

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

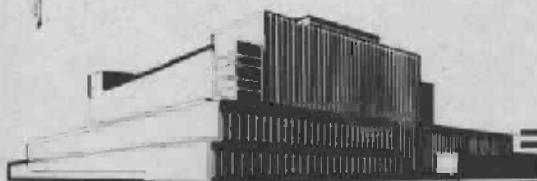
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UNITED STATES DEPARTMENT OF AGRICULTURE

FOREST SERVICE

In Cooperation with the University of Wisconsin

Supplement to

DIRECTIONAL PROPERTIES OF GLASS-FABRIC-BASE-PLASTIC

LAMINATE PANELS OF SIZES THAT DO NOT BUCKLE¹

By

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Summary and Conclusions

This supplement to Forest Products Laboratory Report No. 1803 of the same title presents the results of tension, compression, and shear tests of two glass-fabric-base plastic laminates tested at various angles to the warp of the laminations. The original report of this title presented results of similar tests of a laminate made of 181-114 fabric, a satin-weave fabric of approximately equal strength in the warp and fill directions. Of the two laminates discussed in this supplement, the 112-114 laminate is made of a plain-weave fabric having a warp-to-fill strength ratio of about 3 to 2, and the 143-114 laminate is made of a unidirectional-weave fabric having a warp-to-fill strength ratio of about 11 to 1. Thus, these laminates represent three glass fabrics having entirely different properties and the theoretical analysis, if applicable to these, should be applicable to any other glass fabrics now being used for aircraft laminates.

Except for the panel-shear test values, there was good correlation between the experimental and theoretical values. The difficulty of making an accurate shear test is recognized, and it may be that the computed shear values are more nearly correct than those measured by the shear tests.

The comparison between experimental and theoretical values for modulus of elasticity, proportional limit, and ultimate stress in tension, compression, or

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

shear can best be made by an examination of the appropriate diagram.

Introduction

It was the purpose of the work discussed in this report to verify the general elastic equations and the interaction formula for two additional glass-fabric-base plastic laminates, by the results of tests in which tension, compression, and shear stresses are applied in the plane of the laminate. The three laminates covered by the original report and this supplement typify the range of fabrics used in aircraft applications. No tests in bearing, edgewise shear, and inter-laminar shear are included in this supplement.

Description of Material

Two types of glass-fabric-base plastic laminate were tested in this study, and will hereafter be referred to as 112-114 laminate and 143-114 laminate. Four panels, approximately 1/4 by 36 by 36 inches, were made of each laminate at the Forest Products Laboratory. The panels of 112-114 laminate were made of 84 plies of 112-114 plain-weave fabric (having a warp-to-fill strength ratio of about 3 to 2) and parallel-laminated with resin B, a high-temperature-setting, low viscosity laminating resin of the polyester (alkyd-styrene) type. The panels of 143-114 laminate were made of 26 plies of 143-114 unidirectional weave fabric (having a warp-to-fill strength ratio of about 11 to 1) and also parallel-laminated with resin B. For all panels, the resin was catalyzed with 0.8 percent benzoyl peroxide by weight.

The fabric and resin were laid up between cellophane-covered, papreg-faced plywood cauls. Immediately after impregnation and lay-up, the panel was cured at a pressure of 14 pounds per square inch for 1 hour in a press at 250° F. Pressure was controlled by means of an oil-filled steel bladder located on the bottom plate of the press. The resin content and specific gravity of each panel are given in table 4.

Tension, compression, and panel-shear specimens were cut from each panel as indicated in the cutting diagram of figure 1.

Testing

The tension, compression, and panel-shear tests were made by the same general methods employed in testing the laminate made of 181-114 fabric (referred to in this supplement as 181-114 laminate). In the following discussion, therefore, no detailed description of testing procedures for the 112-114 laminate or the 143-114 laminate is given except where there is a difference from that described in the original report.

Tension Tests

The specimens were tested in a testing machine using templin grips (fig. 2). The load was applied at a head speed of 0.035 inch per minute, and the strains were measured parallel to the applied load across a 2-inch gage length with a pair of Marten's mirrors. The specimens failed suddenly when the maximum load was reached.

The failures of the 112-114 laminate were primarily tension failures of the material, but the 0° and 90° specimens also showed interlaminar shear failures. The specimens of 143-114 laminate tested parallel to the warp of the laminations ($\theta = 0^\circ$) failed in tension and then shattered transversely, thereby developing a splintering type of failure. At the other angles, 15°, 45°, 75°, and 90°, the failure was perpendicular to the warp of the laminations.

Values of Poisson's ratio were obtained from six tension specimens of each laminate. In three of each, the stress was applied in the direction of the warp of the laminations, and in three it was applied perpendicular to the warp.

Compression Tests

The compression specimens were 1 inch wide, 4 inches long, and of the thickness of the laminate. They were loaded on the 1-inch ends and restrained from buckling by means of the apparatus illustrated in figure 3. The testing machine, equipped with a spherical head, was run at a head speed of 0.012 inch per minute, and the strains were measured across a 2-inch gage length with a pair of Marten's mirrors. The load increased steadily until the maximum load was reached, at which point the specimen failed suddenly.

Failures were generally similar with both types of laminates, crushing of the fibers being combined with a transverse shear failure that was sometimes followed by slight delamination of the specimen.

Panel-Shear Tests

The panel-shear specimens (fig. 8) were loaded at a testing-machine head speed of approximately 0.01 inch per minute, and load and compressive strain were read at regular intervals of load. The strain measurements were made with a dial compressometer having a gage length of 1 inch and reading to 0.0001 inch.

The type of failure sustained by panel-shear specimens of 112-114 laminate was predominately a diagonal tension failure. Usually there was a tendency to split along the warp or fill direction, but the 0° specimens failed at 45° to the panel edges. Considerable difficulty was encountered in testing the 45° and -45° specimens; in fact, none of the 45° specimens and only two -45° specimens appeared to have satisfactory failures. Apparatus of special design might be necessary to develop the additional shear stress required to get satisfactory failures with this laminate at these orientations.

The panel-shear specimens of 143-114 laminate failed as expected. At the 45° angle of loading, when the warp of the laminate is subjected to tensile stresses, the panel failed in diagonal compression along the warp of the laminations. At the other angles of loading, $+30^\circ$, 0° , -30° , and -45° , the specimens failed in tension or shear along the warp direction. In all cases except the 0° load angle, at which specimens failed in shear, the load increased steadily to the maximum load and the specimens failed suddenly.

Presentation of Data

The average mechanical properties of specimens in tension, compression, and shear at various angles (0) to the warp of the laminations are given in table 5. Values of modulus of elasticity, stress at proportional limit, 0.2 percent offset yield stress, and ultimate stress are given for each group of specimens. The 112-114 laminate has both initial and secondary values for modulus of elasticity and proportional limit in tension (as was observed with the 181-114 laminate), but this characteristic was not observed in the tensile tests of the 143-114 laminate.

Figures 28 through 33 show average stress-strain curves at various angles of applied stress for tension, compression, and shear specimens of both laminates.

Curves showing the relationship between tangent modulus and stress have been drawn for each laminate for both compression (fig. 34) and shear (fig. 35). The curves are based on the average compression curves of figures 30 and 31, and on the average shear curves of figures 32 and 33.

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 36 through 41. The theoretical values are represented by curves that, in each case, bear the number of the equation from which the curve was obtained.

Analysis of Data

General

The three laminates tested for these directional properties studies represent three widely different types of glass fabric used in aircraft laminates. If the theoretical analysis can be successfully applied to these laminates, it may be assumed to apply to any of the glass fabrics presently being used in aircraft laminates.

Since appreciable variations occur within a laminated panel, a few tests, such as those discussed in this report, cannot be expected to give exact average values for the material. Thus variation between experimental and calculated values must be expected.

Except for the panel-shear tests, there was good correlation between experimental and theoretical values.

Stress-Strain Curves

Average stress-strain curves in tension, compression, and shear are presented in figures 28, 30, and 32 for the 112-114 laminate, and in figures 29, 31, and 33 for the 143-114 laminate. Each group of five curves was drawn to the same coordinates to show best the general tendencies as affected by the angle of loading. As with the 181-114 laminate, the mechanical properties are considerably affected by the angle of loading.

The 112-114 laminate exhibited a low initial proportional limit in tension at 0° and 90°, as was observed with the 181-114 laminate. This characteristic may be present at intermediate angles, but was not clearly defined and is therefore not given. The low initial proportional limit may also be present in the 143-114 laminate, but it was not clearly shown in these tests, and no conclusion could be drawn from the specimens tested.

A study of the compression load-deformation data for the 112-114 laminate (and the 181-114 laminate previously tested) indicates that there may be an initial and a secondary modulus of elasticity for some laminates. For these laminates, the dual values definitely appear to exist in some cases, are possibilities in others, and in still others do not exist at all. Where the dual values do exist, the differences between the initial and secondary moduli are small. Because this small difference does not appear to be important for practical applications, a single straight line has been drawn through the plotted points and thus a mean modulus of elasticity and proportional limit is given. There was no indication of dual values in compression from tests of the 143-114 laminate.

Mathematical Equations

The values obtained from the general elastic equations and the interaction formula are in good agreement with the test values obtained from tension and compression tests. The correlation with the shear values, however, is not good. The difficulties of making an accurate shear test are recognized, and as has been mentioned before, it may be that the computed shear values may be more nearly correct than those measured by the shear tests. For these reasons, as with the 181-114 laminate, the values of F_{ab} and P_{ab} used in the various equations were based on the results of tension tests.

Tension Tests

Values of Poisson's ratio were computed from tests on tensile specimens. For the 112-114 laminate σ_{ab} is equal to 0.15 and σ_{ba} is equal to 0.15. For the 143-114 laminate σ_{ab} is equal to 0.25 and σ_{ba} is equal to 0.08. These values apply to strains below the initial proportional limit.

For the 112-114 laminate curves are presented that indicate theoretical values at various angles for both the initial and secondary values of modulus of elasticity and proportional limit stress (fig. 36). For modulus of elasticity, the theoretical and experimental values must be in exact agreement at angles of 0° and 90° . Since it is difficult to determine whether there is an initial and secondary line at intermediate angles, the value picked may vary considerably. The experimental values of modulus of elasticity are, however, in reasonable agreement with the theoretical curves. The experimental values of initial proportional limit, secondary proportional limit, and ultimate stress are in good agreement with the theoretical curves.

There is good agreement between the experimental and theoretical tension values of modulus of elasticity, proportional limit, and ultimate stress for the 143-114 laminate (fig. 37).

Compression Tests

The compression "pack" test was used for the compression tests of both laminates. As has been mentioned previously, the experimental values of modulus of elasticity, stress at proportional limit, and ultimate stress would be expected to fall somewhere between the theoretical values for no restraint and complete restraint.

As a whole, there is reasonable agreement between the experimental and theoretical values for both laminates (figs. 38 and 39). The experimental values of ultimate stress for the 112-114 laminate, however, are slightly lower than expected at the intermediate angles.

Panel-Shear Tests

The theoretical values of modulus of elasticity and stress at proportional limit were calculated on the basis of the appropriate values from the initial tension data.

For the 112-114 laminate the correlation between experimental and theoretical values is shown in figure 40. Experimental values of modulus of rigidity are too high, being about 27 percent too great at -45° . Except at -45° , there is good agreement between the proportional limit values. The experimental values of ultimate stress fall below the theoretical curves except when θ is 0° . Failure of the -30° , 0° and 30° specimens was by diagonal tension or shear, as expected. The two -45° specimens reported on failed in diagonal tension, and the failure appeared satisfactory. The failure of the one 45° specimen was such that it is questionable if the maximum load was attained. This value, however, is reported to show the maximum stress that was reached. From the physical characteristics of the material, one would expect about the same values at -45° and 45° . It is inconsistent that no satisfactory failure was obtained at 45° , yet the one value reported is considerably greater than the average for -45° . The correlation between experimental and theoretical values is not good.

The correlation between experimental and theoretical values for the shear tests of the 143-114 laminate are shown in figure 41. Experimental values for modulus of rigidity are much higher than expected at -45° and -30° , but are in reasonable agreement with the no-restraint curve at the other angles tested. There is fair agreement between the proportional limit values at -30° , 0° , and 30° but poor agreement at -45° and 45° . The experimental values for ultimate strength fall below the no-restraint curve at -45° and -30° , but are in reasonable agreement with these values at the other angles tested. As with the 112-114 laminate the correlation between the experimental and theoretical values is generally not good for the shear properties mentioned.

It has been recognized that the ultimate stress in shear at 0° , F_{ab} , can be obtained for orthotropic materials from tension tests at 0° , 45° , and 90° . The values of F_0 , and F_{45} , and F_{90} are substituted in equation (15) and F_{ab} can be calculated. It can be seen from figures 40 and 41 that the experimental values at 0° are in good agreement with the computed values, which are based on this equation.

Table 4.--Resin content and specific gravity of test panels
made from 112-114 and 143-114 fabrics

Panel No.	: 112-114 Laminate, Resin B : 143-114 Laminate, Resin B			
	: Resin ¹ : Specific	:	: Resin ¹ : Specific	:
	: content : gravity	:	: content : gravity	:
	: <u>Percent</u> :	:	: <u>Percent</u> :	:
1	: 40.1 :	: 1.71 :	: 31.0 :	: 1.86 :
2	: 44.0 :	: 1.70 :	: 30.5 :	: 1.87 :
3	: 43.2 :	: 1.70 :	: 31.6 :	: 1.85 :
4	: 43.2 :	: 1.70 :	: 32.0 :	: 1.84 :

¹Based on weight of finished laminate.

Table 5.-Average tension, compression, and panel-shear test values from specimens of two glass-fabric-base plastic laminates with stresses applied at various angles (θ) to the warp of the lamination

Angle of loading: θ	Tension				Angle of loading: θ				Compression				Angle of loading: θ				Shear			
	Modulus of elasticity	Proportional limit stress	0.2 percent offset stress	Ultimate stress	Specific gravity	Modulus of elasticity	Proportional limit stress	0.2 percent offset stress	Ultimate stress	Modulus of elasticity	Proportional limit stress	0.2 percent offset stress	Ultimate stress	Modulus of elasticity	Proportional limit stress	0.2 percent offset stress	Ultimate stress			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)			
Degrees	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	Degrees	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	Degrees	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	Degrees			
112-114 Laminates, Resin B																				
0	2,744	2,098	8,690	34,240	29,750	42,910	0	1.69	2,572	25,190	44,500	44,500	-45	1,428	9,960	220,680	220,680			
15	2,253	2,253	8,170	17,650	33,940	33,940	15	1.70	2,448	13,420	30,690	31,300	-30	1,166	4,630	10,290	14,910			
45	1,493	1,493	3,880	5,880	8,600	22,240	45	1.70	1,574	5,480	11,150	18,870	0	557	1,990	4,200	512,780			
75	1,898	1,898	7,460	15,010	29,940	29,940	75	1.71	2,287	13,110	26,200	26,400	30	1,085	5,140	9,620	14,940			
90	2,556	1,970	8,520	28,920	27,040	41,200	90	1.71	2,667	20,420	32,350	32,350	45	1,329	8,410	24,070	24,070			
143-114 Laminates, Resin B																				
0	4,839	.....	26,240	.....	87,320	87,320	0	1.84	5,011	24,200	56,800	56,800	-45	2,317	6,510	6,510	6,510	
15	3,788	.....	8,310	.....	23,550	33,750	15	1.86	3,794	16,860	34,510	34,710	-30	1,612	4,540	7,060	7,060	
45	1,721	.....	3,750	.....	7,470	14,530	45	1.86	1,878	5,800	12,170	19,730	0	832	2,390	5,090	11,230	
75	1,472	.....	2,640	.....	4,740	10,270	75	1.86	1,554	8,560	18,080	21,540	30	904	4,670	9,760	15,690	
90	1,454	.....	2,430	.....	4,440	9,880	90	1.85	1,557	8,330	19,830	20,950	45	1,071	4,580	11,360	16,520	

¹Values based on tests of four specimens for each property and each laminate.

²Based on initial straight portion of stress-strain curve.

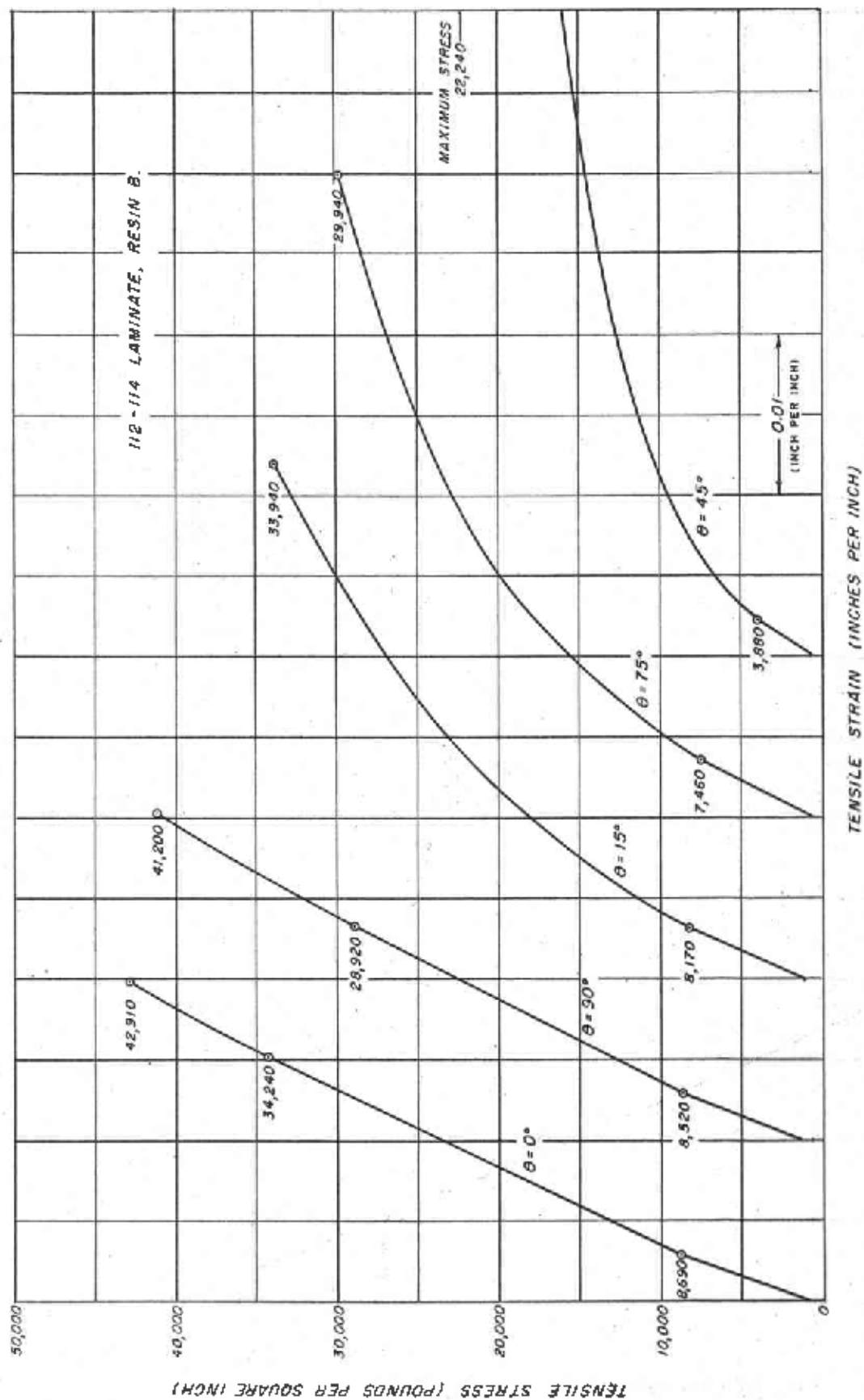
³Based on second straight portion of stress-strain curve.

⁴Value at 0.2 percent offset from initial straight line of stress-strain curve.

⁵Based on two specimens.

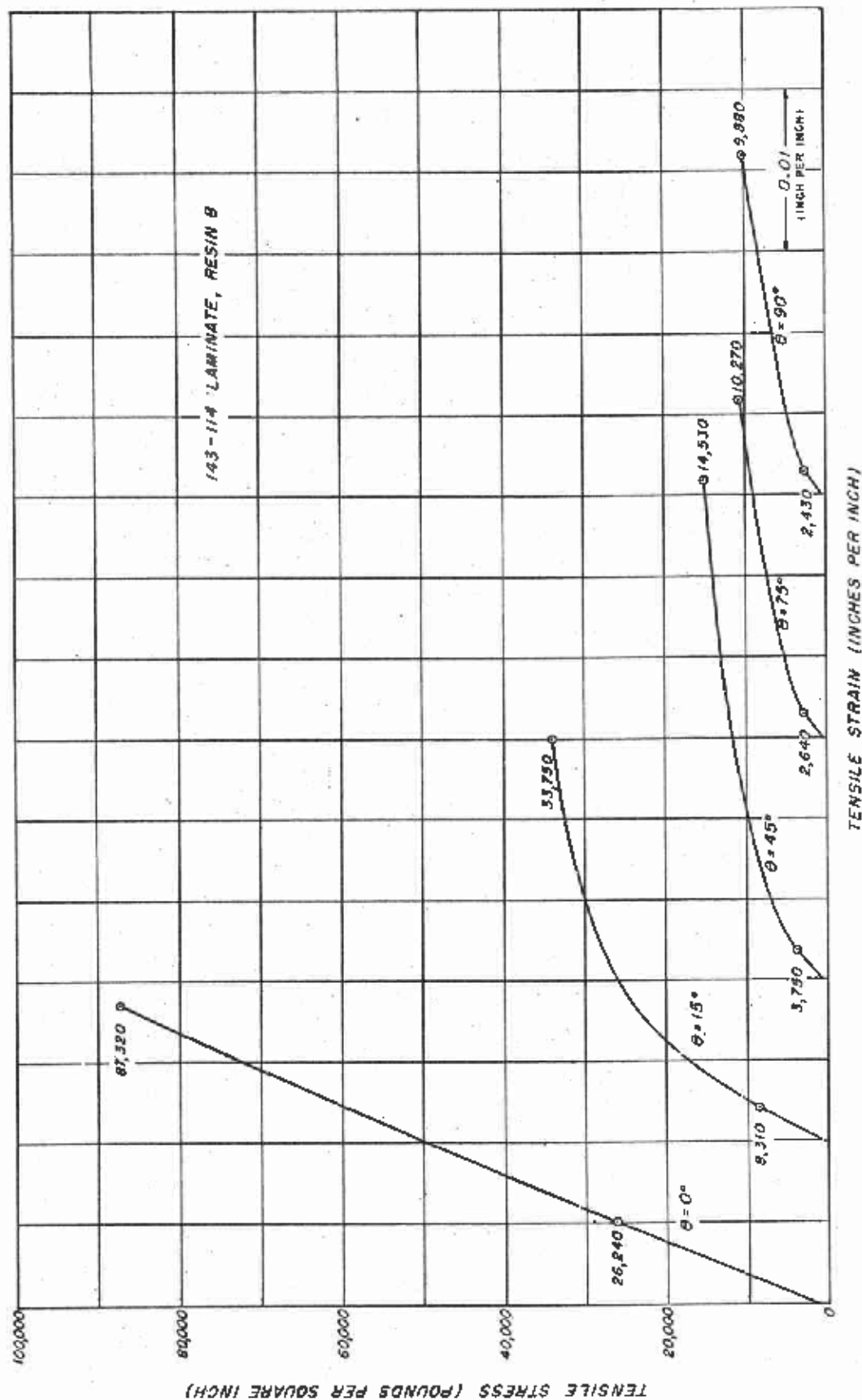
⁶Based on three specimens.

⁷Maximum shear stress obtained from one specimen. No satisfactory failures at this angle.



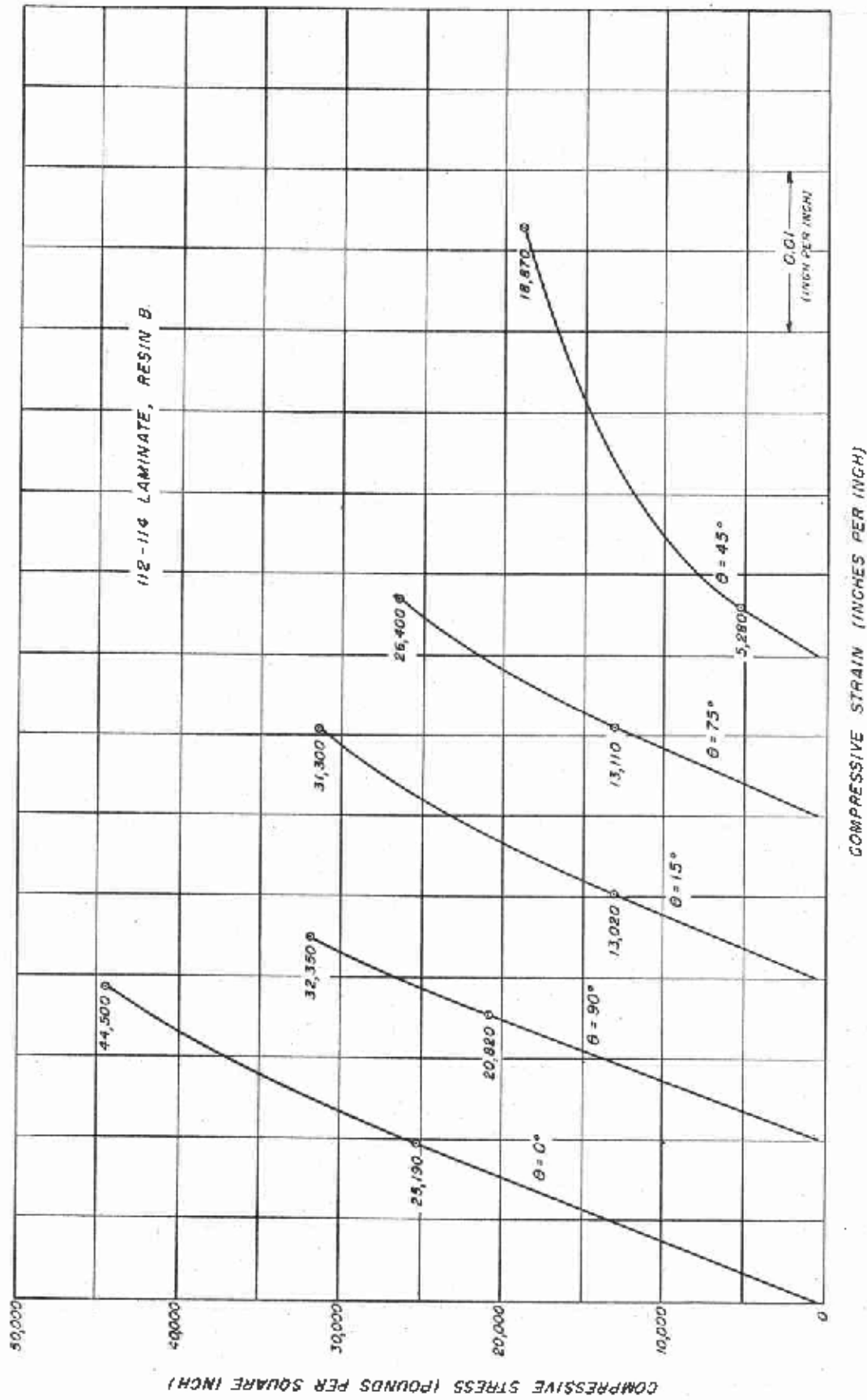
Z 86541 P

Figure 28. --Average stress-strain curves for parallel-laminated tension specimens of 112-114 laminate, tested at 0, 90, 15, 75, and 45 degrees to the warp of the fabric.



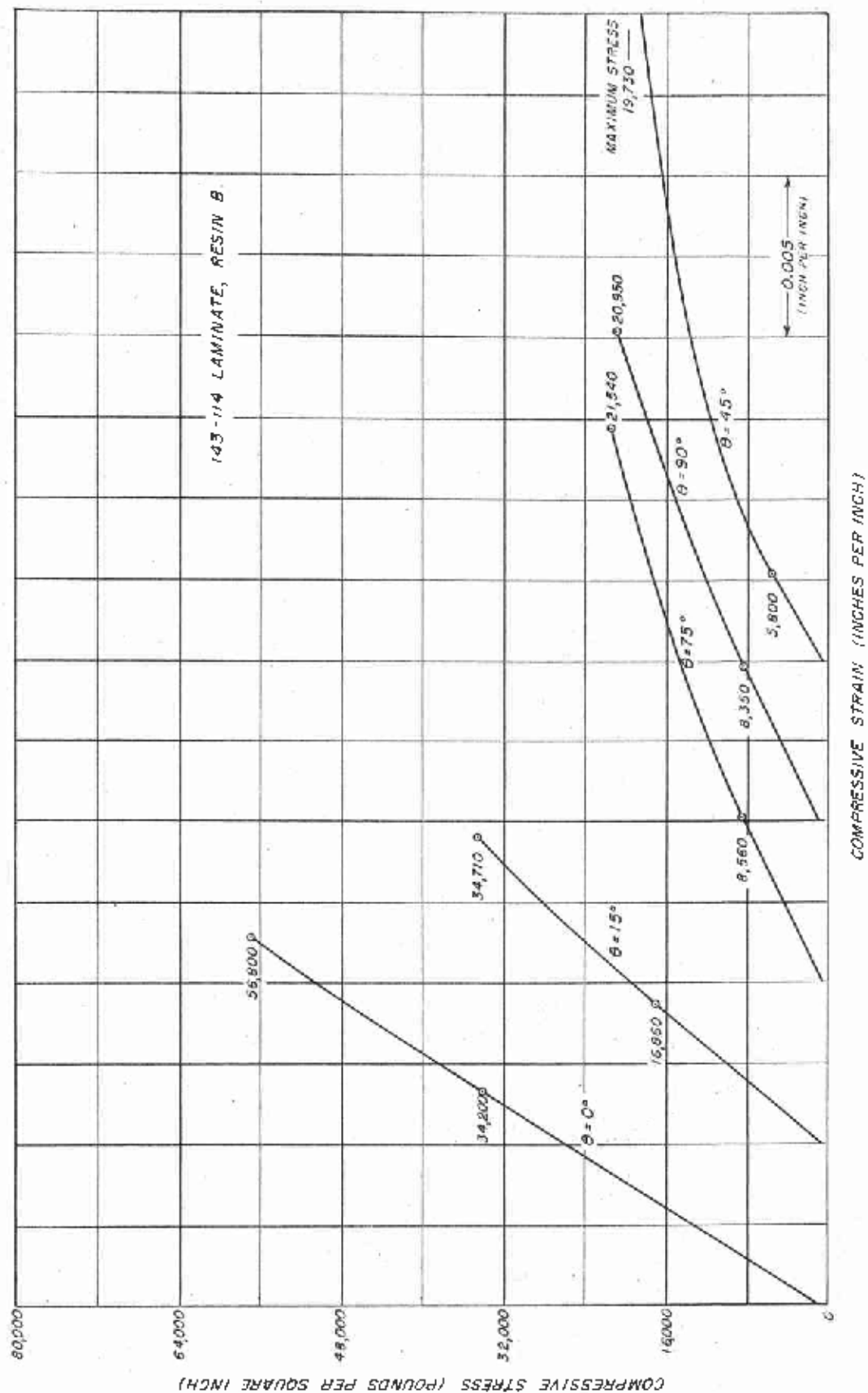
Z M 84342 P

Figure 29. --Average stress-strain curves for parallel-laminated tension specimens of 143-114 laminate tested at 0, 15, 45, 75, and 90 degrees to the warp of the fabric.



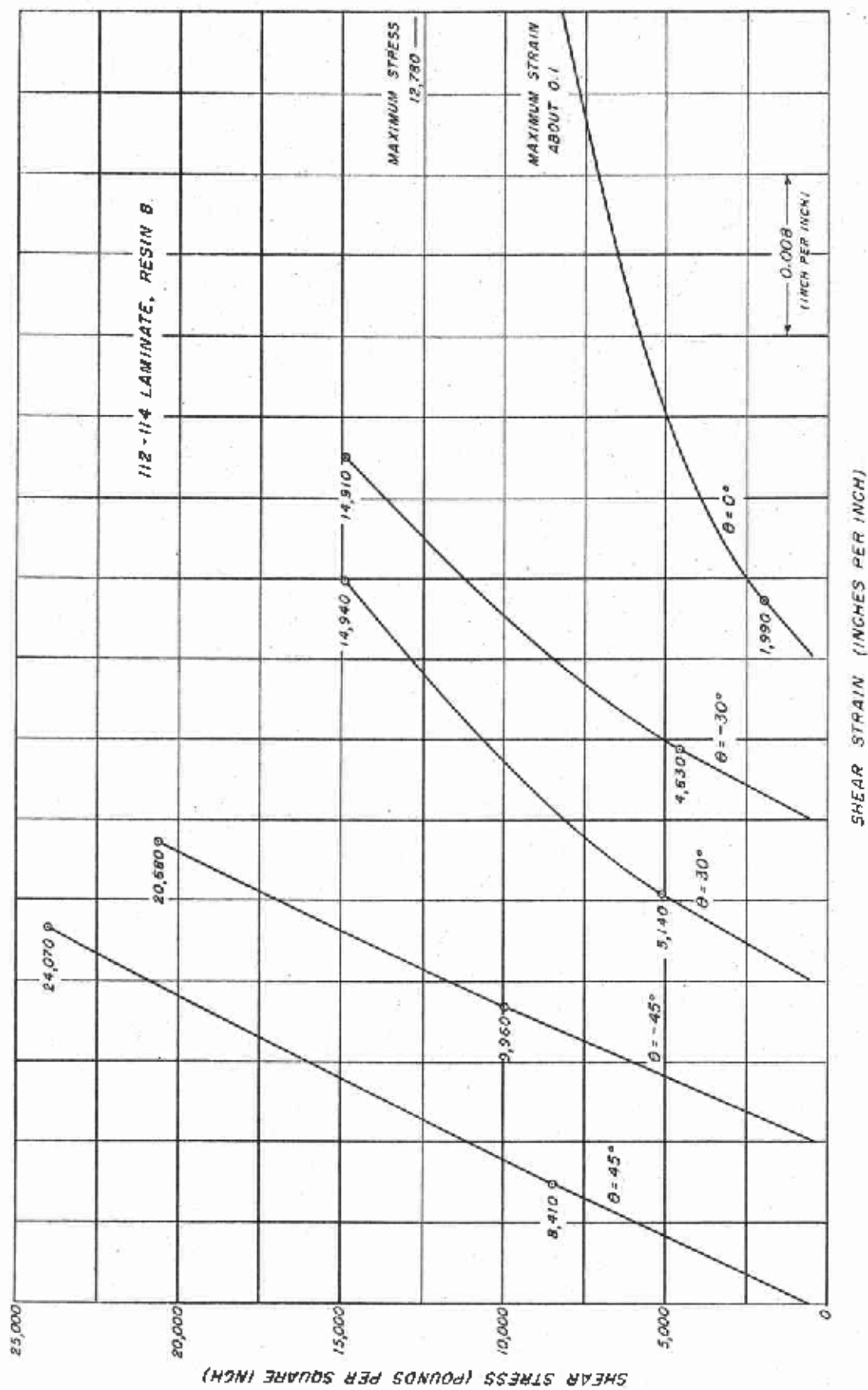
2 N 81543 B

Figure 30. --Average stress-strain curves for parallel-laminated compression specimens of 112-114 laminate tested at 0, 90, 15, 75 and 45 degrees to the warp of the fabric.



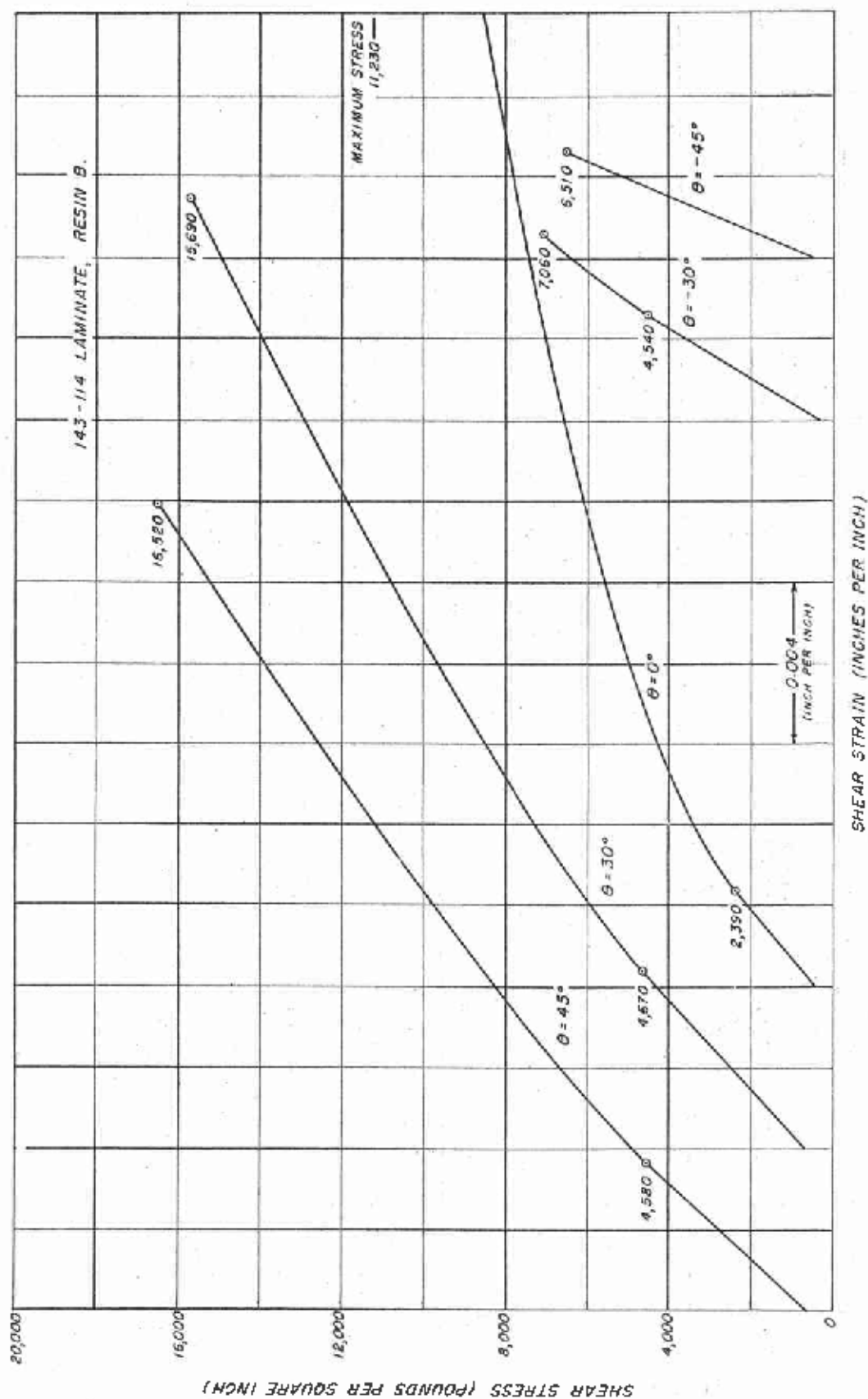
Z M 84544 F

Figure 31. --Average stress-strain curves for parallel-laminated compression specimens of 143-114 laminate tested at 0, 15, 75, 90, and 45 degrees to the warp of the fabric



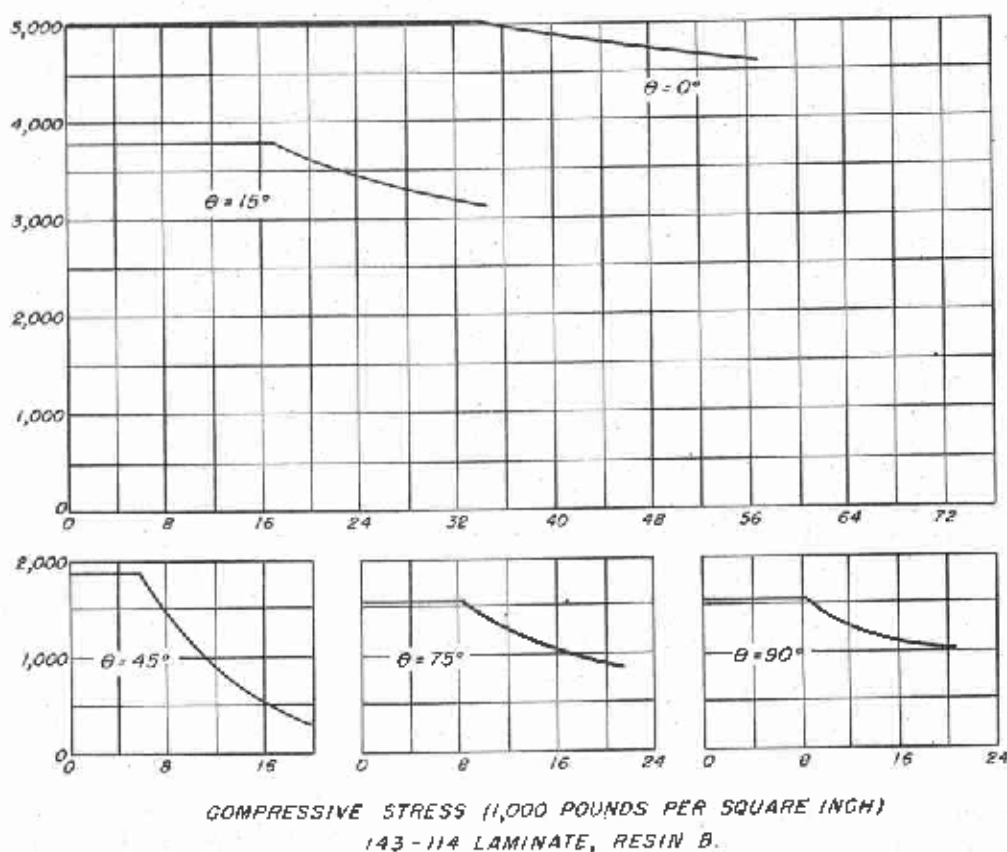
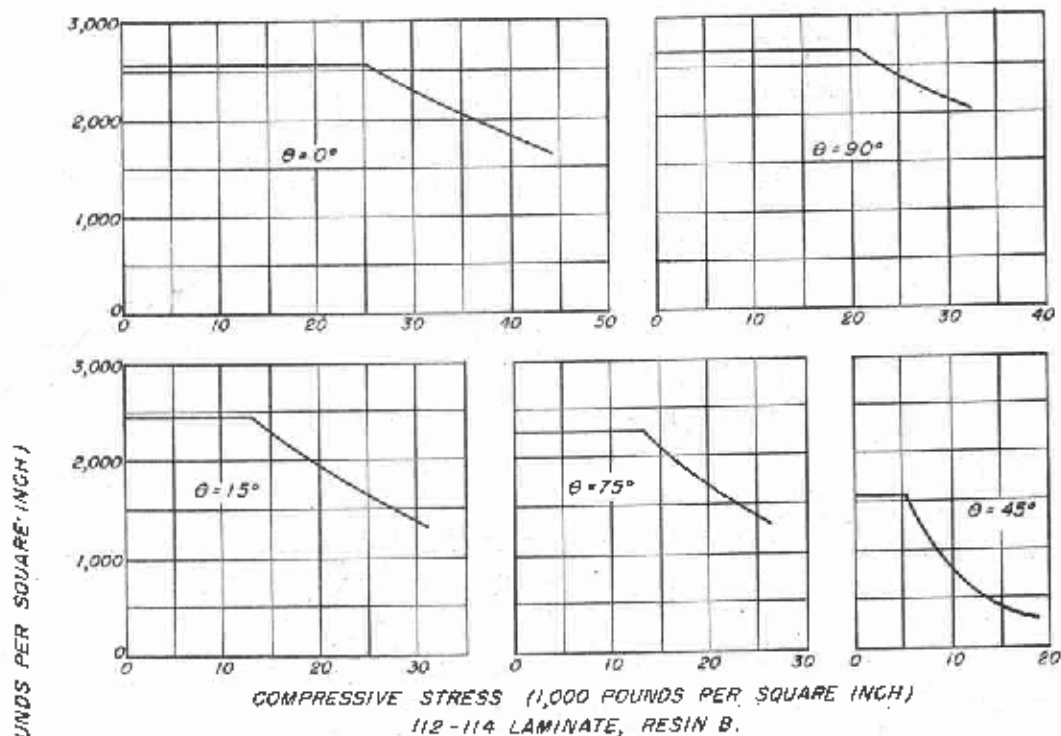
7 M 84545 F

Figure 32. --Average stress-strain curves for parallel-laminated shear specimens of 112-114 laminate tested at 45, -45, 30, -30, and 0 degrees to the warp of the fabric.



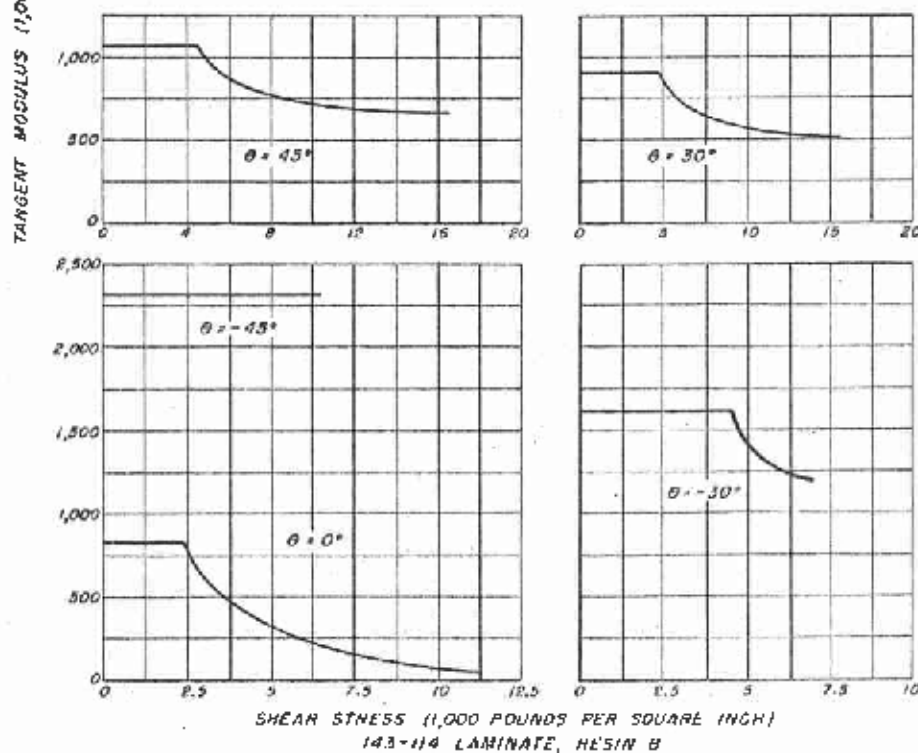
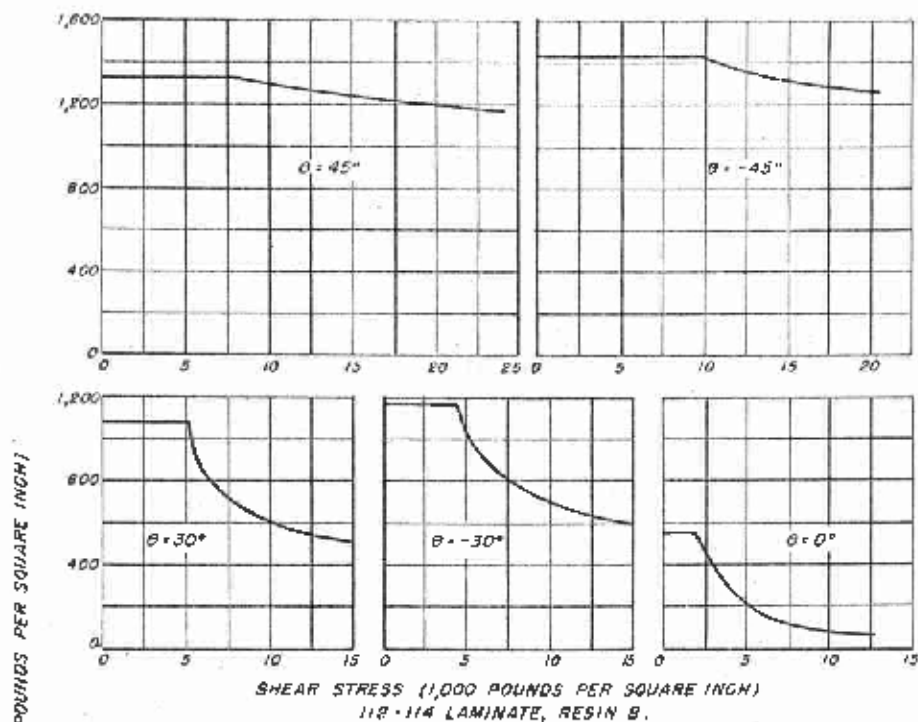
Z N 88346 P

Figure 33.--Average stress-strain curves for parallel-laminated shear specimens of 143-114 laminate tested at 45, 30, 0, -30, and -45 degrees to the warp of the fabric.



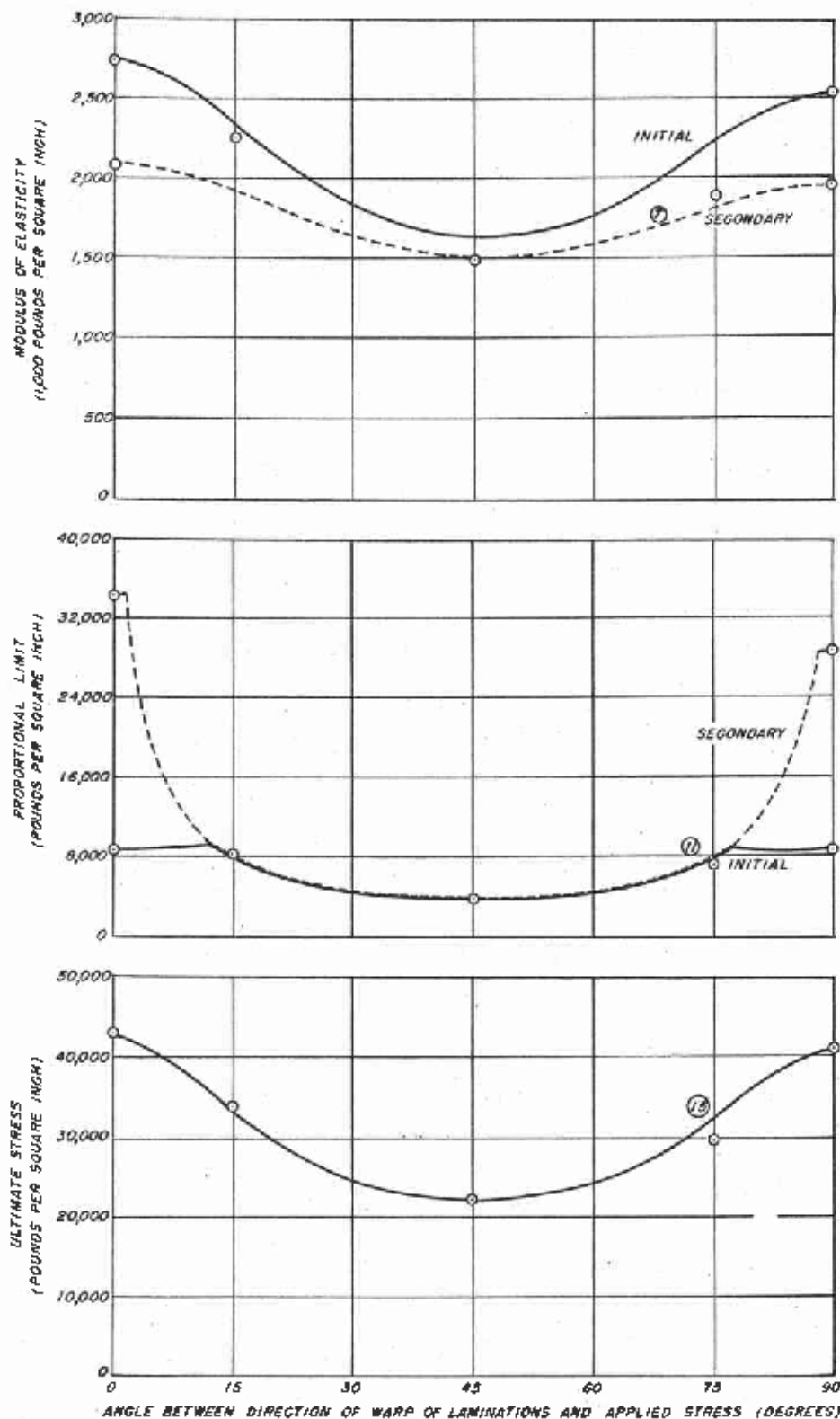
2. N 84547 P

Figure 34. --Relationship between tangent modulus and compressive stress for 112-114 and 143-114 laminates. (Based on average curves of figures 30 and 31.)



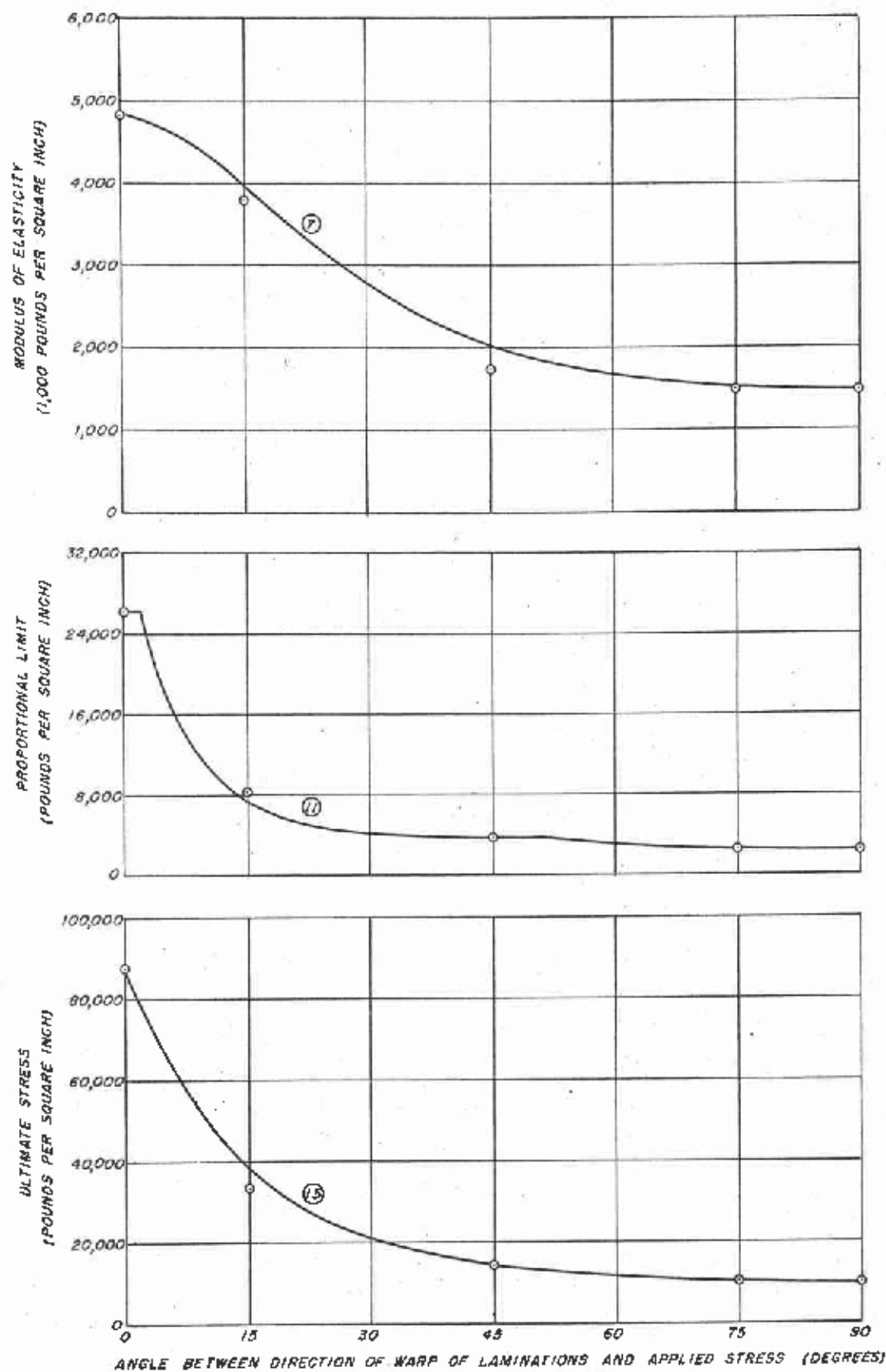
2. N 64548 P

Figure 35. --Relationship between tangent modulus and shear stress for 112-114 and 143-114 laminates. (Based on average curves of figures 32 and 33.)



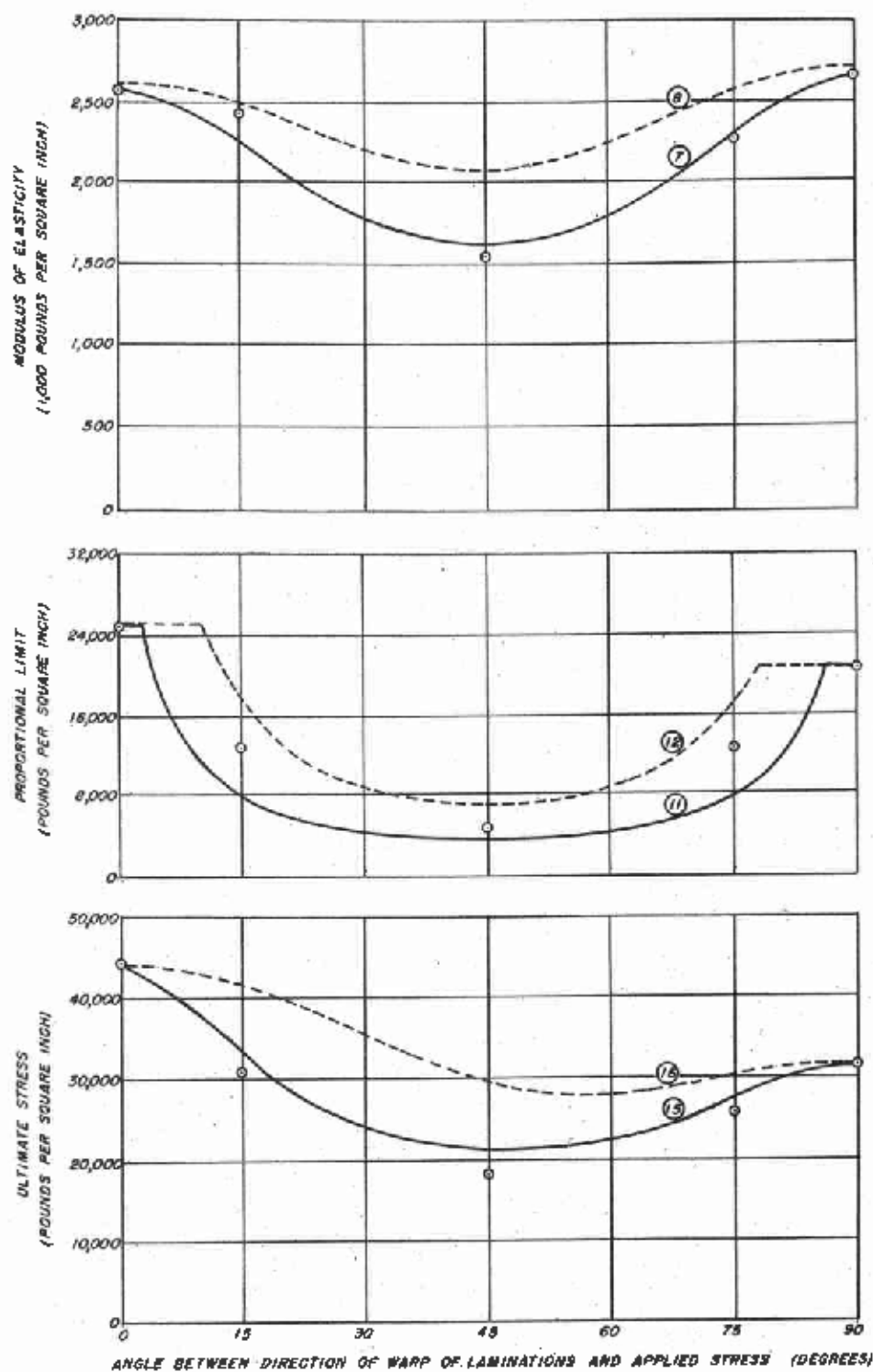
- W 8358A F

Figure 36. --Theoretical and experimental values from tension tests of 112-114 laminate. Equation number is given for each curve.



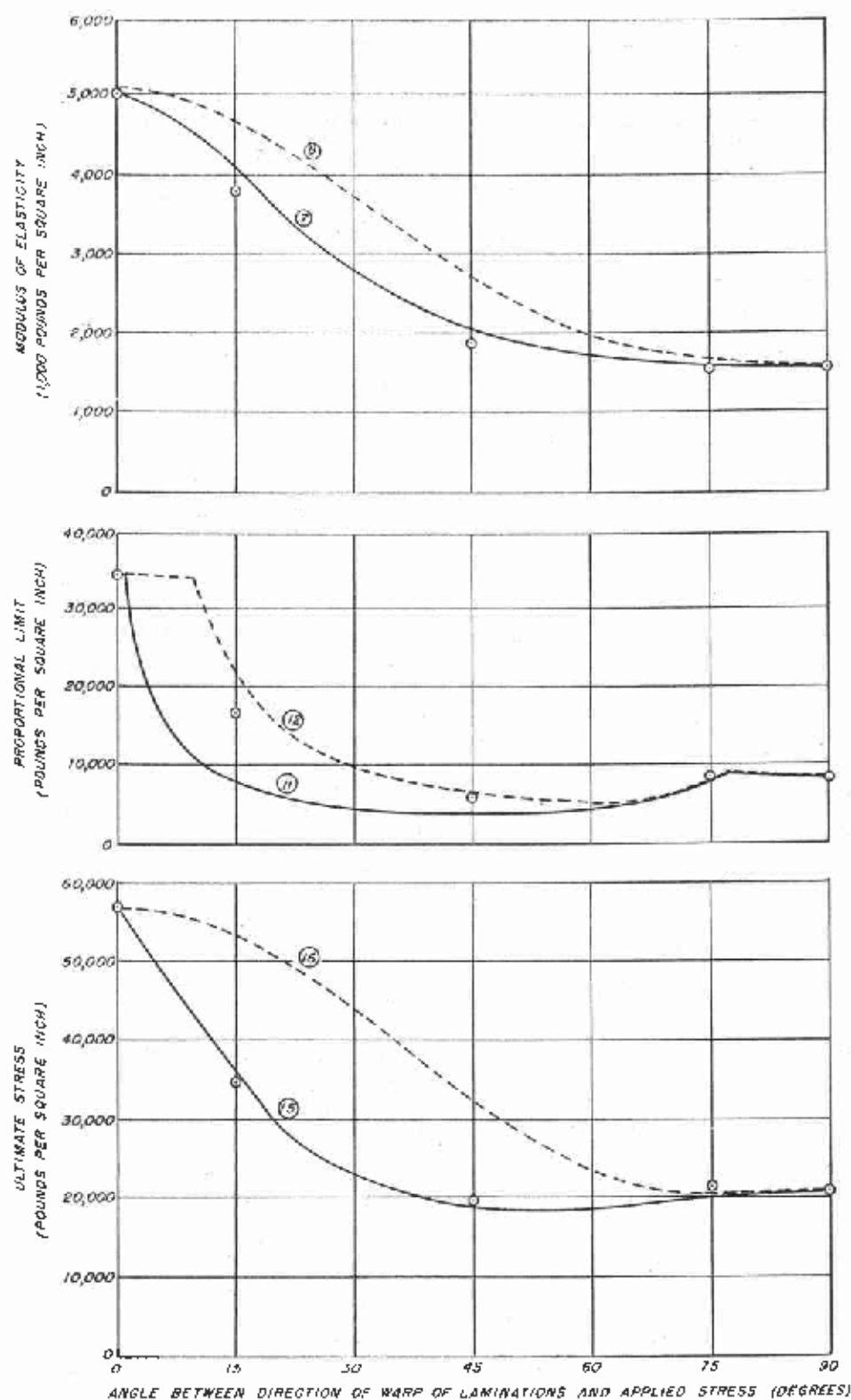
8 W 83585 F

Figure 37. --Theoretical and experimental values from tension tests of 143-114 laminate. Equation number is given for each curve.



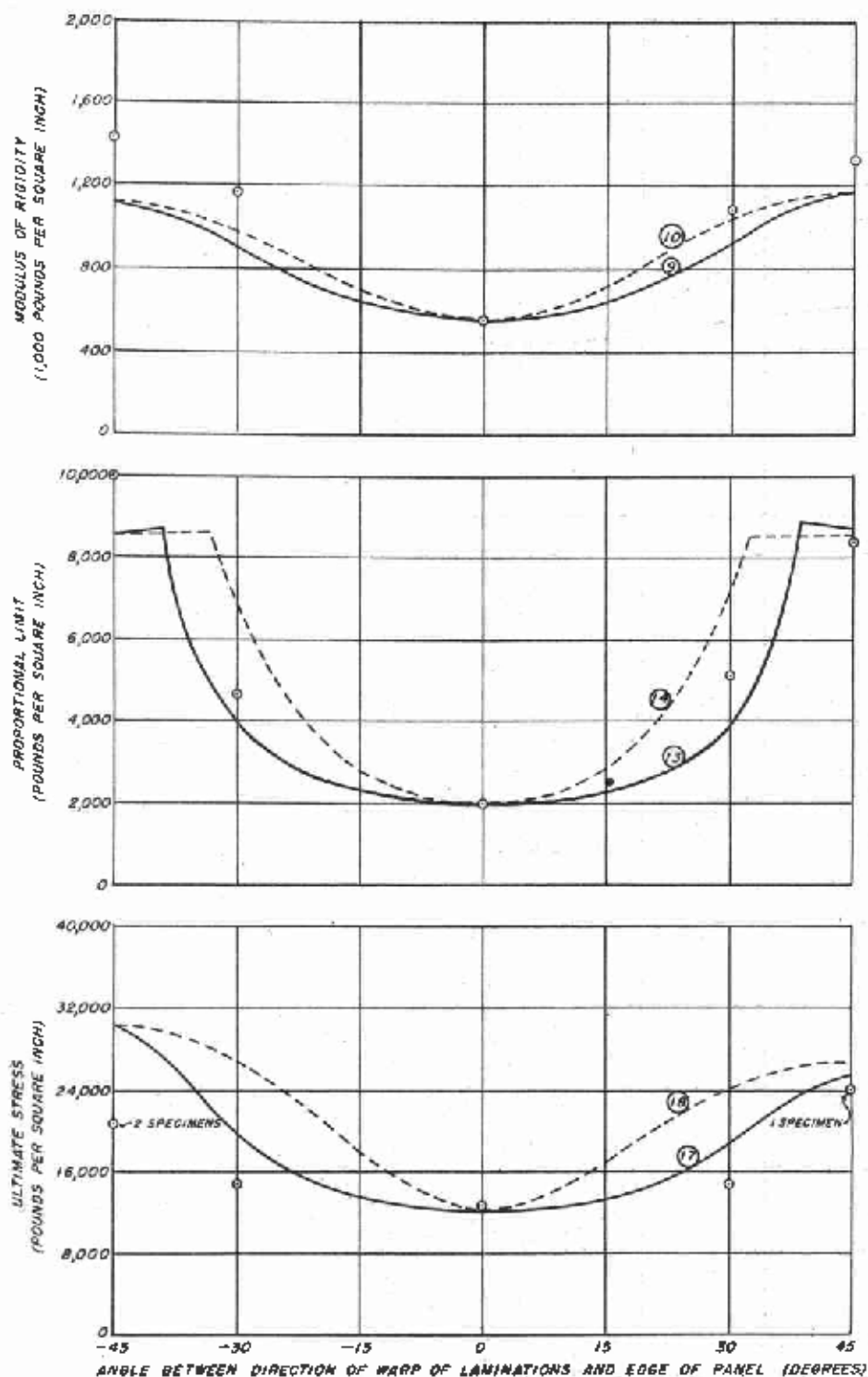
2 M 89586 2

Figure 38. --Theoretical and experimental values from compression tests of 112-114 laminate. Equation number is given for each curve.



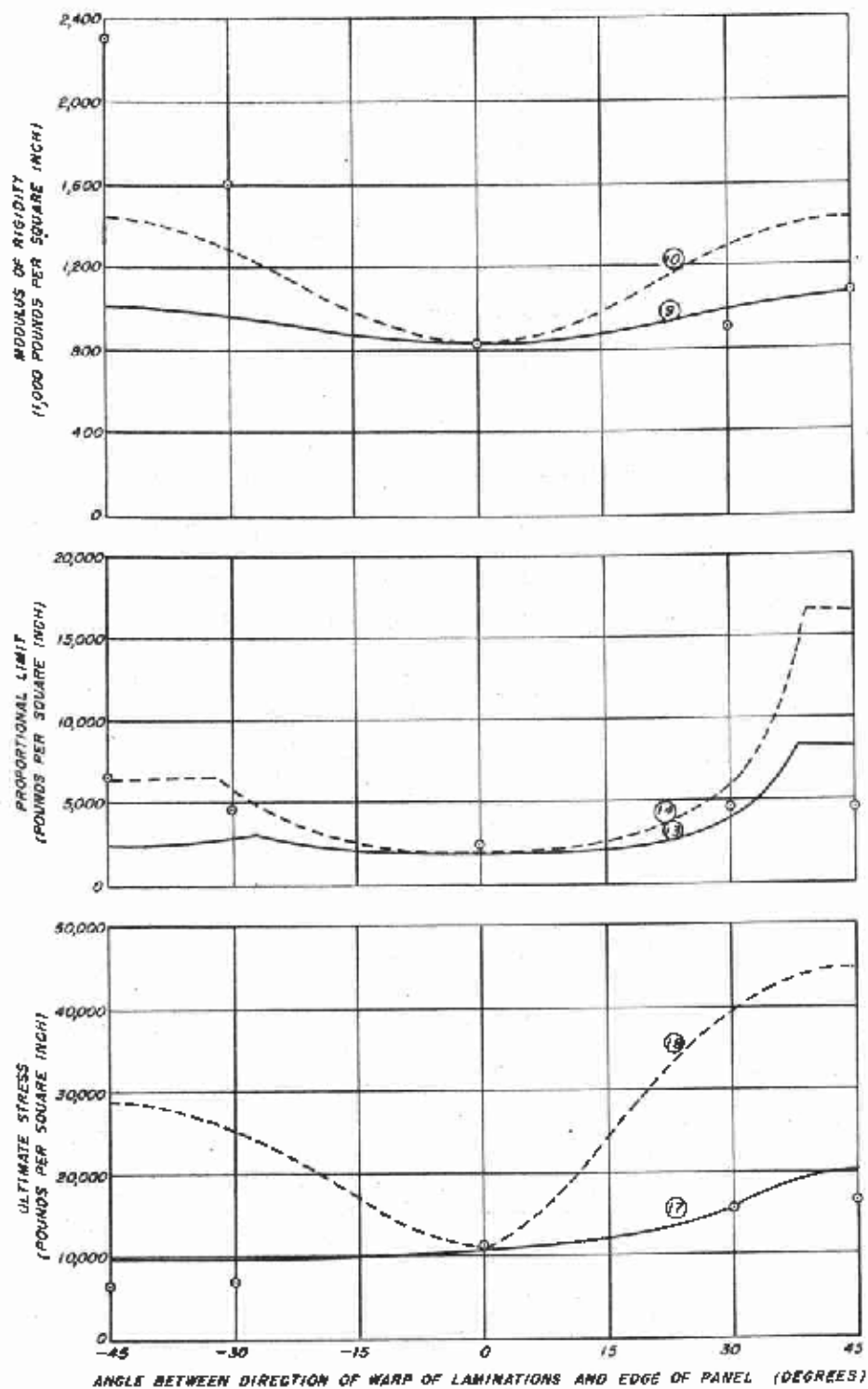
143-114

Figure 39. --Theoretical and experimental values from compression tests of 143-114 laminate. Equation number is given for each curve.



2 N 57588 2

Figure 40. --Theoretical and experimental values from panel shear tests of 112-114 laminate. Equation number is given for each curve.



W 87799

Figure 41. -- Theoretical and experimental values from panel shear tests of 143-114 laminate. Equation number is given for each curve.