EFFECT OF THICKNESS ON STRENGTH OF GLASS-FABRIC-BASE PLASTIC LAMINATES

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EFFECT OF THICKNESS ON STRENGTH

OF GLASS-FABRIC-BASE PLASTIC LAMINATES[1]

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Summary

This investigation was conducted to determine the effect of thickness on the tensile, compressive, and flexural strength of glass-fabric-base plastic laminates and of such laminates molded as facings on sandwich constructions. Tests were made on laminates 1/64, 2/64, 3/64, and 1/4 inch thick and on facings 1/64, 2/64, and 3/64 inch thick. The results of these tests show (1) that the tensile, compressive, and flexural strengths of glass-fabric-base plastic laminates decrease with decreases in thickness; (2) that the tensile and compressive strengths of any thickness of the five types of laminate tested were found to conform to the empirical relationship, $S = S_m - a/t$; (3) that neither the shape nor the test method used on the tensile or compressive specimens affected the trend indicated by this empirical relationship; (4) that the flexural properties at any thickness was found to conform to the empirical relationship, $S = S_m - a/t^2$; (5) that the effect of the experimental variations in resin content on strength was a small percent of the effect of thickness on strength so that these empirical relationships for all primary, practical purposes represent the effect of thickness alone on the respective strength properties.

The average quantitative values of strength that result from this series of tests on 5 types of fabrics indicate (1) that if the tensile strength of an infinitely thick laminate is the optimum or 100 percent value, as the empirical relationship indicates, then the tensile strength of a 1/16-inch-thick laminate would be about 90 percent of the optimum, of a 1/32-inch-thick laminate, about 79 percent, and of a 1/64-inch-thick laminate, about 50 percent; (2) that if the compressive strength of an infinitely thick laminate were also 100 percent, then the compressive strength of a 1/16-inch-thick laminate would be about 86 percent, of a 1/32-inch-thick laminate, about 72

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

percent, and of a 1/64-inch-thick laminate, about 36 percent; and (3) that if the flexural strength of an infinitely thick laminate were 100 percent, then the flexural strength of thinner laminates would be 98 percent at 1/16 inch thick, 94 percent at 1/32 inch thick, and 72 percent at 1/64 inch thick.

Introduction

Results of compressive tests of sandwich constructions having balsa-wood or honeycomb-type cores and glass-fabric-base facings have shown that the ultimate compressive strength in the facings was considerably lower than the ultimate compressive strength reported for the same glass-fabric-base laminates that had been fabricated independently of core materials. Results of tests presented in Forest Products Laboratory Report No. 1810 (5)[3] show compressive-strength values as low as 16,000 pounds per square inch for the stress at failure in facings of a sandwich having glass-fabric-base facings (112-114 fabric, cross-laminated) and balsa-wood core. The compressive strength of these facings, tested independently of the core material, was only 19,840 pounds per square inch. The results of tests presented in Forest Products Laboratory Reports Nos. 1804 (4), 1809 (2), and 1558 (3) show compressive-strength values as low as 13,100 pounds per square inch at failure for glass-fabric-base facings having 112-114-type fabric and a polyester-type resin. These values may be compared with the results of tests on laminates made with the same fabric as presented in Forest Products Laboratory Report No. 1821 (1), where the compressive strength was shown to be on the order of 37,000 to 39,000 pounds per square inch.

Certain differences are recognized as affecting these strength values. The low values were obtained from thin facings fabricated by wet-laminating on strong but porous cores. The high values were obtained from thick (1/4-inch) panels that were laminated between the platens of a hot press. When sandwich facings are wet-laminated onto a core, it is known that some resin either bleeds into the core adjacent to the facing or collects on the cell walls of honeycomb material as fillets. Also, in sandwich fabrication, there is a variation in pressure on the facings during the curing period. There is a high-pressure area where the facing is in contact with the cell walls and a low-pressure area in the center of the cell.

The results cited above were obtained from facing material and laminates having widely different thicknesses. The thickness of the facings that had low strength values was about 1/64 inch, while the thickness of the laminates that had high strength values was about 1/4 inch. The results of tensile and compressive tests on laminates 1/16, 1/4, and 1/2 inch thick, as reported in Forest Products Laboratory Report No. 1807 (6), show strength differences among these 3 thicknesses. Since facings are commonly

[3]Underlined numbers in parentheses refer to Literature Cited at the end of this report.

as thin as 1/64 inch, much thinner than the laminates generally used for determination of mechanical properties, this investigation was proposed to determine the flexural, tensile, and compressive strengths of thin sheets, 1/64, 2/64, and 3/64 inch thick of glass-fabric-base laminates, made as sandwich facings and as laminates, to permit comparison with properties at laminate thicknesses of 1/4 inch. A relation between properties and thickness would permit designers to adapt ordinarily available data to their particular application. The investigation did not include a detailed study of fabrication variables such as effect of pressure or resin content or of both, but was intended to show the collective effect on the unit strength of a thin laminate, such as a sandwich facing, compared with the unit strength of a similar, but thicker, laminate.

The experimental testing and analysis progressed in 3 stages: First, tensile, compressive, and flexural strengths were determined on 4 thicknesses of a conventional glass-fabric-base plastic laminate and on 3 thicknesses of similar laminates wet-laminated on 2 core materials; the second stage was to determine the tensile and compressive strength of various thicknesses of laminates made with different fabrics; and the third stage was to check the test methods and analysis used in the previous 2 stages and included a comparison of properties of thick laminates formed by bonding together several thin laminates with the properties of a similar thick laminate formed in 1 operation.

Materials

Glass-fabric-base plastic laminates and sandwich panels having glass-fabric-base facings were made by the Forest Products Laboratory for use in this investigation. All of the panels were of a cross-laminated construction using a laminating resin (resin 2) of the alkyd-styrene type of polyester. The panels were made 18 inches square and in thicknesses that varied from 1/64 to 1/4 inch. The panels were made with a molding pressure of 14 pounds per square inch at 220° to 250° F. for 1 hour and 40 minutes.

Panels fabricated for the first series of tests were made without special attention to render them void-free, and consequently these laminates and sandwich facings contained voids; all other panels were void-free. The sandwich constructions in the first series were made by the wet-laminating process, that is, they were made by impregnating the fabric, then assembling this fabric on either a balsa-wood core or a glass-fabric honeycomb-type core, and then curing the assembly with heat and pressure. The sandwich construction used in the second series was made by bonding a previously made laminate to the core with a single sheet of impregnated fabric. Both types of core material had a density of about 7 pounds per cubic foot. The honeycomb core was further identified by its 1/4-inch cell size. Each core was 1/2 inch thick. Since the core materials served only as a supporting medium during fabrication of the facings, and since they were subsequently removed to facilitate the testing of the facings only, no more descriptive data were obtained concerning them.

The initial series of panels was made with 112-114-type fabric; the second series repeated the use of 112-114- and added 181-114- and 183-114-type fabrics; and the third series repeated the 181-114-type fabric.

Data on resin content, specific gravity, Barcol hardness, and number of plies in each panel are presented in tables 1, 2, and 3 for series 1, 2, and 3, respectively. The resin content of the laminates in the first series (table 1) was determined from their dimensions and weights and was checked by the ignition method described in Federal Specification L-P-406 b, Method No. 7061. The resin content of the facings was determined only by the ignition method after they had been removed from their respective cores and after they were free from excess resin due to fillets. Resin contents of laminates in the second and third series were determined from their weight and dimensions.

As indicated earlier, some tests in the third series were made on specimens from panels formed by bonding together layers of thin laminates. These are indicated in table 3 by panels 6-18SB, 6-18USB, 6-29SB, and 6-29USB. The first 2 were formed by bonding six 4-inch-wide strips of the 2-ply laminate, and the others by bonding three 4-inch-wide strips of the 4-ply laminate, with a resin-impregnated layer of 181-114 fabric at each interface. In some cases, the original surfaces of the thin laminate were lightly sanded before bonding (SB) and, in other cases, were left unsanded (USB).

Test Specimens

Strength tests in tension, compression, and flexure were made on specimens cut both from the laminated panels and from the sandwich facings. The cutting and machining of specimens from the single sheets of laminated panels were done on a carborundum saw and grinder. The cutting and machining of specimens from the facings of the sandwich constructions, however, required extra operations. The tension specimens, for example, were cut and shaped as a sandwich specimen; then the facings were separated from the core by a saw cut that was as close to the facing as irregularities in the resin line permitted. Final sanding of this inner surface removed the fillets and irregularities, leaving what was considered the effective thickness of the facing. In series 1, 10 specimens were cut for each strength test, 10 from each laminate, and 5 from each facing of each sandwich construction. In series 2, 5 specimens were cut for each strength test except when bundles of specimens were used in compressive tests, then 3 to 5 specimens were used to make a bundle. In series 3, 6 specimens were cut for each strength test, except again when bundles of specimens were used in compression tests. All the specimens from a given cross-laminated sheet were cut parallel to each other.

The tension specimens were 3/4 by 9 inches overall, with a 1/2-inch-wide net section conforming to the type 1 tension specimen of Federal Specification L-P-406a, Method 1011. The specimens were tested at a rate of movable-head travel of 0.015 inch per minute so that load-deformation data could be obtained.

The compression specimens in series 1 were 2 inches wide, and all specimens except those 1/4 inch thick were cut to a height equal to 4 times their thickness plus 1 inch. This additional 1 inch was allowed on the 5-, 10-, and 15-ply material to provide 1/2 inch for clamping at each end of the specimen. The clamps at each end were two 1/2-inch-square steel bars, 3 inches long, bolted together. The distance between the clamping bars, (free length of the specimen) was equal to 4 times the thickness of the specimen, conforming to Federal Specification LP406b, Method 1021. The 84-ply, 1/4-inch-thick specimens were cut to a height equal to 4 times their thickness, i.e., 1 inch, and were tested without end clamps. The specimens were loaded at a rate of head travel of 0.03 inch per minute to maximum load. No attempt was made to obtain load-deformation data.

Two types of compression specimens were used in series 2. One type was a rectangular specimen necked down to a reduced cross section, while the other was not necked down. The necked-down specimen was 1-1/2 inches wide at the bearing ends and was reduced to a 1/2-inch-wide net section by means of a 4-inch radius on each side. The length was 3-15/16 inches (the length of the jig) plus 4 times the specimen thickness. The rectangular specimen, with a uniform cross section, was 1/2 inch wide by 2-7/8 inches (the length of the jig) plus 2 times the specimen thickness in length.

Compression tests in series 3 were made on the necked-down specimens described for series 2. In addition to tests of single specimens, groups (bundles) of specimens were tested. In some cases, a number of single specimens were bonded and tested as a unit; in other cases, groups of unbonded specimens were tested as a unit. A few specimens were sanded at the net section prior to test.

The flexure specimens were 1 inch wide and had various lengths depending on their thickness. The 84-ply, 1/4-inch-material specimens were 7 inches long so that they could be tested over a 6-inch span with a center load (Federal Specification LP406b, Method 1031). The thin specimens, however, were tested for their flexural properties as long columns, for which there is no standard test method. The lengths of these columns were such that the direct stress would be small compared to the bending stress and the lateral deflection at failure would be large compared to the thickness of the specimen. These lengths were 7/16, 13/16, and 1-1/4 inches for 0.015-, 0.030-, and 0.045-inch-thick specimens, respectively. After the columns had been cut to length, their ends were carefully rounded about an axis parallel to the wide dimension to provide a round-end condition. The columns were loaded between parallel plates in a compression jig, which prevented lateral movement of the loading heads. Lateral deflections were obtained during the test by means of a 0.0001-inch dial at the center of the 0.015-inch-thick specimens and a 0.001-inch dial at the center of the other specimens.

Since the method for obtaining the flexural properties from column specimens is different than the ordinary simple-beam flexure test, the steps necessary to compute the flexural properties from the column data are shown below:

(1) the modulus of elasticity, $\underline{E}$, was computed from the Euler column formula

$$E = \frac{kP_{cr}\ell^2}{\pi^2 \, bd^3/12}$$

where $\underline{k}$ = a constant depending on end condition. It is equal to 1 for round ends.

$\underline{\ell}$ = column length in inches.

$\underline{b}$ = width in inches.

$\underline{d}$ = thickness in inches.

$\underline{P_{cr}}$ = critical buckling load in pounds.

The critical buckling load was determined by the Southwell method, which consists of determining the slope of the deflection vs. deflection/load curve (8). The values of E as computed by this method are actually values of the tangent modulus at the value of P_{cr}. In order to have the experimental values of E equal to the initial tangent modulus, the lengths of the columns were made relatively long; hence it is believed that a value of P_{cr} below the proportional limit was obtained.

(2) The modulus of rupture or maximum stress in the outer fibers at failure was computed to include the direct stress, even though the latter was small, from the formula

$$S = \frac{6Pe}{bd^2} + \frac{P}{bd}$$

where $\underline{b}$ and $\underline{d}$ are the same as above.

$\underline{P}$ = load in pounds.

$\underline{e}$ = lateral deflection in inches.

It should be noted that the maximum stress does not necessarily occur at the maximum load or at the maximum deflection, but occurs at the maximum moment, Pe.

All of the test specimens were conditioned for about 2 weeks at a temperature of 75° F. and at 50 percent relative humidity before testing.

Discussion of Results of Tests

Series 1

Data on certain physical properties of the laminates and of the sandwich facings in series 1 are presented in table 1. These values show (1) that there is less than 2 percent difference in resin content between the thin and thick laminate; (2) that the composition of the thick laminate is the same as that shown in Forest Products Laboratory Report No. 1821 (1); and (3) that the resin content of none of the facings is so high as that of the laminates. The laminates have resin contents between 45.3 and 47.0 percent, while the facings have resin contents between 36.9 and 43.1 percent. These smaller resin contents reflect the losses that occur during fabrication of the sandwich facing. More resin was applied to the sandwich facings than to the laminates, but "squeeze-out," bleeding into the core, and formation of fillets, all of which were removed before resin-content determinations were made, account for the lesser final resin content. The variation in the resin content between the top and bottom facing probably indicates the presence of fillets that were not entirely removed.

The results of the tension, compression, and flexural tests for series 1 are tabulated in tables 4, 5, and 6, respectively. The results shown are the average values of 10 specimens from the laminates and of 5 specimens from each of the sandwich facings.

The accumulative effect of pressure variations, resin contents, and thicknesses on the strength properties is shown in figures 1, 2, and 3. These figures confirm earlier observations, cited in the introduction, that the thin sandwich facings have lower strength values than thick laminated material. The data plotted on these figures show a decrease in strength from the thickest laminate or facing to the thinnest. In general, the decrease takes place for material thinner than about 0.045 inch. The unit strength of material 0.045 inch thick is about equal to the unit strength of material 1/4 inch thick.

The results of tensile tests (fig. 1) show that the ultimate unit tensile strength of the laminates and facings of the balsa sandwich decreases from about 104 percent of the control strength at 0.045-inch thickness to about 82 percent of the control strength at the 0.015-inch thickness. The facings of the honeycomb sandwich were the weakest of the three. The strength for 0.015-inch-thick facing was only about 77 percent of the control. These tension tests show that the modulus of elasticity of the laminates was not changed by decreasing the thickness, while that for the facings was decreased. The average values of modulus of elasticity for the various materials were between 2,264,000 and 2,718,000 pounds per square inch. The control strength is in agreement with data in Forest Products Laboratory Report No. 1821 (1).

The results of compressive tests (fig. 2) show that these tests were also affected by the decrease in thickness. The unit strength of the laminates decreased 24 percent, and that of the facings decreased as much as 56 percent below the control value. The control strength was 32,400 pounds per square inch, which is 4,200 pounds per square inch less than the data in Forest Products Laboratory Report No. 1821 (1), so that if the strengths of the thin materials were compared with 38,600 pounds per square inch, the strength of this material as reported in Forest Products Laboratory Report No. 1821 (1), the percentage reduction is even greater, 63 percent, leaving about one-third of the accepted value. The trend is quite definite in these compressive tests, and it confirms the difference in values experienced in previous separate investigations (5, 4, 2, 3).

The magnitude of the effect of thickness on unit strength of thin laminates in flexure is between that indicated by tension and compression tests. The data shown in figure 3, however, scatter more than do those in figures 1 or 2. This divergence is undoubtedly due to the method of test and of evaluating the data. The modulus-of-rupture values for some thicknesses are higher than for the controls, but are in agreement with the values reported in Forest Products Laboratory Report No. 1821 (1). The unit-strength values for the thin materials are between 112 and 72 percent of the control values. The modulus-of-elasticity values show an increase with increases in thickness, but the values are 52 percent above and 27 percent below the control values. That may be due to the fact that the control values were obtained from simple beam tests and the values for thin materials were obtained from column tests. Since, in the column tests, the modulus of elasticity is directly proportional to the constant, k, which depends on the end condition, a slight irregularity in the roundness of the ends would affect the modulus-of-elasticity values. A slightly flat end condition would therefore cause an increase in the computed modulus.

It has been shown that, for the thinnest samples tested, the accumulative effect of variations in pressure, resin content, and thickness is a change in tensile strength of about 27 percent of the controls; in compressive strength, a change of 56 percent; and in flexural strength, a change of 40 percent. It is known that the molding pressure has some effect on the strength properties. Strengths, in general, are increased when the pressure is increased from 2-1/2 pounds per square inch to 50 pounds per square inch. The strengths of the facings from the honeycomb-type core would be the only strengths that would be affected by pressure variations. The portion of the facing that spanned the honeycomb-cell walls would be weaker than the rest. The strengths of the laminates and of the facings from balsa sandwich, however, had a uniform molding pressure of 14 pounds per square inch across the panel, so that the strength variations of those materials were not due to pressure variations.

It is known also that the resin content affects the strength properties. In the range of resin contents commonly used, 25 to 50 percent by weight, data in Forest Products Laboratory Report No. 1814 (7) show that tensile strengths decrease with increases in resin content and that compressive strengths increase with increases in resin content. The rate of decrease in tensile strength is about 900 pounds per square inch per percent, and the rate of increase in compressive strength is about 500 pounds per square inch per percent (figs. 4 and 5). It is recognized that these strength and percentage figures were obtained on 181-type fabric and that 112-type fabric was used in this effect-of-thickness study; nevertheless, the same trend would be expected. By applying the tensile rate of change of strength to the test data, it may readily be seen that the variations in resin content account for only a small portion of the strength change between the thickest and the thinnest specimens. If the compression rate of change is applied to the compressive data, some instances show that the effect of resin content adds to rather than subtracts from the magnitude of the strength change between the thickest and thinnest specimens.

Series 2

From the physical and mechanical tests made in the first series of tests, it is apparent that the resin content was lower than normal and that the panels were not void-free. It was recognized that these factors might have had some effect on the test results. It was therefore decided to continue the investigation by a second series of tests to evaluate the strength of various thicknesses of void-free laminates having 181-114-, 112-114-, and 183-114-type fabrics and to apply an empirical formula to the data. Data on the physical properties of various thicknesses of these void-free laminates are presented in table 2.

The tensile- and compressive-strength values obtained for these laminates are presented in tables 7 and 8, respectively, and figures 6 and 7, respectively. These data show the same trends as those shown in the first series of tests and therefore indicate that, even though laminates have different types of fabrics, they might have a common relationship with respect to strength and thickness. While the reason for these trends is not known, it was considered possible that there is an unknown thickness of material in the cross section of the laminate that is weaker than the rest and that this weaker material or weakening effect is more predominant in the thinner laminates.

In order to simplify the relationships of thickness and strength, it was assumed that the combined thickness of the weak layers is t_w and that the strength of these layers is reduced amount r from the strength of the stronger material (S_m), so that their combined strength is $S_m - r$. If the load on a laminate of thickness t at failure is P pounds per inch of width, then

$$P = (t - t_w)S_m + t_w (S_m - r) = tS_m - t_w r$$

Since the measured strength, S_t, of the laminate is equal to P/t, then by substitution

$$S_t = S_m - \frac{t_w r}{t}$$

Since the thickness of these weak layers t_w and the strength amount r are both unknown, their product may be denoted by a and may be solved along with the unknown S_m by testing the strength of at least two thicknesses of a laminate. Thus,

$$S_t = S_m - a/t$$

If more than two thicknesses of a laminate are evaluated, the least-squares method may be used to find S_m and a. The necessary equations are:

$$a = \frac{\Sigma S_t \Sigma \frac{1}{t} - n\Sigma \frac{S_t}{t}}{n\Sigma \frac{1}{t^2} - (\Sigma \frac{1}{t})^2}$$

and

$$S_m = \frac{\Sigma S_t \Sigma \frac{1}{t^2} - \Sigma \frac{S_t}{t} \Sigma \frac{1}{t}}{n\Sigma \frac{1}{t^2} - (\Sigma \frac{1}{t})^2}$$

which were used in computing $\underline{S_m}$ and $\underline{a}$ from the tensile and compressive data. Their values and the curves for each equation are shown on figures 1, 2, 6, and 7.

It may be seen that $\underline{S_m}$ represents the strength of an infinitely thick panel and that $\underline{a}$ represents a weakening effect having a unit of measure of pounds per inch of width. It is apparent that neither $\underline{S_m}$ nor $\underline{a}$ would be the same for all laminated plastics. However, if the unit stress of a finite thickness of plastic, $\underline{S_c}$ or $\underline{S_t}$, is put on a percentage basis by dividing the equation by $\underline{S_m}$, all of the laminates may be compared. This division results in a factor $\underline{a/S_m}$, which reduces the difference between laminates. The value of this factor, which has units in inches, ranges from 0.0033 to 0.114 inch for both tensile and compressive tests (table 9). The average values for the tensile and compressive tests are 0.0061 and 0.0084 inch, respectively, including values from series 3, heretofore not discussed. The average of these two values is 0.0072 inch. The curve, then, that is represented by:

$$S/S_m = 1 - \frac{0.0072}{t}$$

represents the average strength values with respect to thickness as determined from tests of several thicknesses of several laminates in both tension and compression. The strength of a 1/4-inch laminate is, according to this average curve (fig. 8), within 3 percent of full strength, 1/8 inch is within 6 percent, 1/16 inch is 12 percent below, 1/32 is 22 percent below, and 1/16 is less than 1/2 of the strength of a 1/4-inch laminate.

The curves of figure 8 indicate that reasonable estimates of properties may be made even from data at only one thickness. Thus, if the strength at a thickness of 1/4 inch were known, the average variation in strength indicated by figure 8 could be used to estimate the strength at any other thickness. Obviously, exact values will not result, but the percentage of error should not be great.

An assumption was then made as to the location of this weak layer. It was assumed that it might be on the surface of the laminate and that the strong material might be in the center. In order to explore this assumption, additional strength tests were made on the laminates in series 2 after the surfaces had been sanded, and tests were also made on a laminate in an additional series, series 3, after sanding the surface. The results of these strength tests, compared with strengths of unsanded specimens, are presented in tables 7, 10, and 11, and in figures 9 and 10. These results indicate that if the weak layers are on the surface, they cannot be removed mechanically by lightly sanding the surface. The strength values of the specimens having sanded surfaces theoretically should have been higher than those for the unsanded specimens, but, because the glass fibers are so close to the surface, the sanding operation actually damaged some glass fibers and consequently weakened the specimen. The figures show that, even though the laminates were weakened by the sanding operation, the unit strength of a thin laminate is still less than that of a thick laminate. These tests, therefore, are not conclusive as to the validity of the assumption that weak surface layers exist. Nevertheless, analyses made on the basis of this assumption indicate a trend that conforms to data from a variety of laminates.

A similar analysis, when applied to flexure, results in the relationship:

$$S = S_m - a/t^2$$

Values of $\underline{S_m}$ and $\underline{a}$ were calculated from the data of table 6 by the method of least squares, using the following equations:

$$a = \frac{-n\Sigma \frac{S_t}{t^2} + \Sigma S_t \Sigma \frac{1}{t^2}}{n\Sigma \frac{1}{t^4} - (\Sigma \frac{1}{t^2})^2}$$

$$S_m = \frac{\Sigma S_t \Sigma \frac{1}{t^4} - \Sigma \frac{S_t}{t^2} \Sigma \frac{1}{t^2}}{n\Sigma \frac{1}{t^4} - (\Sigma \frac{1}{t^2})^2}$$

The curves of figure 3, constructed from these data, appear to give a reasonable representation of the variation of properties with thickness.

Thus, with this relationship and data from two or more thicknesses, the properties at any other thickness may be estimated.

Series 3

In order to eliminate the possibility that the method of test might have affected the indicated trends, the compressive-test methods were also checked in series 3. It may be recalled that the method of obtaining the compressive strengths in series 1 was by loading a short column prism, 4t in length, supported at the bearing ends; and that in series 2 a necked-down specimen, supported along its length with 4t extending beyond the jig, was used. When compression failures occurred at the bearing ends, as they sometimes did in series 1, it gave reason to doubt the reliability of the test results. With the necked-down specimen, however, failures always occurred in the net section. This type of failure indicates reliable results, but the specimens were supported by flat plates throughout the length of that net section (fig. 11). The friction between the specimen and these flat plates may have influenced the magnitude of the failing load. In order to eliminate the effect that this friction may have caused, a third type of specimen was used as another method of test. The specimen used in this method was also a prism of uniform cross section, having a length equal to the length of the jig plus 2t. The jig which supported this prism, however, was constructed with vertical fins or grooves in the supporting plate to provide maximum support along the length of the specimen with a minimum of friction (fig. 12). In order to further reduce the friction effect, it was believed that the specimens could be tested in groups in this vertical-groove jig. The compressive-strength values obtained by this method of test were lower than those obtained by the dumbbell specimen (table 8). They were lower for principally one reason; that the individual laminates did not act as a unit. They failed separately, and the failures were not confined to the center of the specimen. In spite of the greater scatter in values, they showed a trend of weak, thin laminates to strong, thick laminates.

Since these latter prisms, as a confirming method of test, were unsatisfactory relative to magnitude of loads and location of failure, tests of bundles of specimens were repeated by reverting to the use of the necked-down specimen tested in the flat-plate jig. In this series of tests, single specimens and bundles of specimens, both bonded and unbonded, were evaluated for their compressive strength for three thicknesses of laminate. The results of these tests are presented in table 11 and summarized in table 12. The maximum compressive stress for the various methods of test show that, as stated before, the sanding operation weakened the laminate, that unbonded bundles of specimens are weak because they do not act as a unit, but that the bonded sanded bundles show an increase in strength. An attempt had been made to bond unsanded laminates, but the bond was so poor that no tests were made. The data show also that a thick laminate formed by bonding together a number of thin laminates is weaker than a thick laminate molded in one operation. The phenomonon, therefore, is a function of original thickness.

Conclusions

(1) The net result of the accumulative effect of variations in thickness, pressure, and resin content was a decrease in strength with decrease in thicknesses.

(2) The tensile and compressive strengths at any thickness were found to conform to the empirical relationship

$$S = S_m - a/t$$

(3) Flexural properties at any thickness were found to conform to the empirical relationship

$$S = S_m - a/t^2$$

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(6) WERREN, FRED
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(7) ________ and HEEBINK, B. G.
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(8) TIMOSHENKO, S.
1936. THEORY OF ELASTIC STABILITY, page 177.

Table 1.--Data on laminates and sandwich facings (having voids) made of 112-114 fabric and resin 2[1] (series 1)

Plastic sheet	Number of plies	Resin content	Specific gravity	Barcol hardness
		Percent		
Laminate	5	47.0	1.64	59
	10	46.1	1.69	64
	15	45.7	1.72	66
	84	45.3	1.70	66
	[2]84	44.9	1.70	69
Balsa sandwich facing				
Top	5	41.5		
Bottom	5	40.9		
Av		41.2		
Top	10	40.6		
Bottom	10	41.5		
Av		41.1		
Top	15	42.8		
Bottom	15	43.1		
Av		43.0		
Honeycomb sandwich facing				
Top	5	40.4		
Bottom	5	42.4		
Av		41.4		
Top	10	38.0		
Bottom	10	36.9		
Av		37.4		
Top	15	37.8		
Bottom	15	39.5		
Av		38.6		

[1]Resin 2 is a laminating resin of the alkyd-styrene type of polyester.

[2]Data from Forest Products Laboratory Report No. 1821 (1), table 1.

Table 2.--Physical properties of various thicknesses of four types of glass-fabric-base plastic laminates (void-free) (series 2)

Weave of laminate	Number of plies	Resin content	Specific gravity	Thickness	Barcol hardness
		Percent		Inch	
112-114	5	51.0	1.576	0.018	(2)
	10	47.4	1.614	.034	(2)
	15	49.1	1.656	.052	66
	84	48.8	1.654	.283	67
112-114 facing[1]	5	49.8	1.446	.021	(2)
	10	49.4	1.508	.037	(2)
	15	52.9	1.556	.059	65
183-114	1	44.4	1.588	.024	(2)
	2	37.3	1.745	.040	(2)
	3	35.8	1.770	.058	66
	4	32.5	1.810	.070	67
	14	38.0	1.780	.275	66
181-114	2	46.6	1.604	.027	(2)
	4	43.0	1.695	.047	(2)
	6	46.2	1.676	.076	63
	8	45.4	1.673	.101	61
	23	42.4	1.721	.271	64

[1] Facing material from 1/2-inch-thick sandwich having glass-fabric honeycomb core. One ply of impregnated cloth used as bonding agent that remained on facing after the core was removed.

[2] Material of this thickness is too thin to give Barcol hardness values.

Table 3.--Data on void-free laminates made of 181-114 fabric and resin 2[1] (series 3)

Panel No.	Number of plies	Resin content	Specific gravity	Thickness	Barcol hardness
		Percent		Inch	
6-16	2	46.6	1.65	0.029	(2)
6-16A	2	44.7	1.72	.026	(2)
6-17	2	46.8	1.66	.029	(2)
6-17A	2	46.8	1.66	.029	(2)
6-18	2	42.5	1.72	.025	(2)
6-18A	2	44.0	1.69	.025	(2)
6-18SB	17	47.5	1.70	.232	59
6-18USB	17	46.0	1.67	....	58
6-26	4	39.0	1.77	.046	63
6-29	4	39.7	1.75	.044	63
6-29A	4	38.6	1.72	.044	64
6-29SB	14	40.7	1.72	.166	63
6-29USB	14	40.4	1.72	....	62
6-23	12	37.1	1.77	.128	65

[1]Resin 2 is a laminating resin of the alkyd-styrene type of polyester.

[2]This material is too thin for accurate hardness values.

Table 4.--Tensile strength of glass-fabric laminates of various thicknesses (series 1)

Plastic sheet	Number of plies	Thickness	Modulus of elasticity	Stress at proportional limit	Maximum tensile stress	Ratio of maximum tensile stress to control stress
		In.	1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.	Percent
Laminate[1]	5	0.016	2,552	23.0	32.3	82
	10	.032	2,578	17.6	36.8	93
	15	.047	2,546	21.4	36.2	91
Control	84	.262	2,512	....	39.5	100
Facing of balsa sandwich[2]						
Top	5	.016	2,080	21.3	30.3	....
Bottom	5	.016	2,448	23.8	35.9	....
Grand Av.	....	.016	2,264	22.5	33.1	84
Top	10	.029	2,616	18.2	40.2	....
Bottom	10	.029	2,389	19.7	39.2	....
Grand Av.	....	.029	2,502	18.8	39.7	101
Top	15	.044	2,588	15.4	40.9	....
Bottom	15	.044	2,629	14.0	41.3	....
Grand Av.	....	.044	2,609	14.8	41.1	104
Facing of honeycomb-core sandwich[2]						
Top	5	.016	2,445	26.4	30.1	....
Bottom	5	.016	2,409	19.6	30.5	....
Grand Av.	....	.016	2,427	24.2	30.3	77
Top	10	.028	2,805	19.7	37.7	....
Bottom	10	.028	2,502	18.6	34.0	....
Grand Av.	....	.028	2,653	19.2	35.9	91
Top	15	.044	2,510	11.0	36.0	....
Bottom	15	.044	2,927	22.5	35.3	....
Grand Av.	....	.044	2,718	16.1	35.7	91

[1]Average of 10 specimens.

[2]Average of 5 specimens.

Table 5.--Compressive strength of glass-fabric laminate of various thicknesses (series 1)

Plastic sheet	Number of plies	Thickness	Maximum compressive stress	Ratio of maximum stress to control stress
		In.	1,000 p.s.i.	Percent
Laminate[1]	5	0.016	24.7	76
	10	.032	28.4	88
	15	.046	31.1	96
Control	84	.261	32.4	100
Facing of balsa sandwich[2]				
Top	5	.017	14.6	
Bottom	5	.017	19.5	
Grand Av		.017	17.1	53
Top	10	.031	24.6	
Bottom	10	.033	26.8	
Grand Av		.032	25.7	79
Top	15	.046	33.2	
Bottom	15	.047	27.9	
Grand Av		.047	30.5	94
Facing of honeycomb-core sandwich[2]				
Top	5	.015	13.5	
Bottom	5	.016	14.7	
Grand Av		.016	14.1	44
Top	10	.028	18.3	
Bottom	10	.029	27.6	
Grand Av		.029	23.0	71
Top	15	.039	20.0	
Bottom	15	.041	25.8	
Grand Av		.040	22.9	71

[1]Average of 10 specimens.

[2]Average of 5 specimens.

Table 6.--Flexural strength of glass-fabric laminates of various thicknesses (series 1)

Plastic sheet	Number of plies	Thickness	Modulus of elasticity	Modulus of rupture	Ratio of maximum stress to control stress
		In.	1,000 p.s.i.	1,000 p.s.i.	Percent
Laminate[1]	5	0.017	2,735	48.9	105
	10	.032	3,436	52.4	112
	15	.046	3,389	50.8	109
Control	84	.262	2,545	46.6	100
Facing of balsa sandwich[2]					
Top	5	.018	1,753	32.7	
Bottom	5	.016	2,017	37.1	
Grand Av		.017	1,866	34.6	74
Top	10	.031	2,466	42.0	
Bottom	10	.031	2,479	43.4	
Grand Av		.031	2,472	42.7	92
Top	15	.043	4,033	49.2	
Bottom	15	.043	3,683	49.1	
Grand Av		.043	3,858	49.1	106
Facing of honeycomb-core sandwich[2]					
Top	5	.016	2,056	30.0	
Bottom	5	.016	2,232	36.8	
Grand Av		.016	2,144	33.4	72
Top	10	.028	3,824	47.6	
Bottom	10	.030	3,193	51.9	
Grand Av		.029	3,508	49.8	107
Top	15	.041	3,230	35.3	
Bottom	15	.041	3,943	49.9	
Grand Av		.041	3,586	42.6	91

[1]Average of 10 specimens.

[2]Average of 5 specimens.

Table 7.--Tensile strength[1] of glass-fabric laminates of various thicknesses (series 2)

Weave of laminate	Number of plies	Unsanded laminate: Thickness	Unsanded laminate: Modulus of elasticity	Unsanded laminate: Proportional limit	Unsanded laminate: Maximum	Sanded laminate: Thickness	Sanded laminate: Maximum
		In.	1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.	In.	1,000 p.s.i.
112-114	5	0.020	1,963	21.30	32.88	0.014	22.97
	10	.035	2,144	29.51	37.66	.030	35.22
	15	.050	2,274	29.37	39.67	.039	38.30
	84	.281	2,256	26.02	39.58	.269	39.02
112-114 facing[2]	5	.023	1,952	23.88	31.97	....	....
	10	.039	2,106	26.46	36.14	....	....
	15	.059	2,045	25.91	36.64	....	....
183-114	1	.025	2,184	21.63	34.00	.020	22.72
	2	.040	2,574	29.30	42.80	.032	14.35
	3	.057	2,732	37.23	46.86	.046	37.21
	4	.070	2,918	31.60	48.34	.059	31.88
	14	.278	2,640	26.37	43.32	.259	41.65
181-114	2	.027	2,218	20.33	33.18	.023	33.92
	4	.047	2,476	28.10	36.74	.039	37.46
	6	.076	2,283	27.32	39.00	.067	33.74
	8	.101	2,322	28.00	39.12	.092	37.21
	23	.263	2,515	22.76	41.41	.251	40.78

[1] Each value is the average of 5 specimens.

[2] Facing material from 1/2-inch-thick sandwich having glass-fabric honeycomb core. One ply of impregnated cloth used as bonding agent that remained on facing after core was removed.

Table 8.--Compressive strength[1] of glass-fabric laminates of various thicknesses (series 2)

Weave of laminate	Number of plies	Thickness of laminate	Type of specimen: Dumbbell shape	Rectangular bonded bundles	Rectangular unbonded bundles
		In.	1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.
112-114	5	0.018	30.12	16.60	9.42
	10	.034	37.84	30.83	23.72
	15	.052	39.46	34.85	22.67
	84	.283	45.65	41.47	....
112-114 facing	5	.021	33.92	....	....
	10	.037	41.42	....	....
	15	.059	41.53	....	....
183-114	1	.024	24.71	19.83	15.30
	2	.040	30.22	26.05	19.68
	3	.058	33.92	31.34	24.57
	4	.070	39.69	29.94	24.06
	14	.275	42.88	37.60	....
181-114	2	.027	30.21	21.00	15.04
	4	.047	41.71	30.99	20.56
	6	.076	43.88	35.44	27.67
	8	.101	44.61	34.17	....
	23	.271	50.06	39.81	....

[1] Values under dumbbell-shaped specimen are average of 5 specimens. Values under rectangular-shaped specimen are individual values from a bundle of 3 to 5 specimens.

Table 10.--Tensile strength[1] of glass-fabric laminates of various thicknesses (series 3)

Panel No.	Number of plies	Original laminate: Thickness	Original laminate: Modulus of elasticity	Original laminate: Proportional limit	Original laminate: Maximum	Sanded laminate: Thicknesses: Original	Sanded laminate: Thicknesses: Final	Sanded laminate: Modulus of elasticity	Sanded laminate: Proportional limit	Sanded laminate: Maximum
		In.	1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.	In.	In.	1,000 p.s.i.	1,000 p.s.i.	1,000 p.s.i.
6-16	2	0.0275	2,052	24.80	29.91	0.0277	0.0268	1,904	21.41	27.20
6-16A	2	.0266	2,044	27.54	31.21	.0258	.0251	2,033	19.69	28.41
6-17	2	.0275	2,051	24.64	31.54	.0274	.0266	1,903	21.88	28.10
6-17A	2	.0278	1,876	24.62	31.20	.0278	.0270	1,895	20.15	28.61
6-18	2	.0254	2,015	....	33.41	.0249	.0236	1,910	14.76	25.57
6-18A	2	.0264	2,088	26.88	32.55	.0257	.0248	1,963	18.82	28.56
Av.	2	.0269	2,021	25.70	31.64	.0266	.0256	1,935	19.45	27.74
6-26	4	.0453	2,443	21.05	38.97	.0452	.0443	2,326	22.33	35.28
6-29	4	.0470	2,359	20.60	38.59	.0462	.0453	2,228	28.53	35.49
6-29A	4	.0462	2,309	22.27	38.38	.0448	.0439	2,154	25.53	36.04
Av.	4	.0462	2,370	21.31	38.65	.0454	.0445	2,236	25.46	35.60
6-23	12	.1279	2,466	32.25	44.66	.1274	.1266	2,460	30.43	43.53

[1] Each value is the average of 6 specimens, except the modulus-of-elasticity and proportional-limit stress values of the 2- and 4-ply panels, which are averages of 3 specimens.

Table 11.--Compressive strength of glass-fabric laminates, comparing effect of thickness and method of test (series 3)

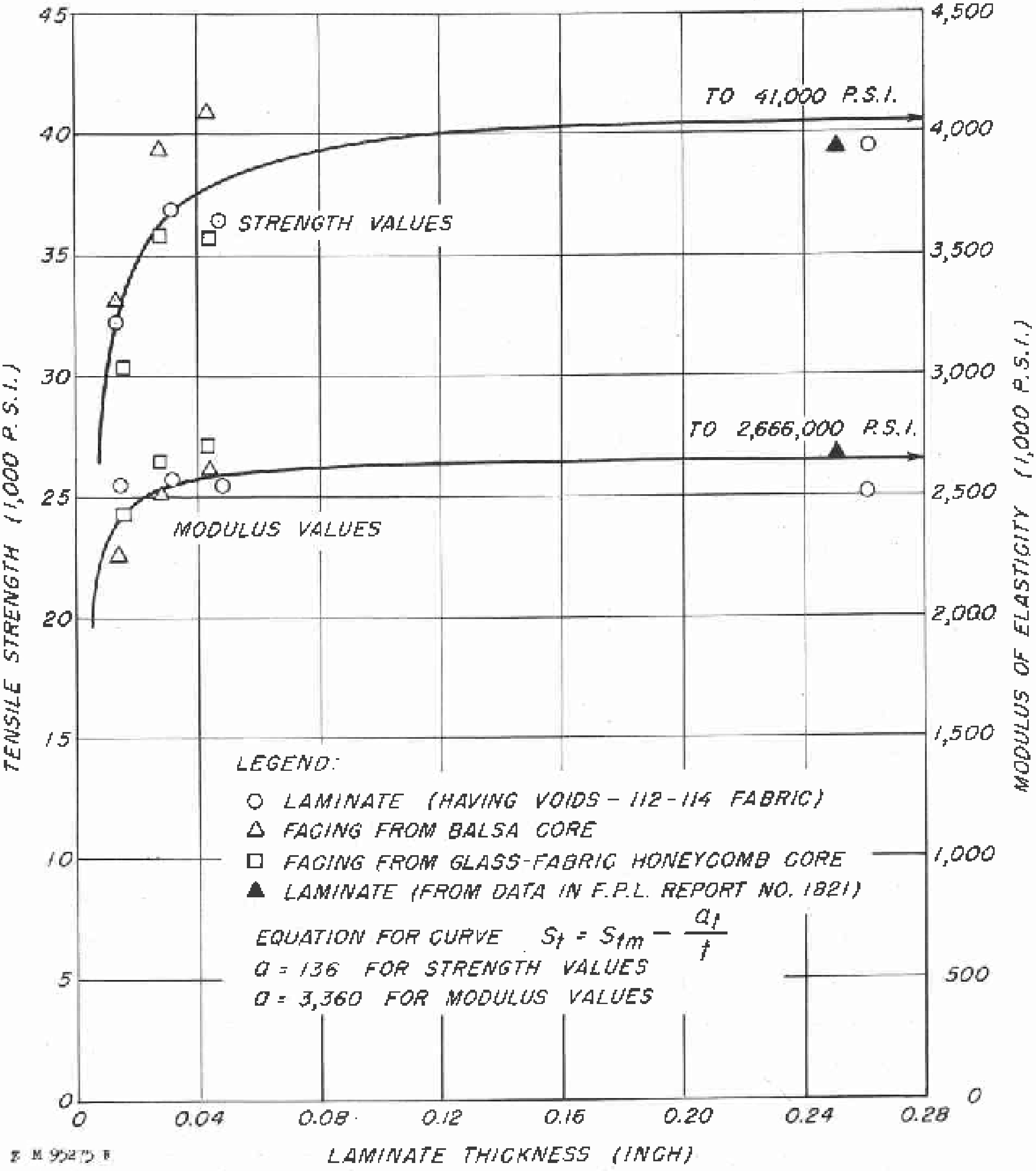
Panel No.	Number of plies	Original laminate: Thickness	Original laminate: Maximum stress	Sanded laminate: Thickness 1	Sanded laminate: Thickness 2	Sanded laminate: Maximum stress	Method of test
		In.	1,000 p.s.i.	In.	In.	1,000 p.s.i.	
6-16	2	0.029	32.33	0.0280	0.0271	25.77	Average of 3 single specimens
6-16A	2	.026	28.33	.0234	.0227	33.86	Do.
6-17	2	.029	34.28	.0279	.0267	33.90	Do.
6-17A	2	.029	34.97	.0280	.0272	36.47	Do.
6-18	2	.025	23.00	.0222	.0215	26.91	Do.
6-18A	2	.025	37.53	.0247	.0237	31.45	Do.
Av.	2	.027	31.74	.0257	.0248	31.40	Average of 18 single specimens
6-16 and 16A	12	.166	25.17	.1614	.1566	22.48	Value of 6, unbonded bundle
6-17 and 17A	12	.176	31.52	.1661	.1608	29.40	Do.
6-18 and 18A	12	.152	22.32	.1472	.1318	20.38	Do.
Av.	12	.165	26.34	.1582	.1497	24.09	Average of unbonded bundle
6-16 through 6-18A	17	....	....	....	.232	35.28	Bundle, bonded, average of 8 specimens
6-26	4	.046	35.97	.0442	.0433	34.07	Average of 3 single specimens
6-29	4	.044	42.85	.0457	.0457	40.43	Do.
6-29A	4	.044	38.41	.0442	.0432	35.19	Do.
Av.	4	.045	39.08	.0447	.0437	36.56	Average of 9 single specimens

Table 11.--Compressive strength of glass-fabric laminates, comparing effect of thickness and method of test (series 3) (Continued)

Panel No.	Number of plies	Original laminate: Thickness	Original laminate: Maximum stress	Sanded laminate: Thickness 1	Sanded laminate: Thickness 2	Sanded laminate: Maximum stress	Method of test
		In.	1,000 p.s.i.	In.	In.	1,000 p.s.i.	
6-26	12	0.141	35.90	0.1350	0.1315	34.27	Value of 3, unbonded bundle
6-29	12	.131	36.65	.1357	.1330	37.95	Do.
6-29A	12	.130	35.60	.1318	.1283	35.19	Do.
Av.	12	.134	36.05	.1342	.1309	33.43	Average of unbonded bundle
6-26 through 6-29A	14	....	....	....	.166	43.11	Bonded bundle, average of 8
6-23	12	.128	46.48	.1278	.1263	44.92	Average of 6 specimens

Table 12.--Summary of compressive strength of various thicknesses of glass-fabric laminates and by various methods of test in series 3

Number of plies	Method of test	Maximum compressive stress
		P.s.i.
2	Single specimen, unsanded	31,740
	Single specimen, sanded	31,400
	Bundle, unsanded	26,340
	Bundle, sanded	24,090
	Bundle, sanded, bonded	35,280
4	Single specimen, unsanded	39,080
	Single specimen, sanded	36,560
	Bundle, unsanded	36,050
	Bundle, sanded	33,430
	Bundle, sanded, bonded	43,110
12	Single specimen, unsanded	46,480
	Single specimen, sanded	44,920



Z M 95275 F

Figure 1. --Tensile strength and modulus of elasticity of glass-fabric-base laminates of various thicknesses (series 1).

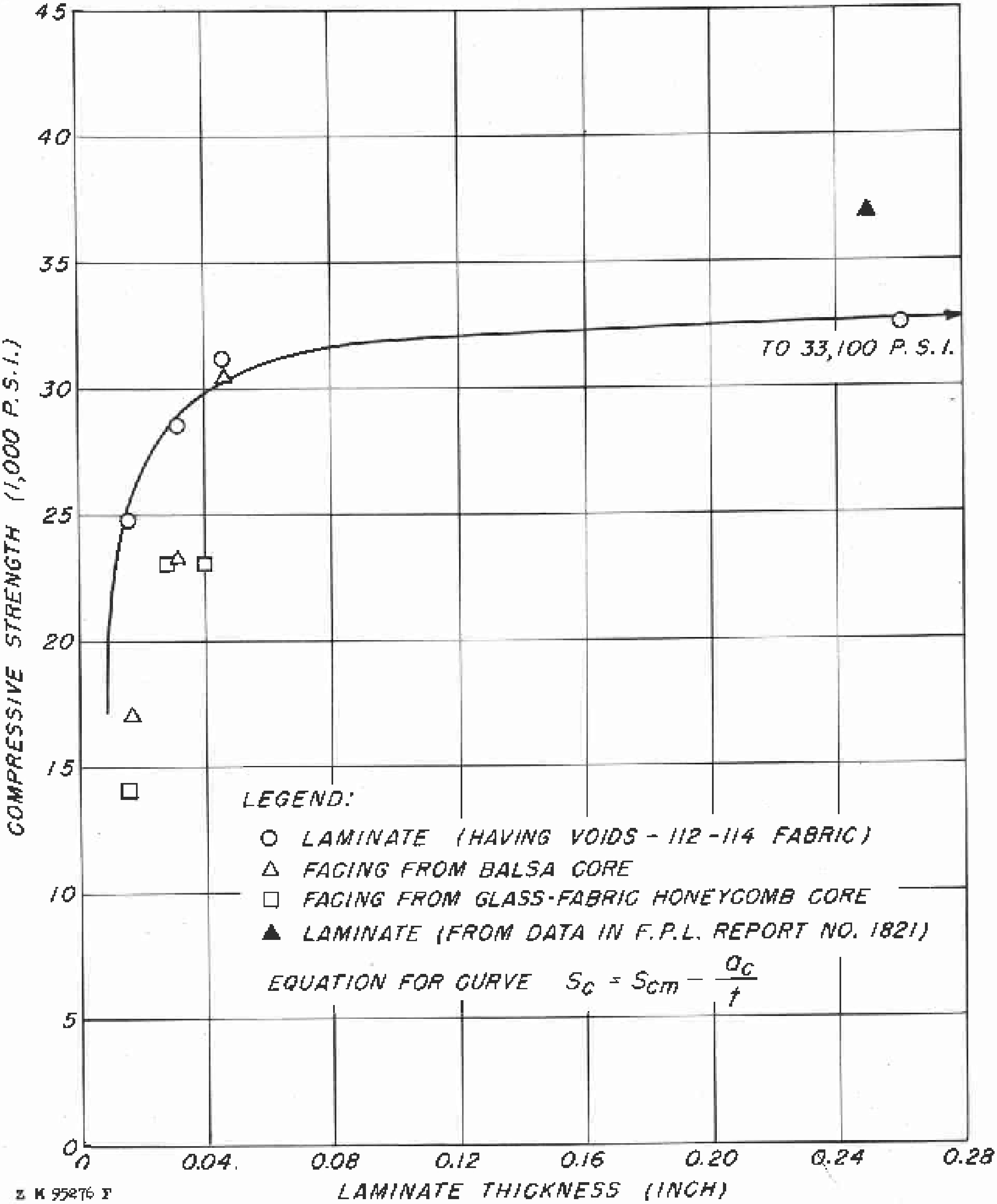


Figure 2. --Compressive strength of glass-fabric-base laminates of various thicknesses (series 1).

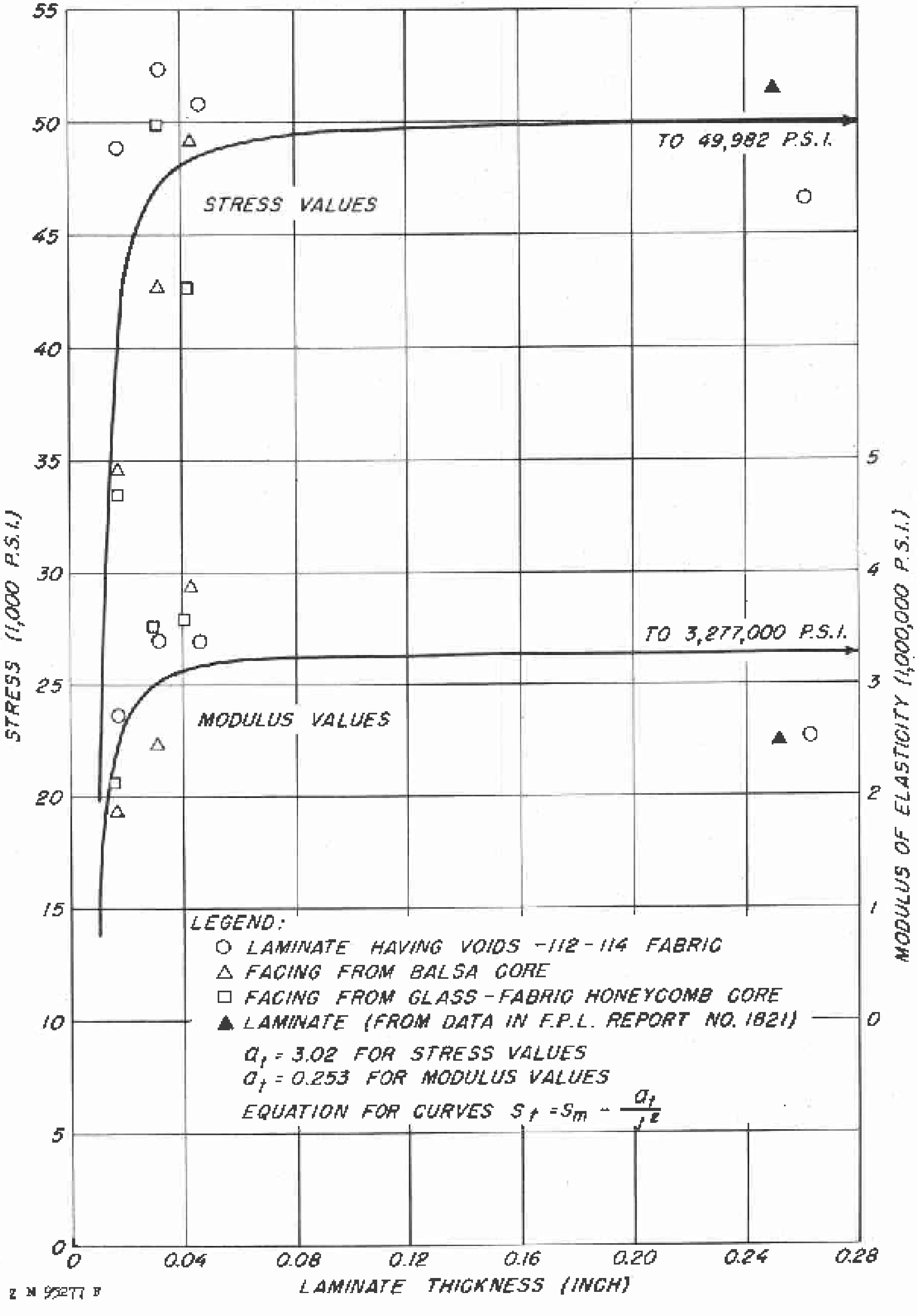


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Figure 3. --Flexural strength and modulus of elasticity of glass-fabric-base laminates of various thicknesses (series 1).

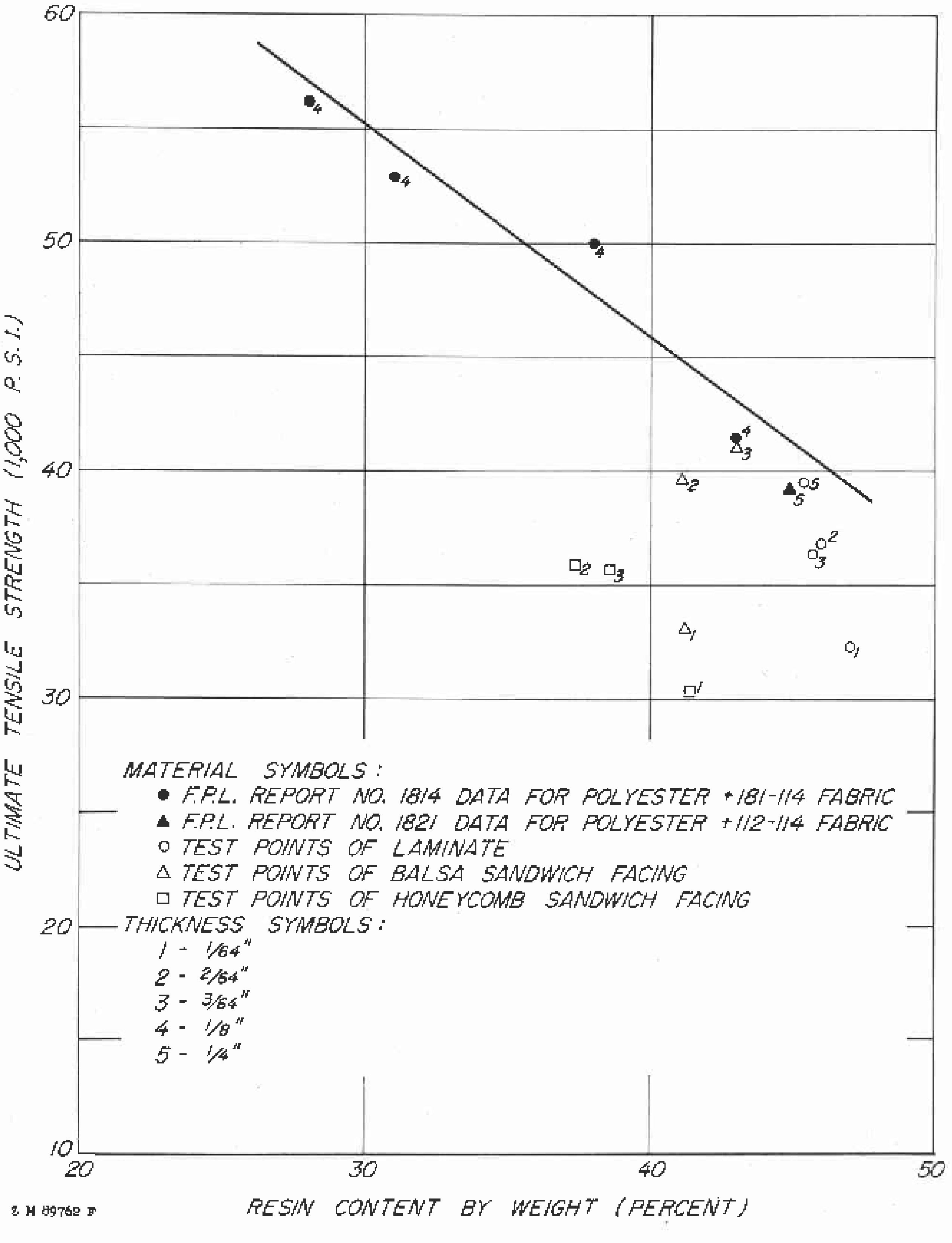

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Figure 4.--Effect of resin content on tensile strength.

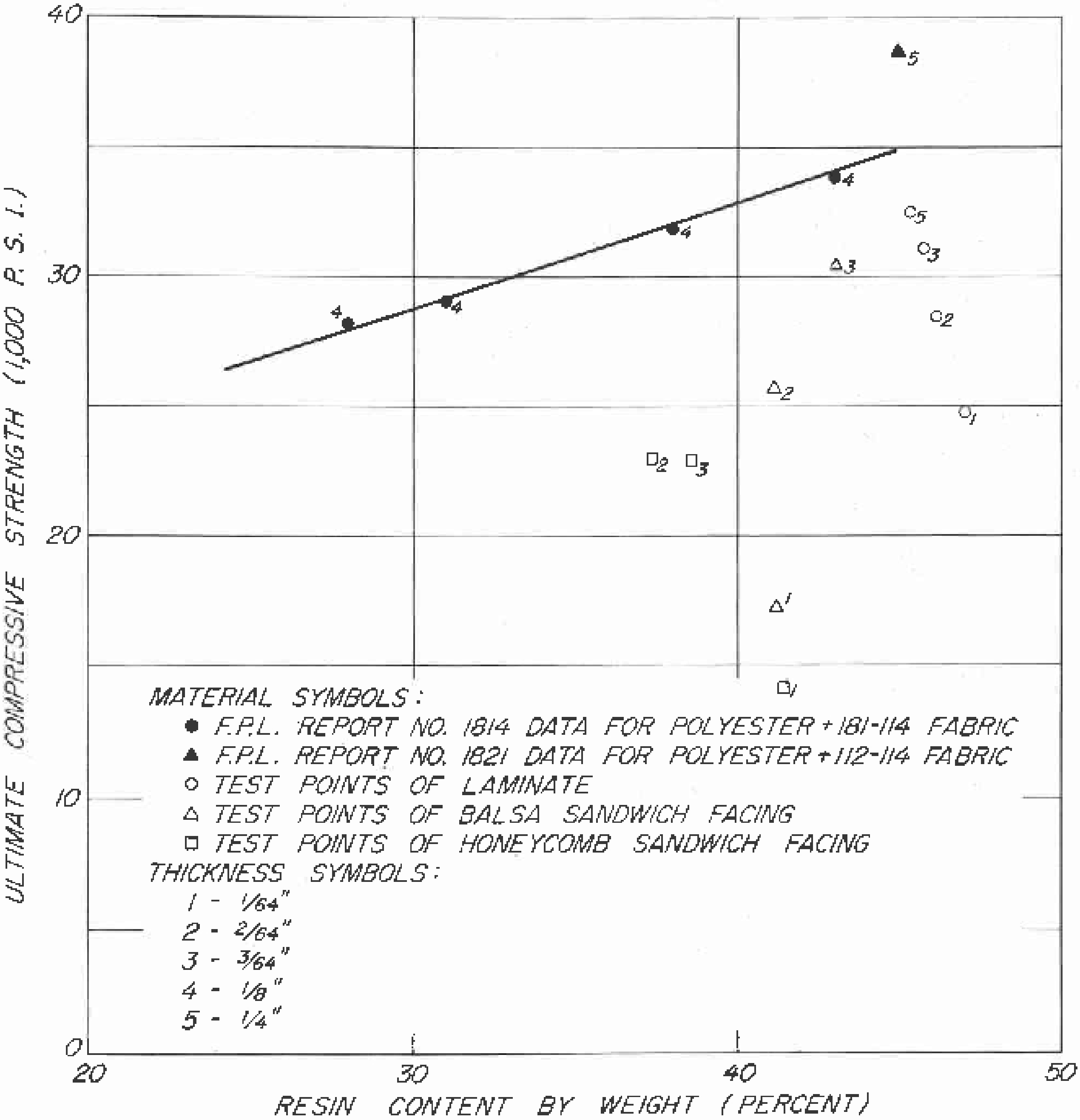

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Figure 5. --Effect of resin content on compressive strength.

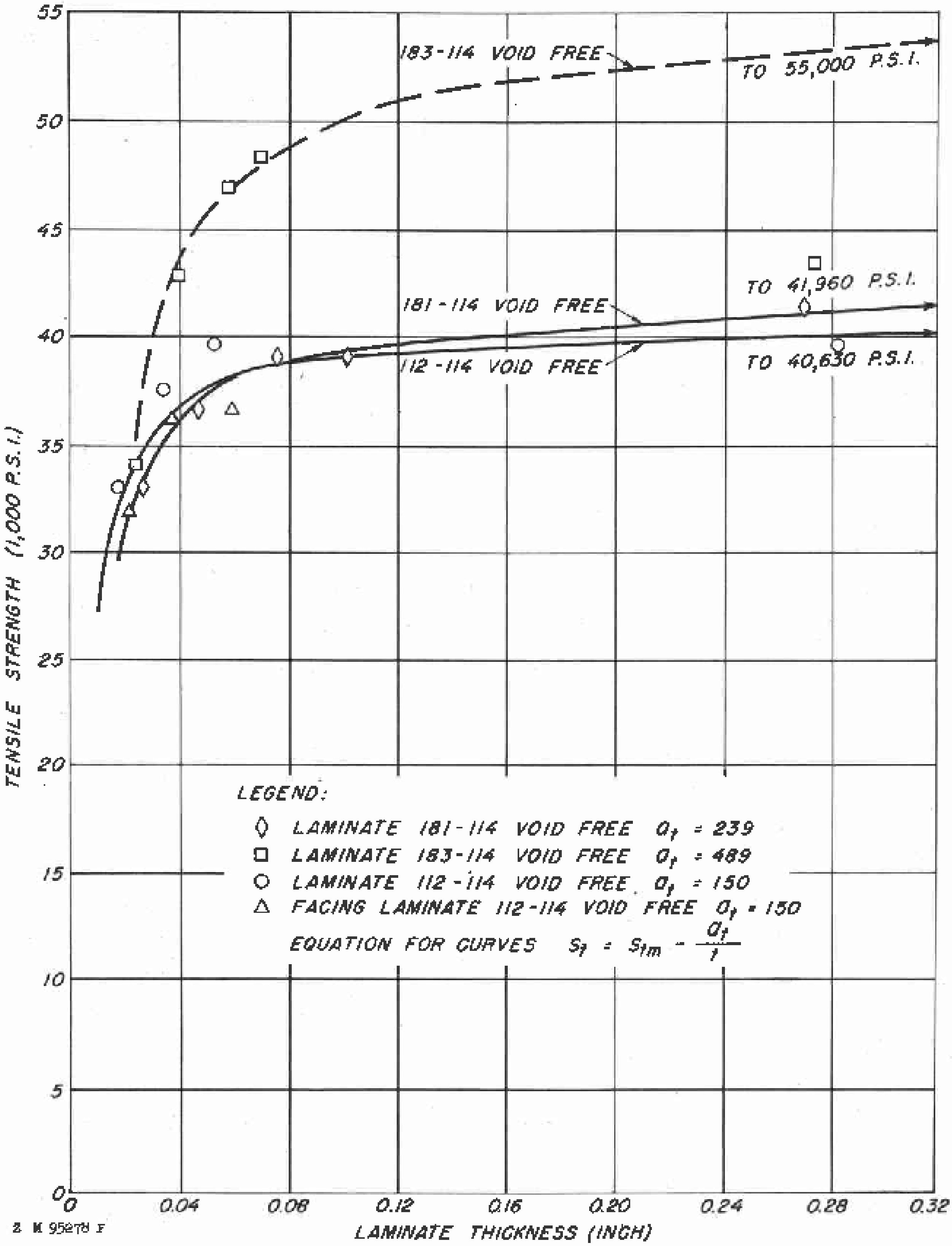

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Figure 6. --Effect of thickness on tensile strength of four types of glass-fabric-base plastic laminates (series 2).

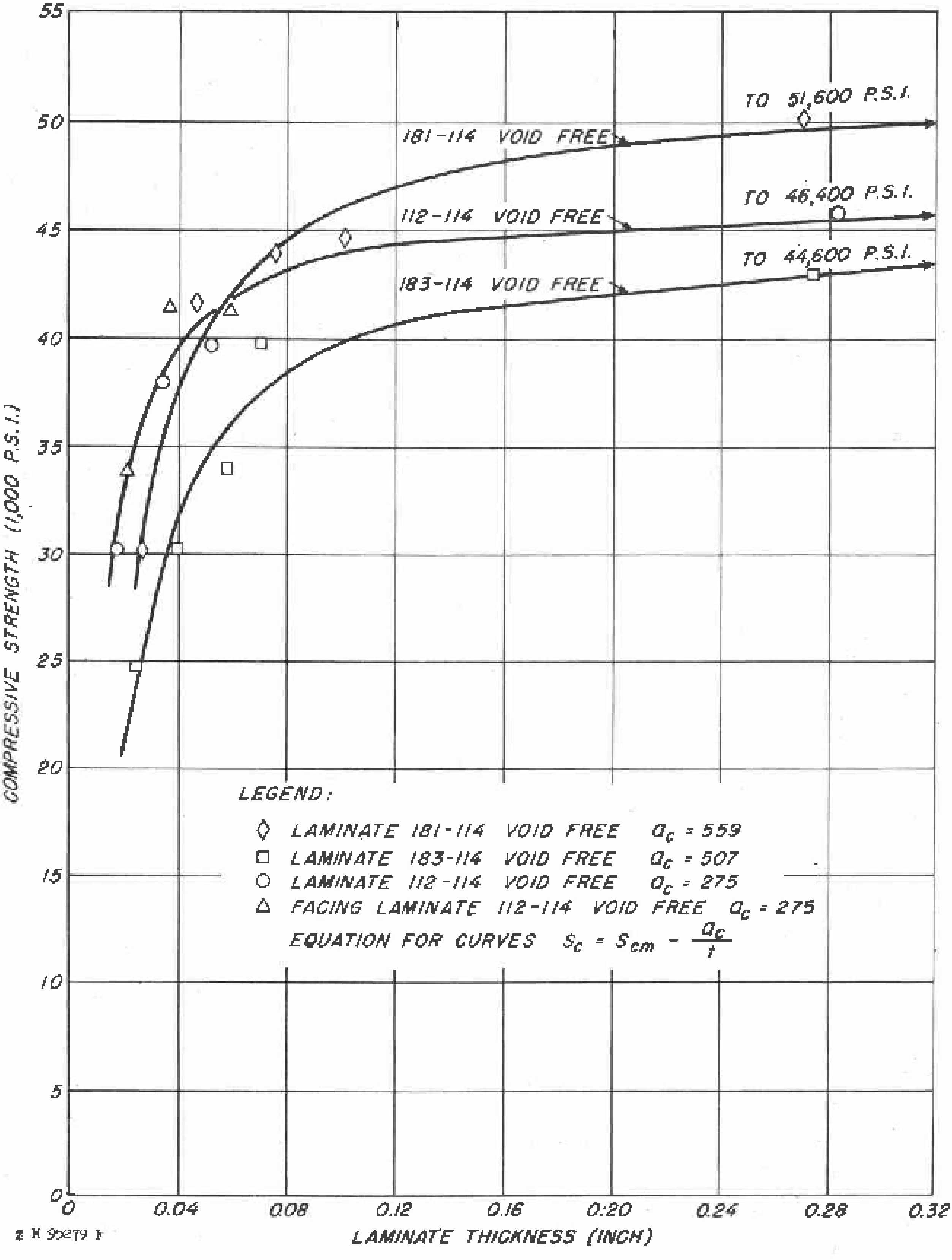

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Figure 7. --Effect of thickness on compressive strength of four types of glass-fabric-base plastic laminates (series 2).

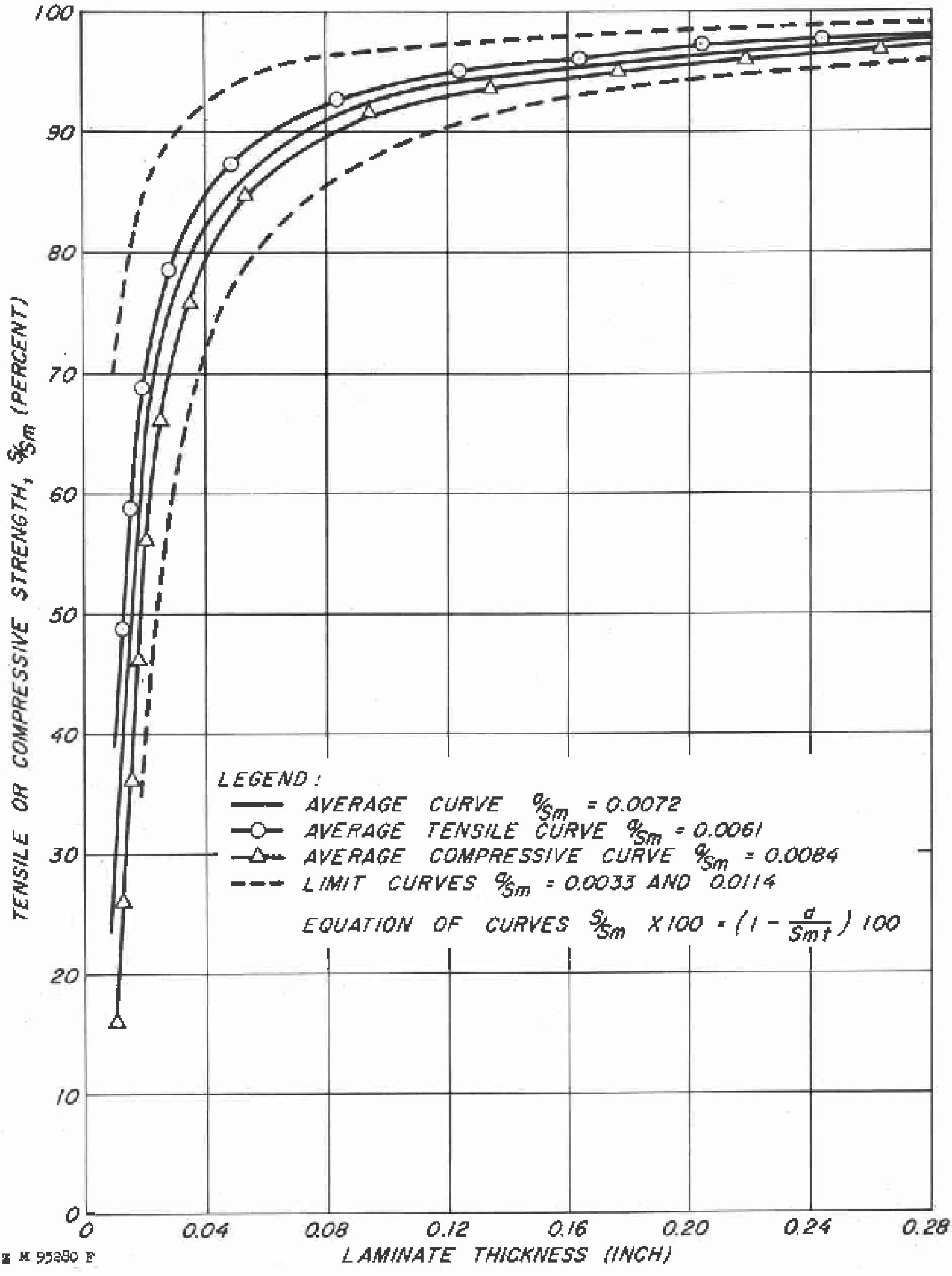

Figure 8. --Empirical curves showing strength versus thickness.

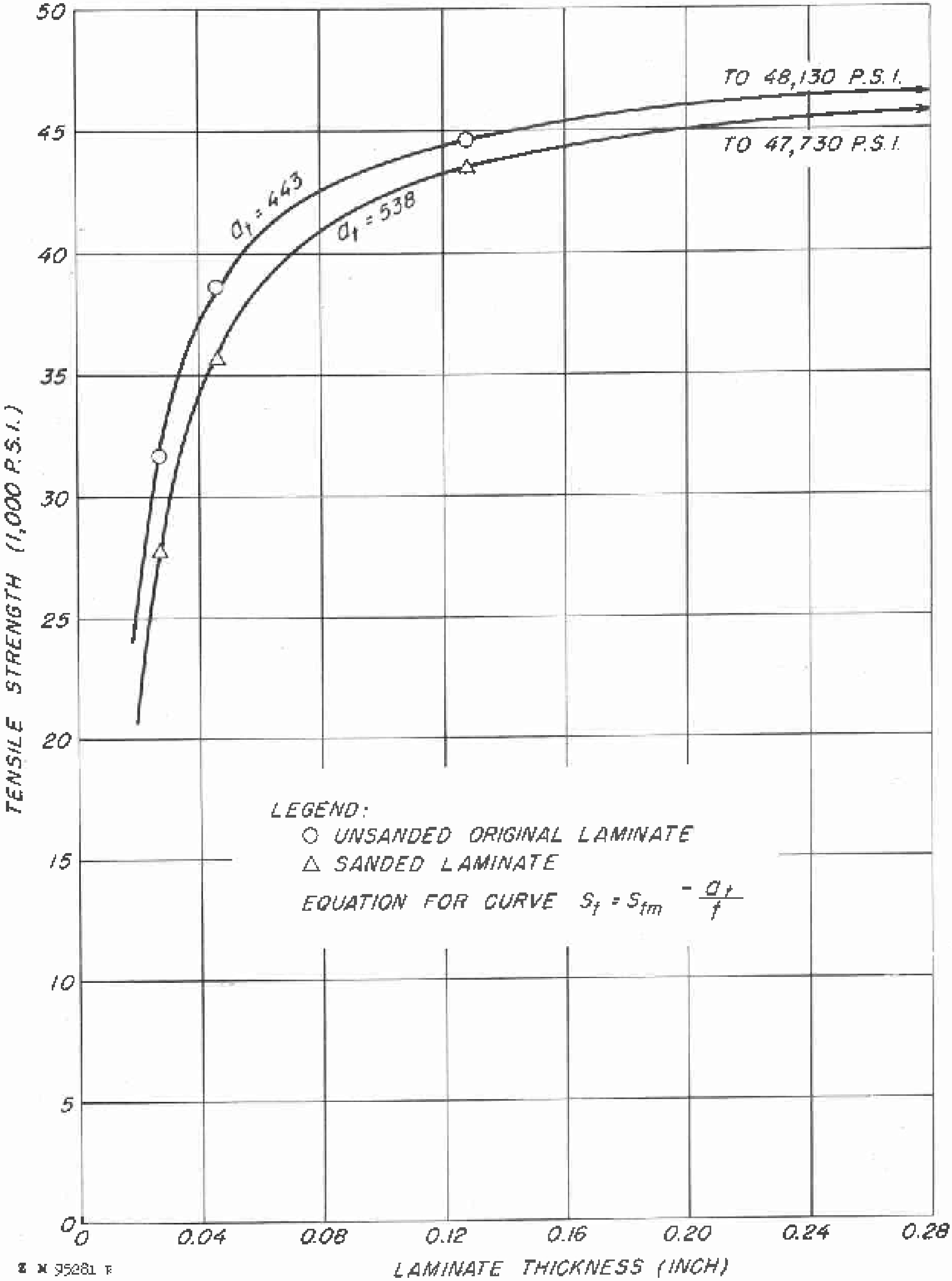

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Figure 9. --Tensile strength versus effect of thickness and sanding of glass-fabric-base plastic laminate (series 3).

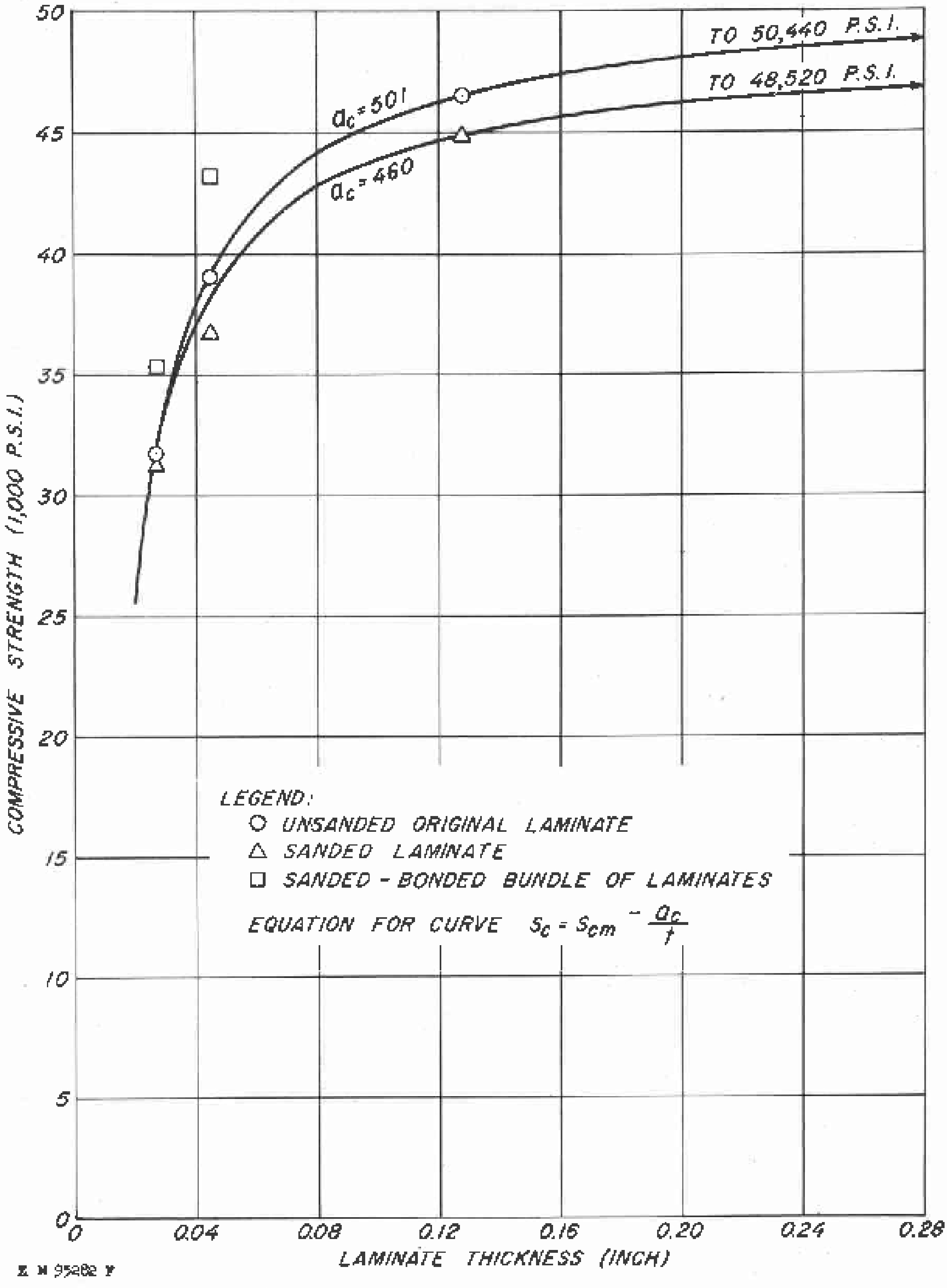

Figure 10.--Compressive strength versus effect of thickness and sanding of glass-fabric-base plastic laminate (series 3).

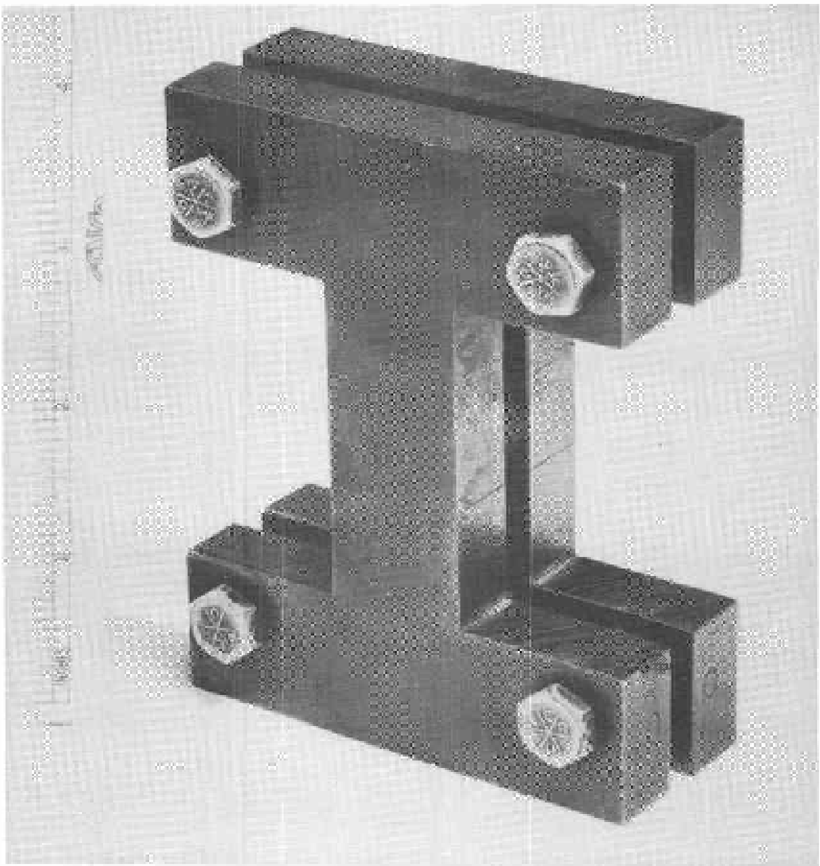

Figure 11. --Jig having flat plates for supporting compression specimens.

Z M 95712 F

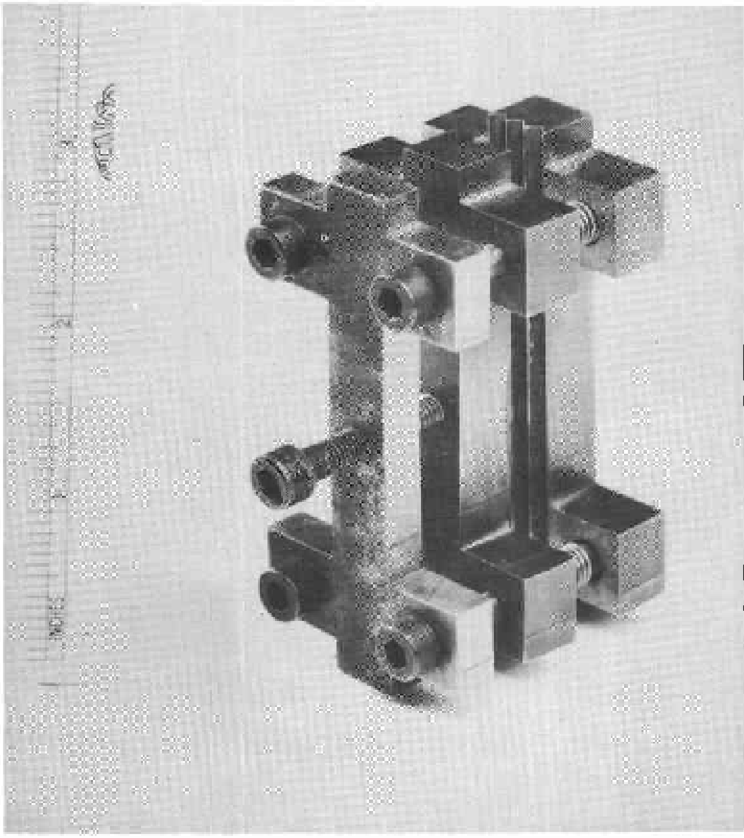

Figure 12. --Jig having grooved plates for supporting compression specimens.

Z M 95713 F