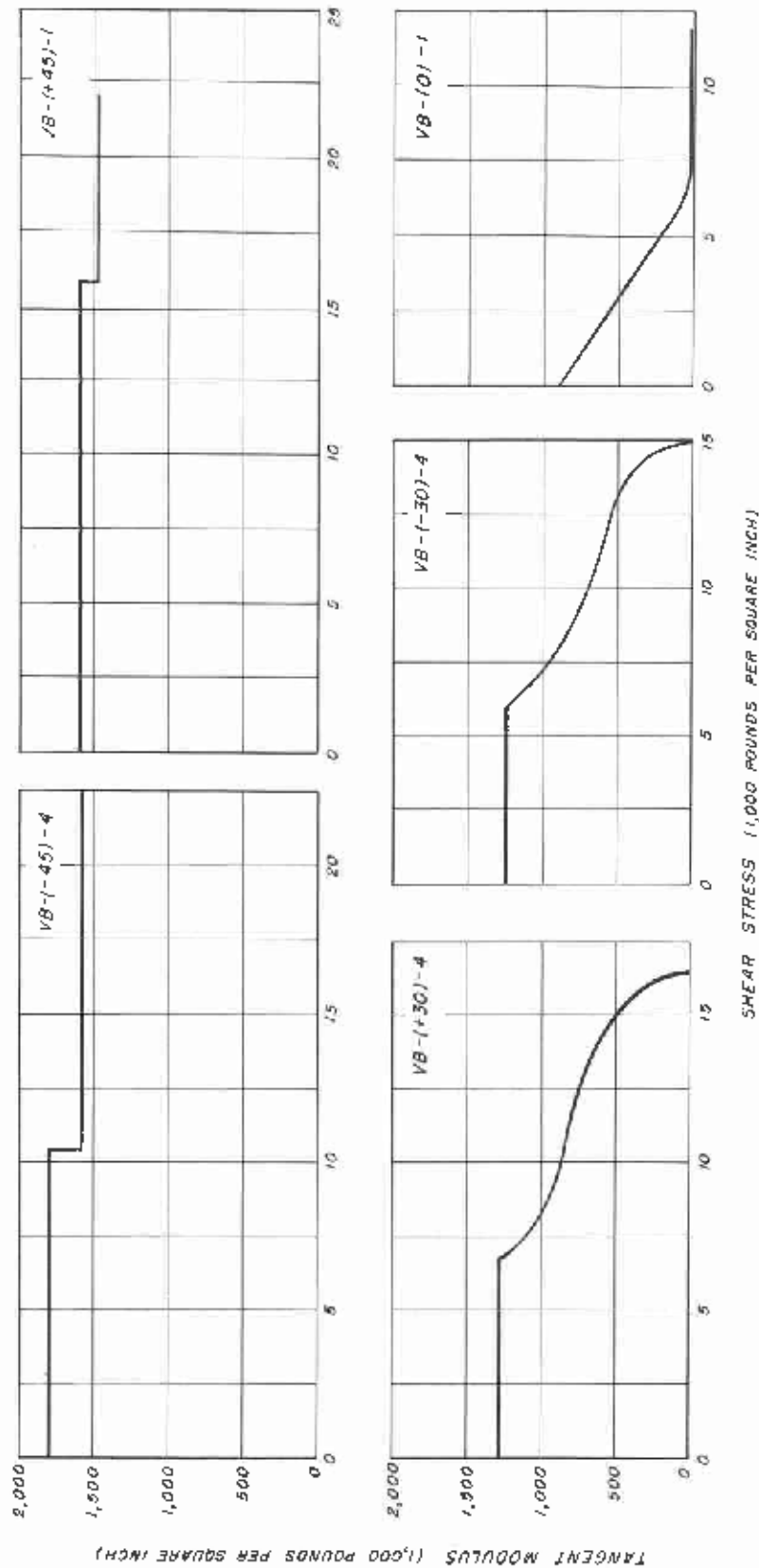


Figure 22.---Relationship between tangent modulus and shear stress for typical glass-fabric-laminate shear specimens, based on curves of figure 15.

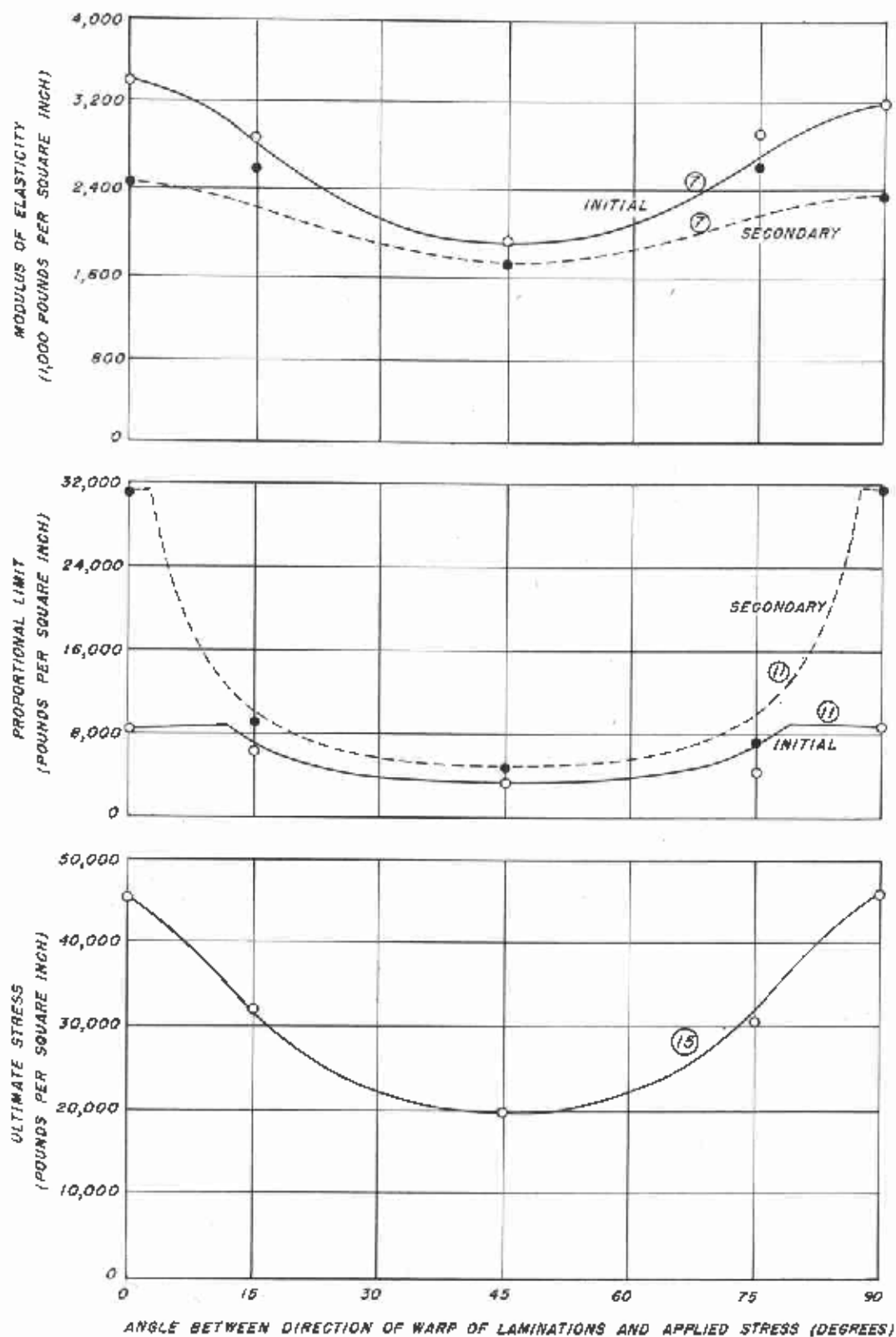


Figure 23.--Theoretical and experimental values from tension tests of glass-fabric-laminate specimens.

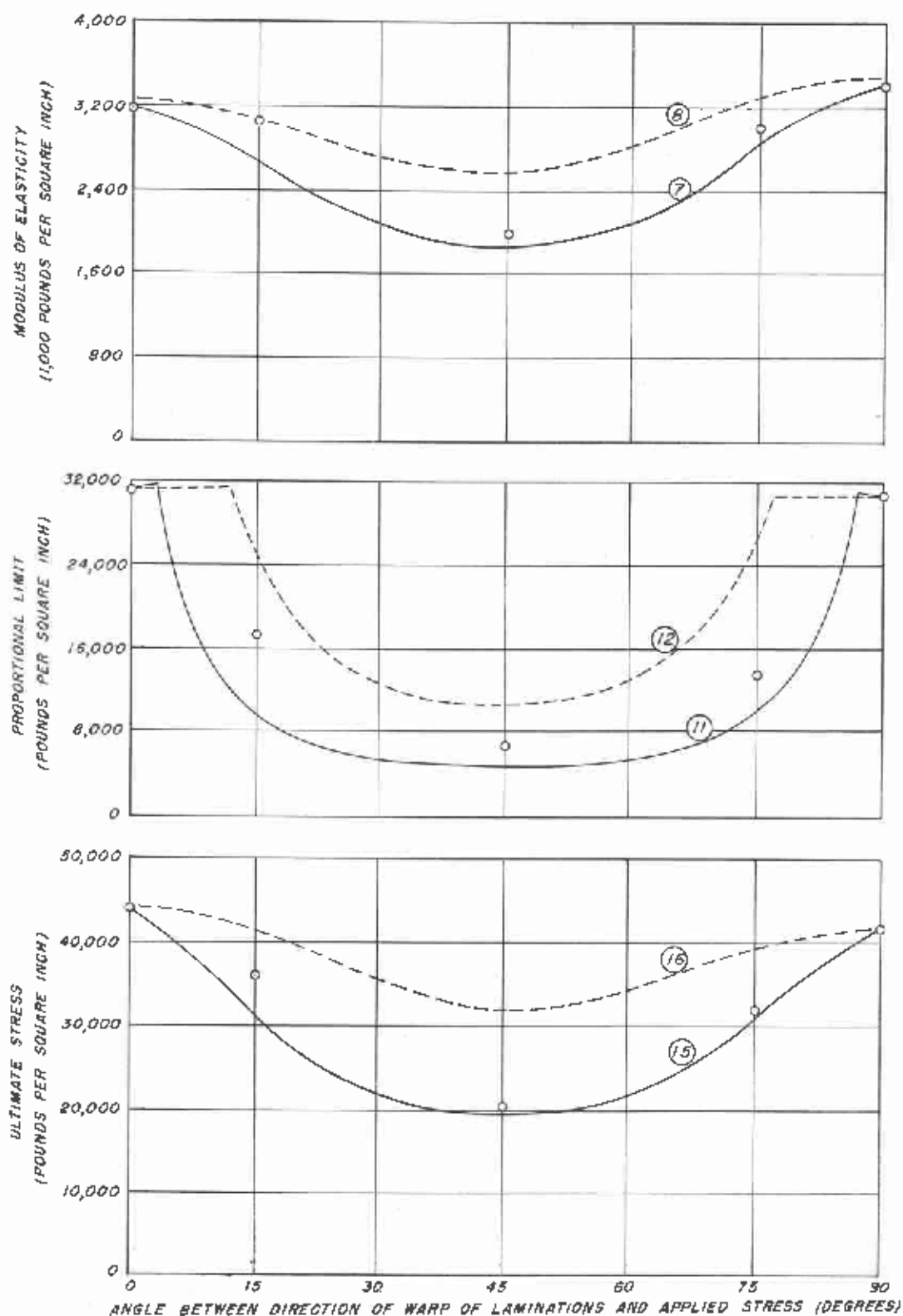


Figure 24.--Theoretical and experimental values from compression tests of glass-fabric-laminate specimens. Specimens 1/4-inch thick, 1 inch wide, and 4 inches high, tested in "pack" test.

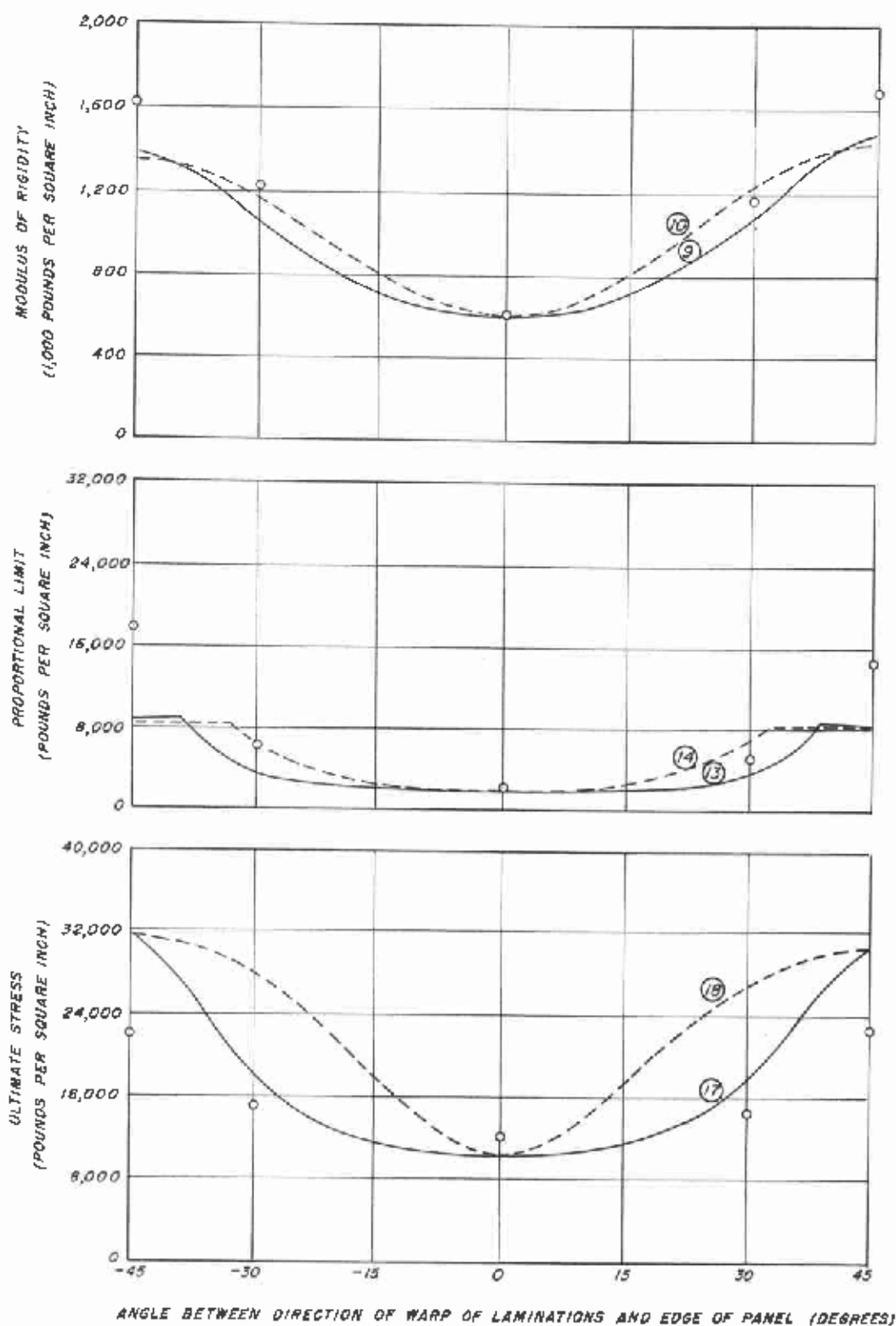


Figure 25.--Theoretical and experimental values from panel shear tests of glass-fabric-laminate specimens. Theoretical values computed by using initial tensile values.

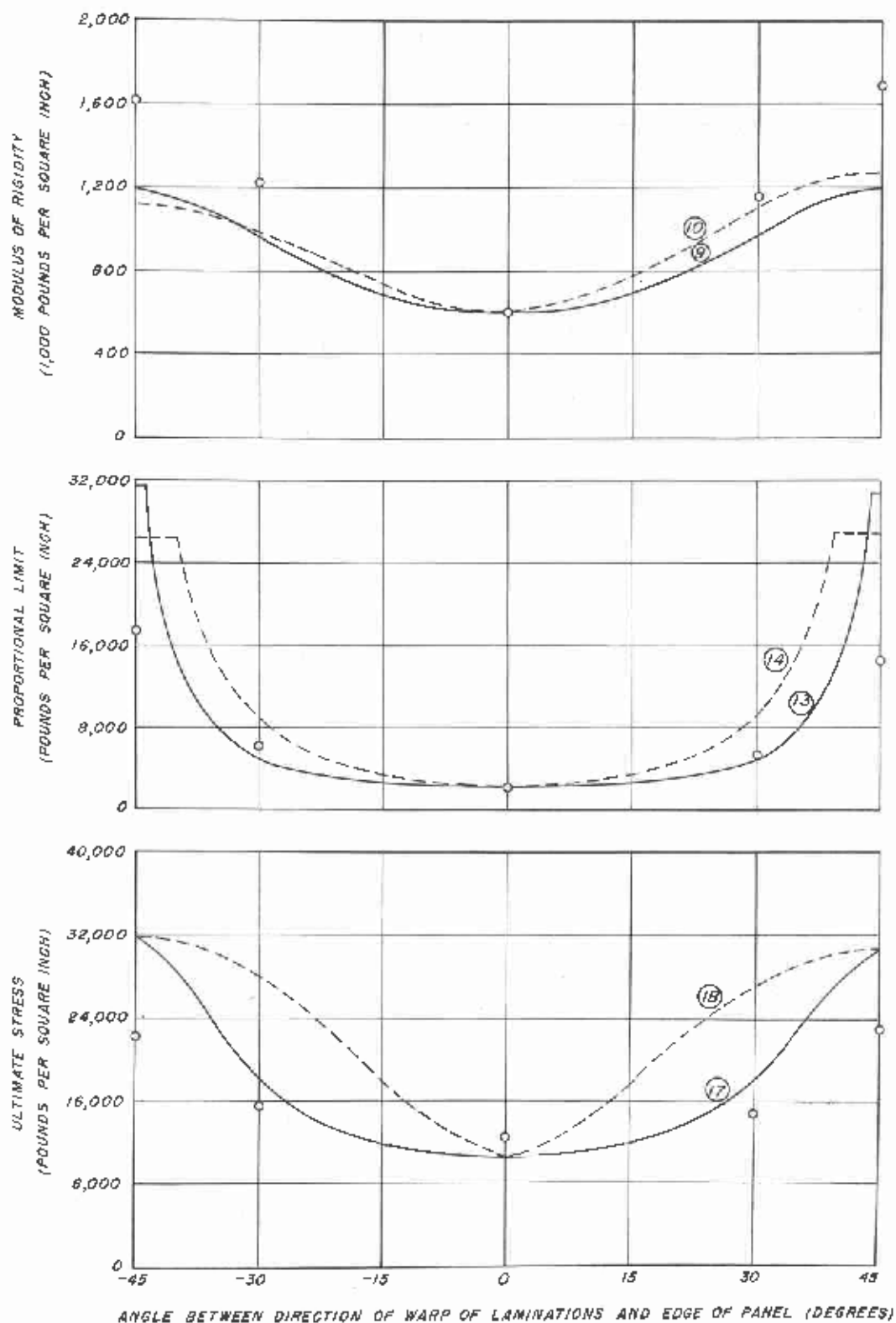


Figure 26.—Theoretical and experimental values from panel shear tests of glass-fabric-laminate specimens. Theoretical values computed by using secondary tensile values.

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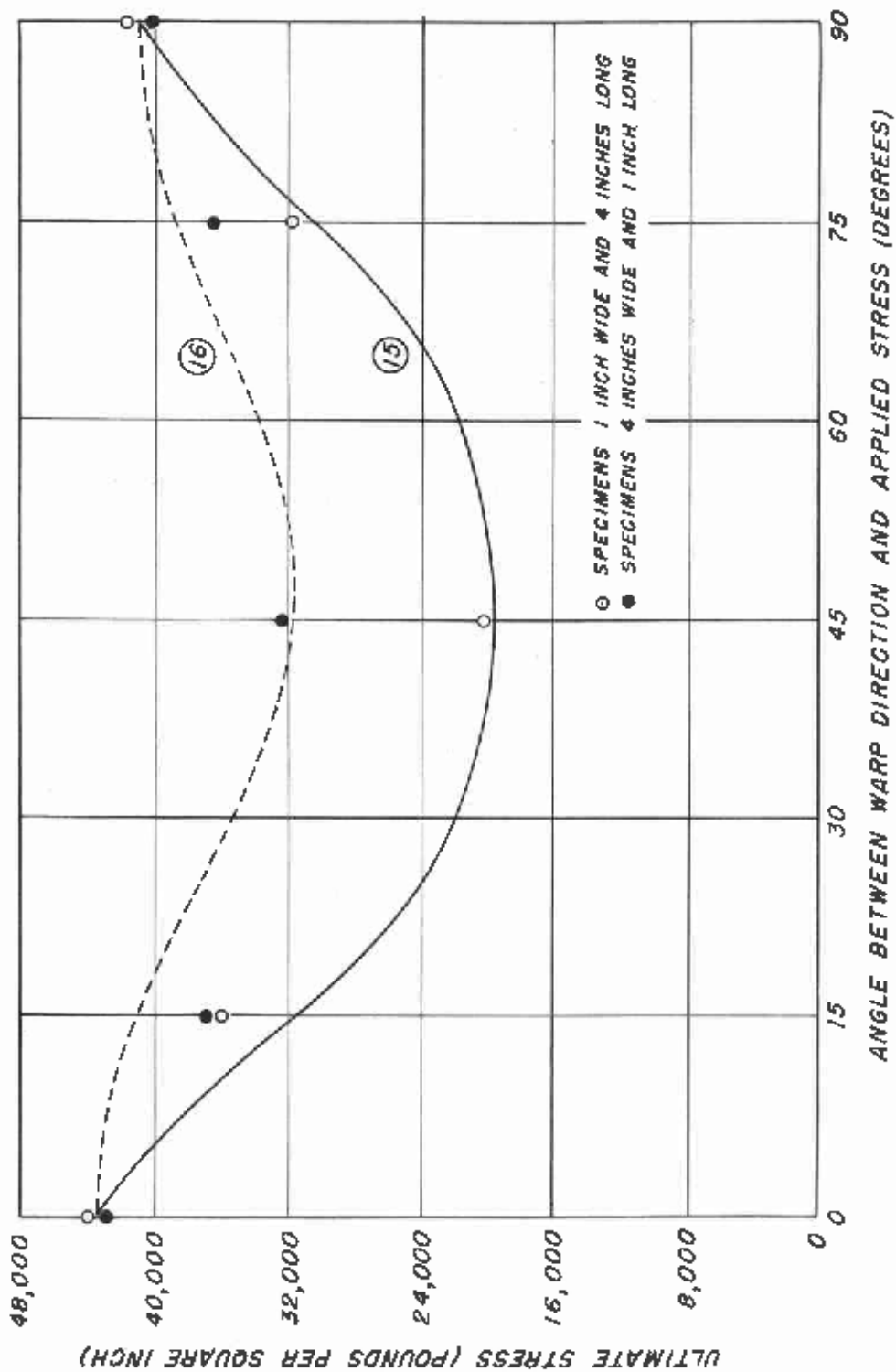


Figure 27.--Effect of width upon the ultimate stress in compression of glass-fabric-laminate specimens as compared to theoretical curves.

2M 80114 F