1803-B

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 BUCKLE[1]

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Introduction

The preceding reports (1803, 1803-A) have presented formulas for computing the directional strength and elastic properties of glass-fabric-reinforced laminates, together with the results of tests confirming the validity of the formulas. Those formulas have also been given in ANC Bulletin 17 for use in computing properties of parallel or cross laminates in any direction from properties parallel and perpendicular to the warp direction.

For use in design, it is more convenient to have the relations between properties and direction given graphically than as formulas. This report presents such graphical relations for tension, compression, and shear based on properties (moduli and ultimate strengths) reduced to specification levels. The computations necessary to prepare the graphs were not complete at the time the ANC-17 Bulletin went to press. This report, therefore, is, in effect, a supplement to the Bulletin.

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[1] This progress report is one of a series prepared and distributed by the Forest Products Laboratory under U. S. Navy, Bureau of Aeronautics No. NAer Order 01610, and U. S. Air Force No. USAF Amend. A2 (55-295) to DO (33-616)53-20. Results here reported are preliminary and may be revised as additional data become available.

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

Formulas for Directional Properties

Directional properties are presented herein only for moduli and for ultimate strengths. Except as noted, the formulas are those given in the basic report.

Tension and Compresssion

Tensile and compressive moduli (E_x) at any angle ϕ to the warp direction of the laminate were computed from

$$\frac{1}{E_x} = \frac{\cos^4 \phi}{E_\alpha} + \frac{\sin^4 \phi}{E_\beta} + \left[\frac{1}{G_{\alpha\beta}} - 2\frac{\mu_{\alpha\beta}}{E_\alpha}\right] \sin^2 \phi \quad \cos^2 \phi \qquad (19)$$

where E_α = tensile or compressive modulus parallel to warp

E_β = tensile or compressive modulus perpendicular to warp

$G_{\alpha\beta}$ = shear modulus when shear forces are applied parallel and perpendicular to warp

$\mu_{\alpha\beta}$ = Poisson's ratio of contraction in the β direction to extension in the α direction due to a tensile stress in the α direction

This equation is the same as equation (7) of the basic report.

The ultimate strength (F_x) in tension or compression at any angle ϕ to the warp direction was computed from

$$\frac{1}{F_x^2} = \frac{\cos^4 \phi}{F_\alpha^2} + \frac{\sin^4 \phi}{F_\beta^2} + \left[\frac{1}{F_{\alpha\beta}^2} - \frac{1}{F_\alpha F_\beta}\right] \sin^2 \phi \quad \cos^2 \phi \qquad (20)$$

where F_α = tensile or compressive strength parallel to warp

F_β = tensile or compressive strength perpendicular to warp

$F_{\alpha\beta}$ = shear strength when shear forces are applied parallel and perpendicular to warp

This equation is the same as equation (15) of the basic report except for the addition of the term $\left(-\frac{\sin^2\phi\cos^2\phi}{F_\alpha F_\beta}\right)$. The derivation leading to this additional term is described in Forest Products Laboratory Report 1816.[3]

Shear

Shear moduli (G_{xy}) when shear forces are applied in the x and y directions, which are at an angle ϕ to the α and β directions, were computed from

$$\frac{1}{G_{xy}} = \frac{\cos^2 2\phi}{G_{\alpha\beta}} + \left[\frac{1}{E_\alpha} + \frac{1}{E_\beta} + \frac{2\mu_{\alpha\beta}}{E_\alpha}\right]\sin^2 2\phi \qquad (21)$$

which is the same as equation (9) of the basic report.

Shear strengths (F_{xy}) when shear forces are applied in the x and y directions described above were computed from

$$\frac{1}{F_{xy}^2} = \frac{\cos^2 2\phi}{F_{\alpha\beta}^2} + \left[\frac{1}{F_\alpha^2} + \frac{1}{F_\alpha F_\beta} + \frac{1}{F_\beta^2}\right]\sin^2 2\phi \qquad (22)$$

which is the same as equation (17) of the basic report except for the addition of the term $\left(\frac{\sin^2 2\phi}{F_\alpha F_\beta}\right)$.[3]

If the shear stresses are applied in such a way that components of stress in the α direction are tension, E_α and F_α are taken as tensile properties parallel to the α axis, while E_β and F_β are taken as compressive properties perpendicular to the α axis. If the shear stresses are applied in such a way that the components of stress in the α direction are compressive, E_α and F_α are taken as compressive properties

[3] Norris, C. B. Strength of Orthotropic Materials Subjected to Combined Stresses. Forest Products Laboratory Report No. 1816. July 1950.

parallel to the $\underline{\alpha}$ axis, while $E_{\underline{\beta}}$ and $F_{\underline{\beta}}$ are taken as tensile properties perpendicular to the $\underline{\alpha}$ axis.

Reduced Properties

Mechanical properties of laminates made with a variety of reinforcements are presented in the ANC-17 Bulletin in reduced form, that is, they have been reduced to values which correspond with the minimum requirements contained in appropriate military specifications. The reduced values used in computing data for the directional curves herein are shown in tables 6 and 7. The methods of obtaining the reduced values are outlined below.

Where specification requirements (wet conditions) were available, as for tensile strength, compressive strength, and modulus of rupture parallel to warp, test values for these properties are reduced to these values. That is, the tabulated values are equal to the specification wet values.

There were no specification values for properties perpendicular to warp or for stress at proportional limit parallel to warp. Tabulated values for these properties have the same ratio to the corresponding test average as does the specification wet value to the average test ultimate. Thus, if the specification value for tensile strength was 40,000 p.s.i. and the average tensile strength from test was 50,000 p.s.i., average values for stress at proportional limit parallel and perpendicular to warp and the average value of tensile strength perpendicular to warp would be multiplied by 0.80 to obtain the reduced values given herein.

Modulus of elasticity requirements were given by specifications only for flexure. For flexure, therefore, the average test value of the modulus is reduced to the specification wet value. Reduced values for tensile and compressive moduli have the same ratio to their average test values as does the specification wet value for flexural modulus to the corresponding test value. Thus, if the specification wet value for flexure was 2,500,000 p.s.i. and the average value from test was 3,000,000 p.s.i., average values of tensile and compressive moduli would be multiplied by 5/6 to give the reduced values tabulated herein.

In the case of the cotton fabric phenolic laminate, wet values are not given by the specification. For this material, properties were first reduced in the proportion of the dry specification value to the average dry test value and then were further reduced by multiplying by the ratio of wet test values to dry test values.

Because of the limited test data on shear properties and the lack of specification values for shear, the values shown in table 7 do not represent reduced test data but are computed from reduced tensile values. If the angle $\underline{\phi}$ is taken as 45 degrees, equations (19) and (20) reduce to

$$\frac{1}{G_{\alpha\beta}} = \frac{4}{E_{45}} - \frac{1}{E_{\beta}} - \frac{1}{E_{\alpha}}(1 - 2\mu_{\alpha\beta})$$

and

$$\frac{1}{F_{\alpha\beta}^{2}} = \frac{4}{F_{45}^{2}} - \frac{1}{F_{\alpha}^{2}} - \frac{1}{F_{\beta}^{2}} + \frac{1}{F_{\alpha}F_{\beta}}$$

From these equations and reduced tensile data (table 6) at 0° (the $\underline{\alpha}$ direction), 90° (the $\underline{\beta}$ direction), and 45°, values of $\underline{G_{\alpha\beta}}$ and $\underline{F_{\alpha\beta}}$ on a reduced basis were calculated.

Forest Products Laboratory Report No. 1821[4] shows that the properties, parallel and perpendicular to warp, of cross-laminated 143 laminates may be taken as the mean of the properties, parallel and perpendicular to warp, of parallel-laminated 143 laminate. Consequently, the values used in computing the directional curves for the cross-laminated 143 laminate were taken as the mean of reduced values at 0° and 90° (table 6).

Description of Directional Graphs

Tension and Compression

The full range of variation in tensile and compressive properties with direction occurs in a single quadrant. Directional tensile and compressive properties are given in figures 43 through 70, therefore, for only one quadrant. Properties in other quadrants than the one shown in the figures may readily be found from the fact that the directional properties curves for tension and compression are symmetrical about both the 0-180 degree and the 90-270 degree axes.

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[4]Freas, Alan D., and Werren, Fred. Mechanical Properties of Cross-Laminated and Composite Glass-Fabric-Base Plastic Laminates. Forest Products Laboratory Report No. 1821. February 1951.

Shear

The full range of variation in shear with direction occurs also in a single quadrant, so that the directional properties in shear of figures 71 to 84 are shown in a single quadrant, from 315 to 45 degrees from the $\underline{\alpha}$ axis. As indicated earlier, the shear properties in any given direction are dependent upon whether the components of force in the $\underline{\alpha}$ direction are tensile or compressive. The directions assumed for shear forces in drawing the directional properties curves are shown in figure 42. Properties in quadrants other than the one shown may be found from the fact that the directional properties curves for shear are symmetrical about the 45-225 degree line and about the 135-315 degree line.

Table 6.--Reduced tensile and compressive properties for parallel laminates of glass fabric, glass mat, and cotton fabric

Laminate	Angle of loading[1]	Tensile properties		Compressive properties	
		Secondary modulus of elasticity	Ultimate strength	Modulus of elasticity	Ultimate strength
	Degrees	1,000 p.s.i.	P.s.i.	1,000 p.s.i.	P.s.i.
GLASS-FIBER REINFORCEMENT, POLYESTER RESIN (MIL-R-7575)[2]					
112 fabric	0	2,310	38,000	2,720	30,000
	90	2,160	34,400	2,540	26,800
	45	1,490	18,300	....	....
116 fabric	0	2,630	38,000	2,800	27,000
	90	2,310	37,700	2,730	24,700
	45	1,600	18,400	....	....
128 fabric	0	2,470	38,000	2,900	21,000
	90	1,700	29,200	2,220	20,900
	45	1,410	17,200	....	....
162 fabric	0	2,240	38,000	2,220	14,000
	90	1,370	25,000	1,730	15,900
	45	1,200	14,400	....	....
164 fabric	0	2,000	30,000	2,470	20,000
	90	1,690	27,000	2,250	18,000
	45	1,570	16,000	....	....
120 fabric	0	2,560	38,000	2,780	30,000
	90	2,410	35,700	2,710	26,100
	45	1,760	17,900	....	....
181 fabric	0	2,340	38,000	2,940	30,000
	90	2,150	35,100	2,820	31,600
	45	1,570	17,800	....	....
182 fabric	0	2,510	40,000	2,810	29,000
	90	2,330	39,100	2,690	23,500
	45	1,640	17,000	....	....
183 fabric	0	2,040	40,000	2,730	27,000
	90	1,820	37,200	2,590	25,600
	45	1,540	16,300	....	....

Table 6.--Reduced tensile and compressive properties for parallel laminates of glass fabric, glass mat, and cotton fabric (continued)

Laminate	Angle of loading[1]	Tensile properties: Secondary modulus of elasticity	Tensile properties: Ultimate strength	Compressive properties: Modulus of elasticity	Compressive properties: Ultimate strength
	Degrees	1,000 p.s.i.	P.s.i.	1,000 p.s.i.	P.s.i.
GLASS-FIBER REINFORCEMENT, POLYESTER RESIN (MIL-R-7575)[2] (continued)					
184 fabric	0	2,710	40,000	2,900	23,000
	90	2,140	33,500	2,580	20,800
	45	1,680	14,100	....	....
143 fabric	0	5,390	75,000	4,910	43,000
	90	420	8,950	1,510	18,100
	45	1,570	11,700	....	....
Mat	0, 90, 45	1,110	18,000	i[3] 1,550	18,000
		....	....	s 1,300	....
GLASS-FIBER REINFORCEMENT, EPOXIDE RESIN (MIL-R-9300)					
181 fabric	0	2,880	45,000	3,280	45,000
	90	2,660	42,400	3,140	38,200
	45	2,200	26,600	....	....
COTTON-FABRIC REINFORCEMENT, PHENOLIC RESIN (AMS 3605, MIL-P-8655)[4]					
Cotton fabric	0	670	6,800	680	10,600
	90	670	6,800	680	10,600
	45	590	5,600	....	....

[1]Angle between load and warp direction of fabric.

[2]Glass-fabric and glass-mat laminates conforming to requirements of Military Specification MIL-P-8013, Plastic Materials, Glass Fabric Base, Low Pressure Laminated, Aircraft Structural.

[3]i = initial; s = secondary.

[4]Cotton fabric conforming to requirements of Aeronautical Material Specification AMS 3605A, Plastic Sheet, Post-forming (Society of Automotive Engineers, Inc.) and to MIL-P-8655, Plastic Material, Laminated, Thermo-setting Sheets, Cotton Fabric Base, Post-forming.

Table 7.--Reduced edgewise shear properties of parallel laminates of glass fabric, glass mat, and cotton fabric. Shear loads applied parallel and perpendicular to warp direction of laminate.

Laminate	Modulus of rigidity	Ultimate stress
	1,000 p.s.i.	P.s.i.
GLASS-FIBER REINFORCEMENT, POLYESTER RESIN (MIL-R-7575)[1]		
112 fabric	510	9,460
116 fabric	540	9,480
128 fabric	500	8,920
162 fabric	430	7,440
164 fabric	600	8,350
120 fabric	620	9,230
181 fabric	550	9,180
182 fabric	565	8,700
183 fabric	570	8,340
184 fabric	590	7,190
143 fabric	550	7,440
Mat	580	9,200
GLASS-FIBER REINFORCEMENT, EPOXIDE RESIN (MIL-R-9300)		
181 fabric	810	14,000
COTTON-FABRIC REINFORCEMENT, PHENOLIC RESIN (AMS-3605, MIL-P-8655)[2]		
Cotton fabric	225	3,070

[1] Glass-fabric and glass-mat laminates conforming to requirements of Military Specification MIL-P-8013, Plastic Materials, Glass Fabric Base, Low Pressure Laminated, Aircraft Structural.

[2] Cotton fabric conforming to requirements of Aeronautical Material Specification AMS 3605A, Plastic Sheet, Post-forming (Society of Automotive Engineers, Inc.) and to MIL-P-8655, Plastic Material, Laminated, Thermo-setting Sheets, Cotton Fabric Base, Post-forming.

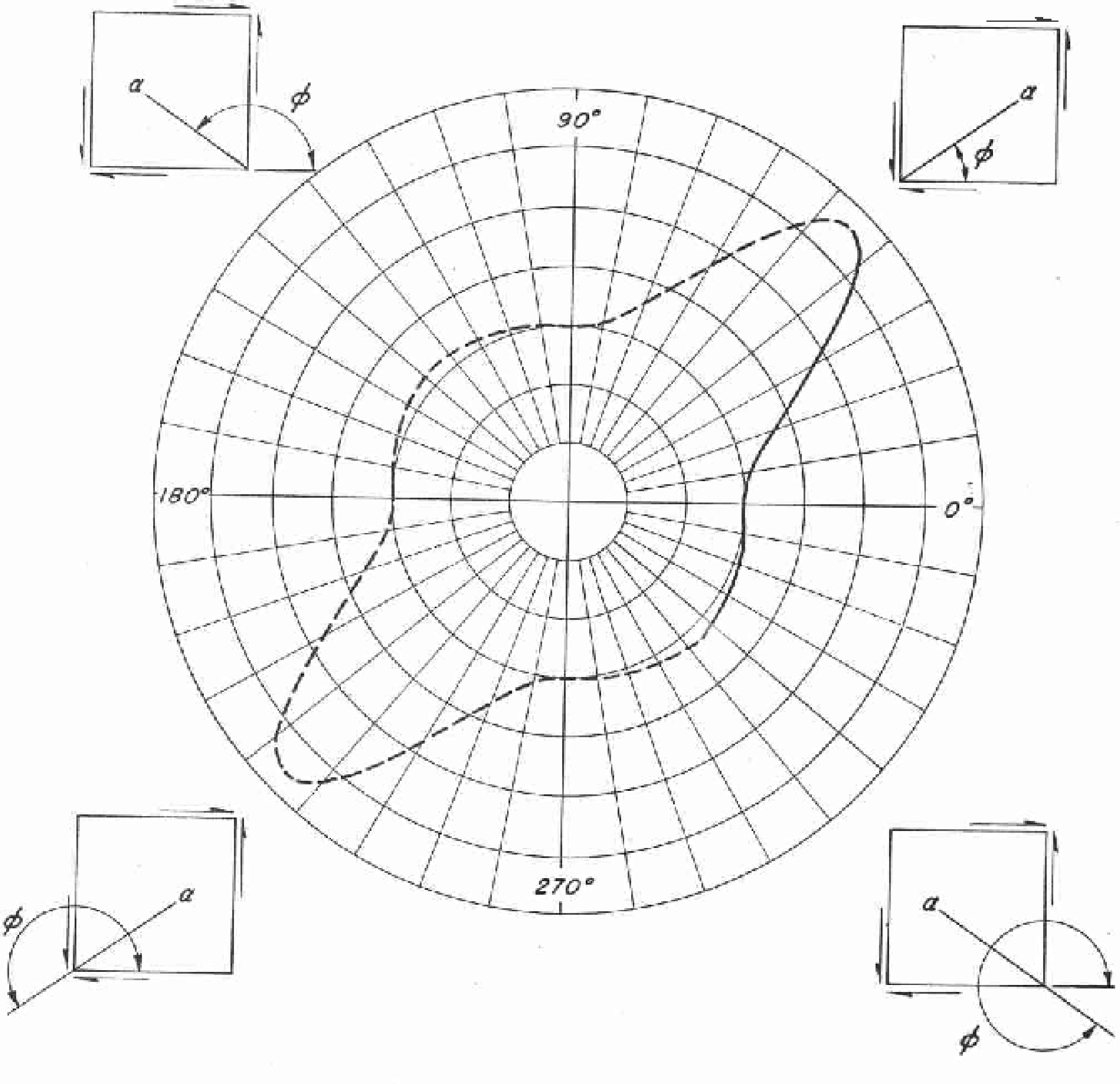

Figure 42. --Typical curve relating the shear strength of a glass-fabric-reinforced laminate to the direction of application of the shear forces. The solid portion of the curve represents that part of the complete curve which is shown in later figures.

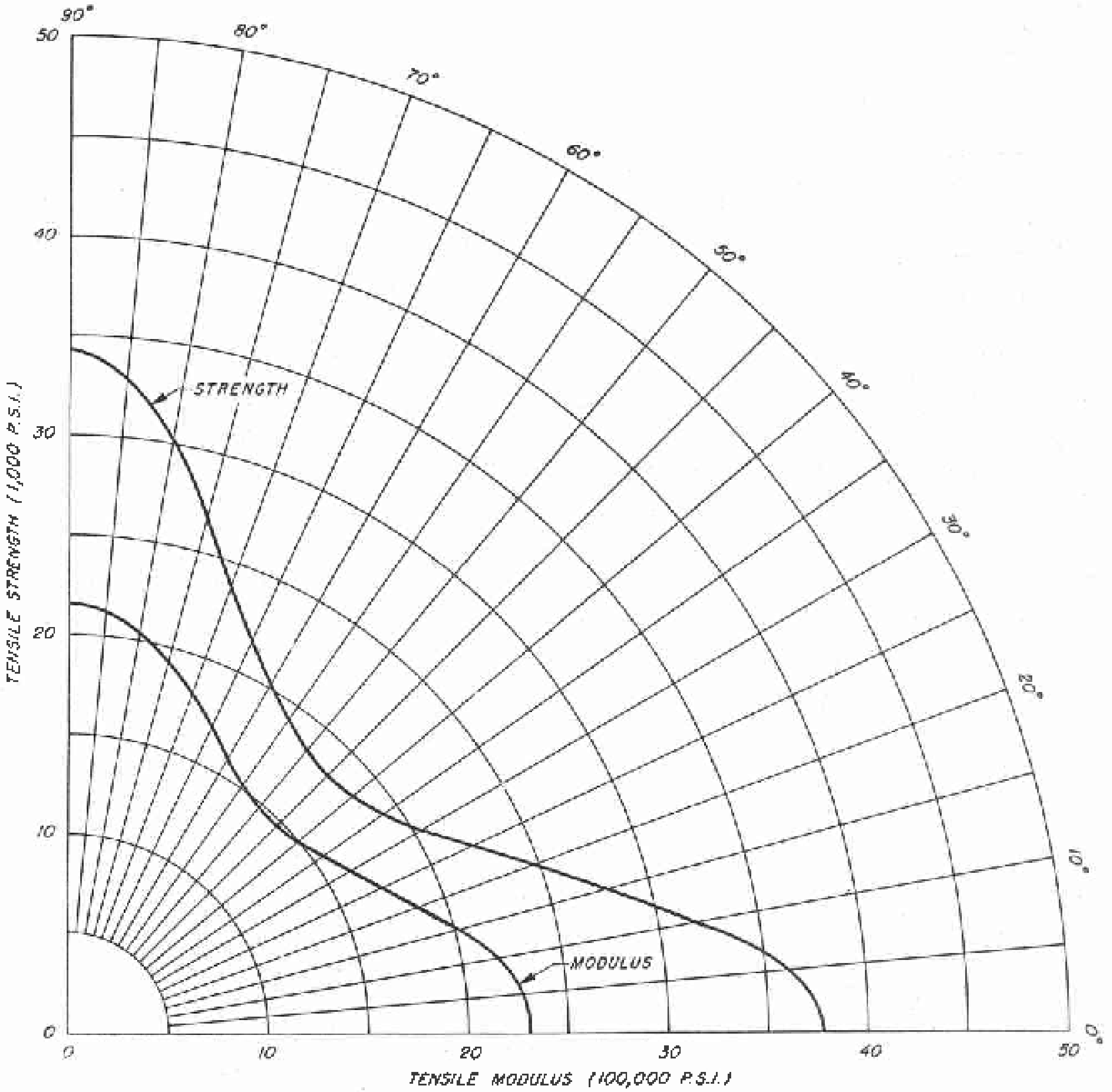

Figure 43. --Directional properties in tension of parallel-laminated 112 glass-fabric laminate made with polyester resin (MIL-R-7575).

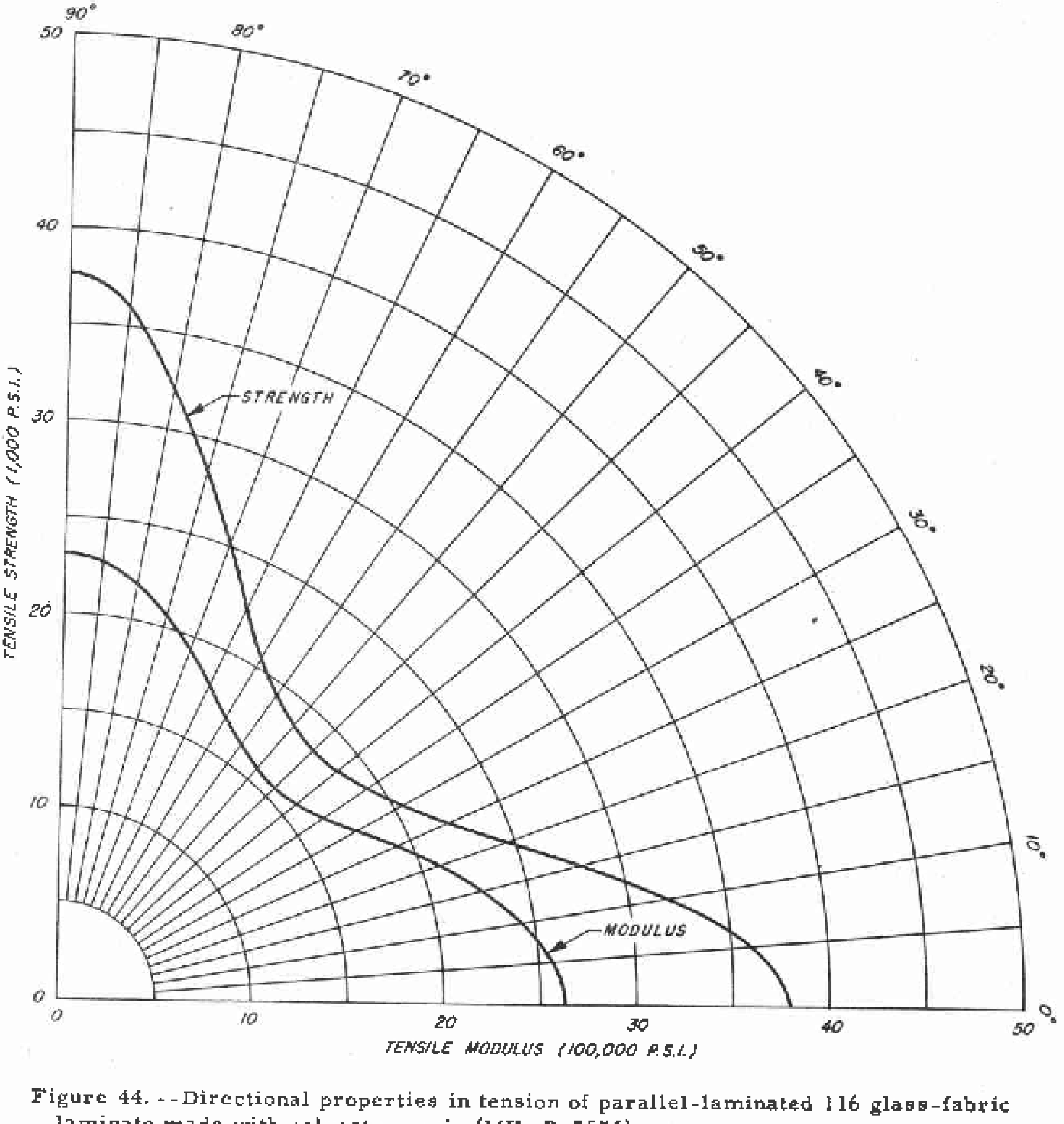

Figure 44.--Directional properties in tension of parallel-laminated 116 glass-fabric laminate made with polyester resin (MIL-R-7575).

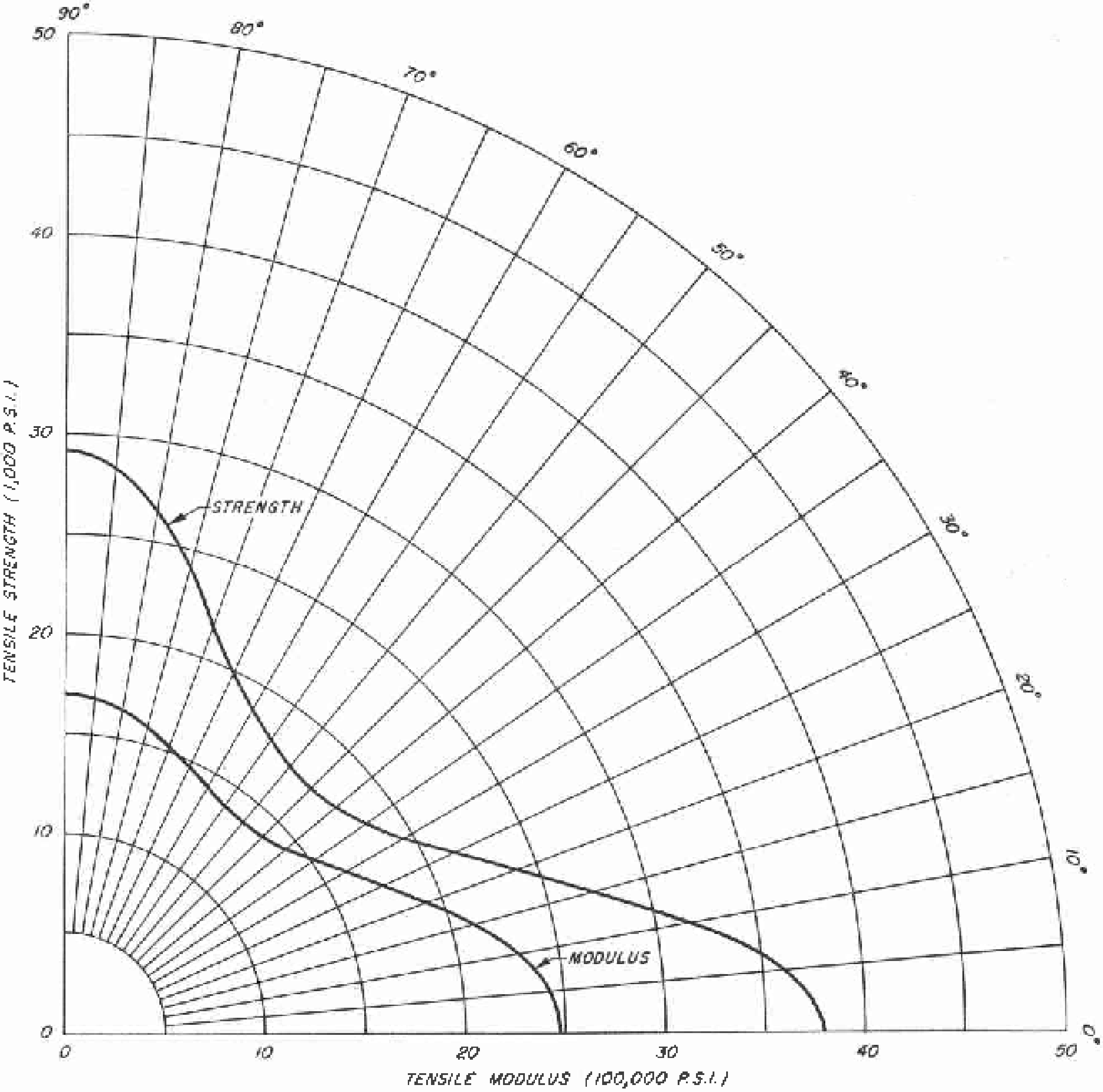

Figure 45. --Directional properties in tension of parallel-laminated 128 glass-fabric laminate made with polyester resin (MIL-R-7575).

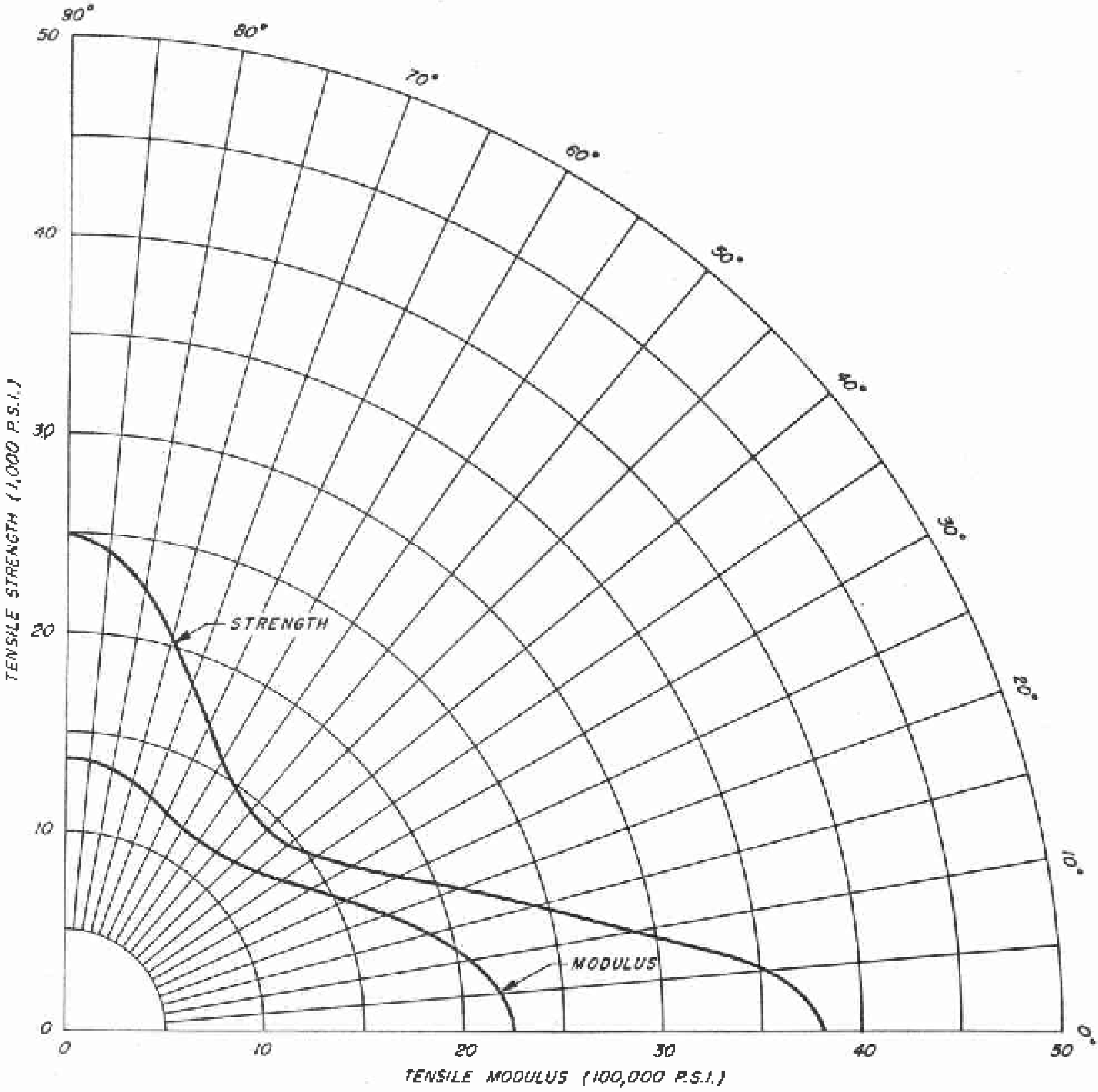

Figure 46. --Directional properties in tension of parallel-laminated 162 glass-fabric laminate made with polyester resin (MIL-R-7575).

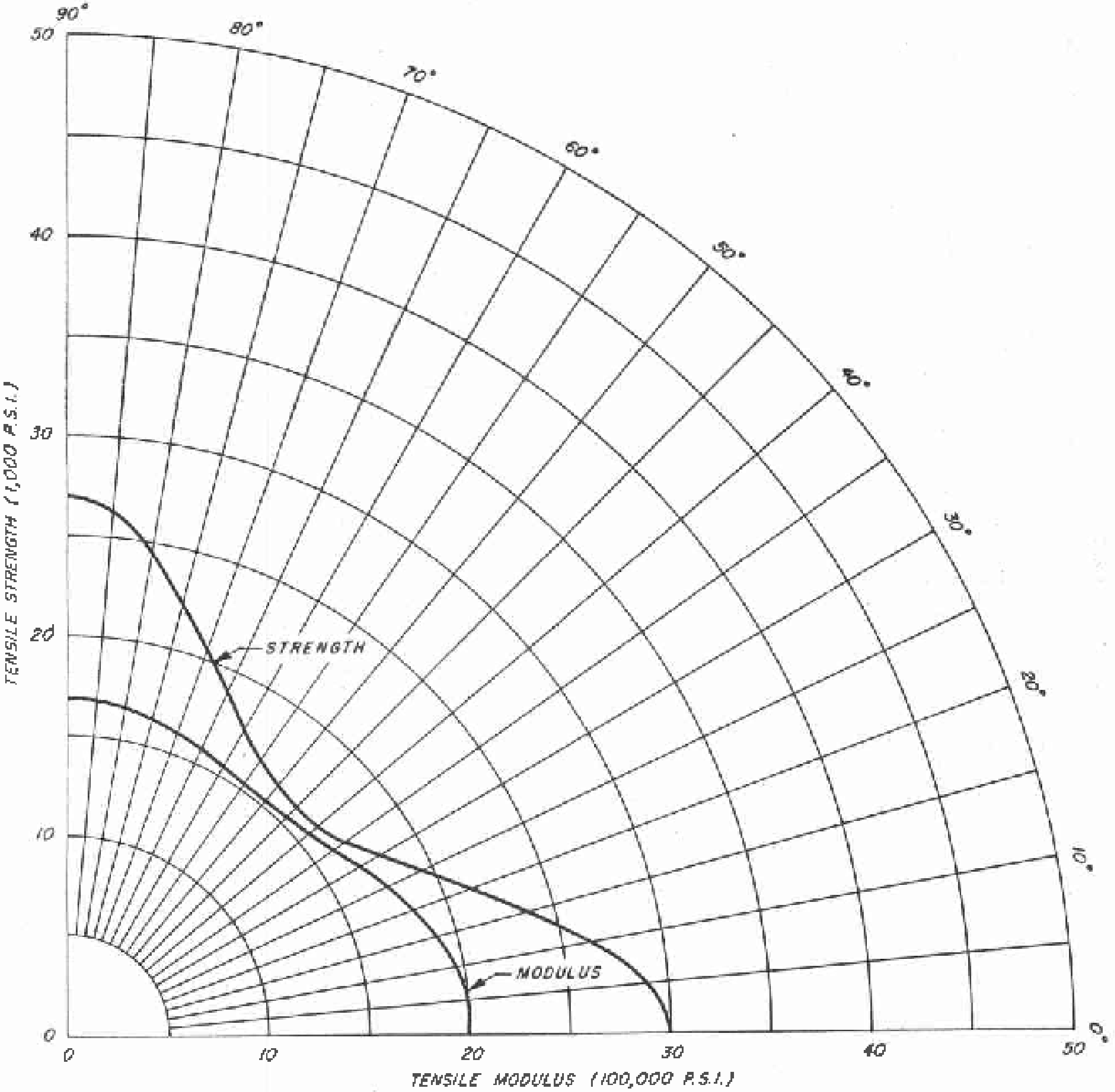

Figure 47. --Directional properties in tension of parallel-laminated 164 glass-fabric laminate made with polyester resin (MIL-R-7575).

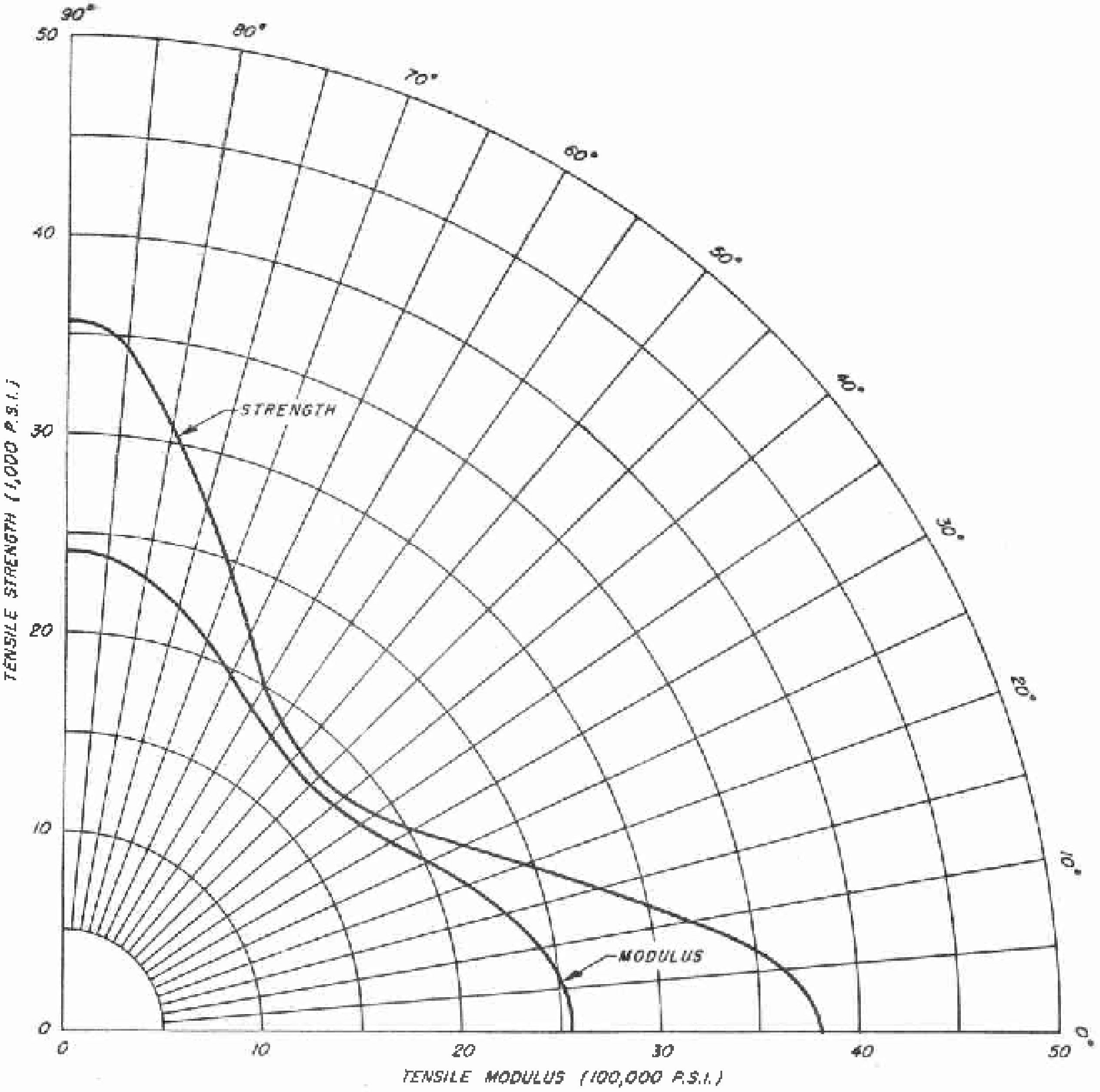

Figure 48. --Directional properties in tension of parallel-laminated 120 glass-fabric laminate made with polyester resin (MIL-R-7575).

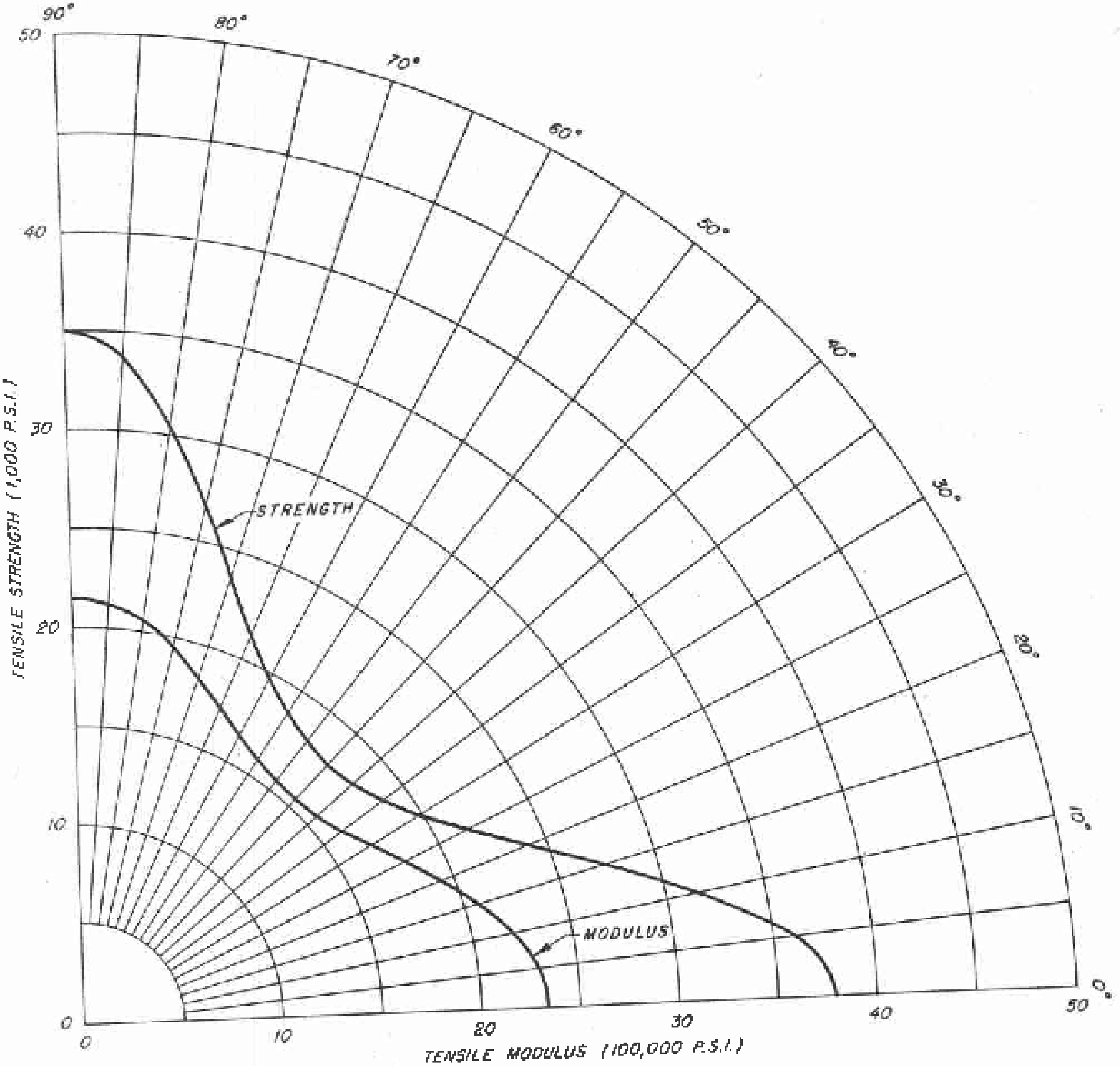

Figure 49. --Directional properties in tension of parallel-laminated 181 glass-fabric laminate made with polyester resin (MIL-R-7575).

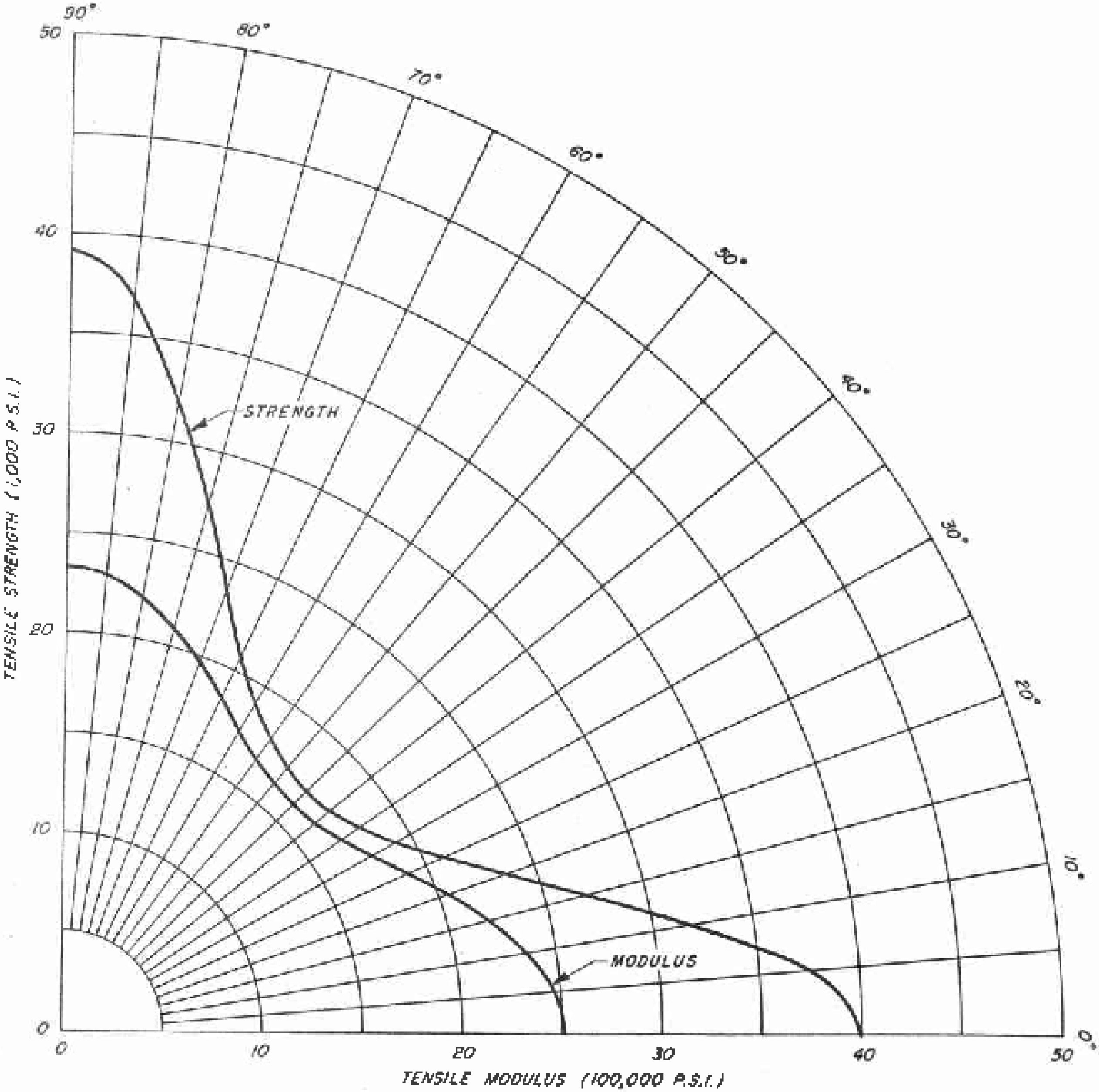

Figure 50. --Directional properties in tension of parallel-laminated 182 glass-fabric laminate made with polyester resin (MIL-R-7575).

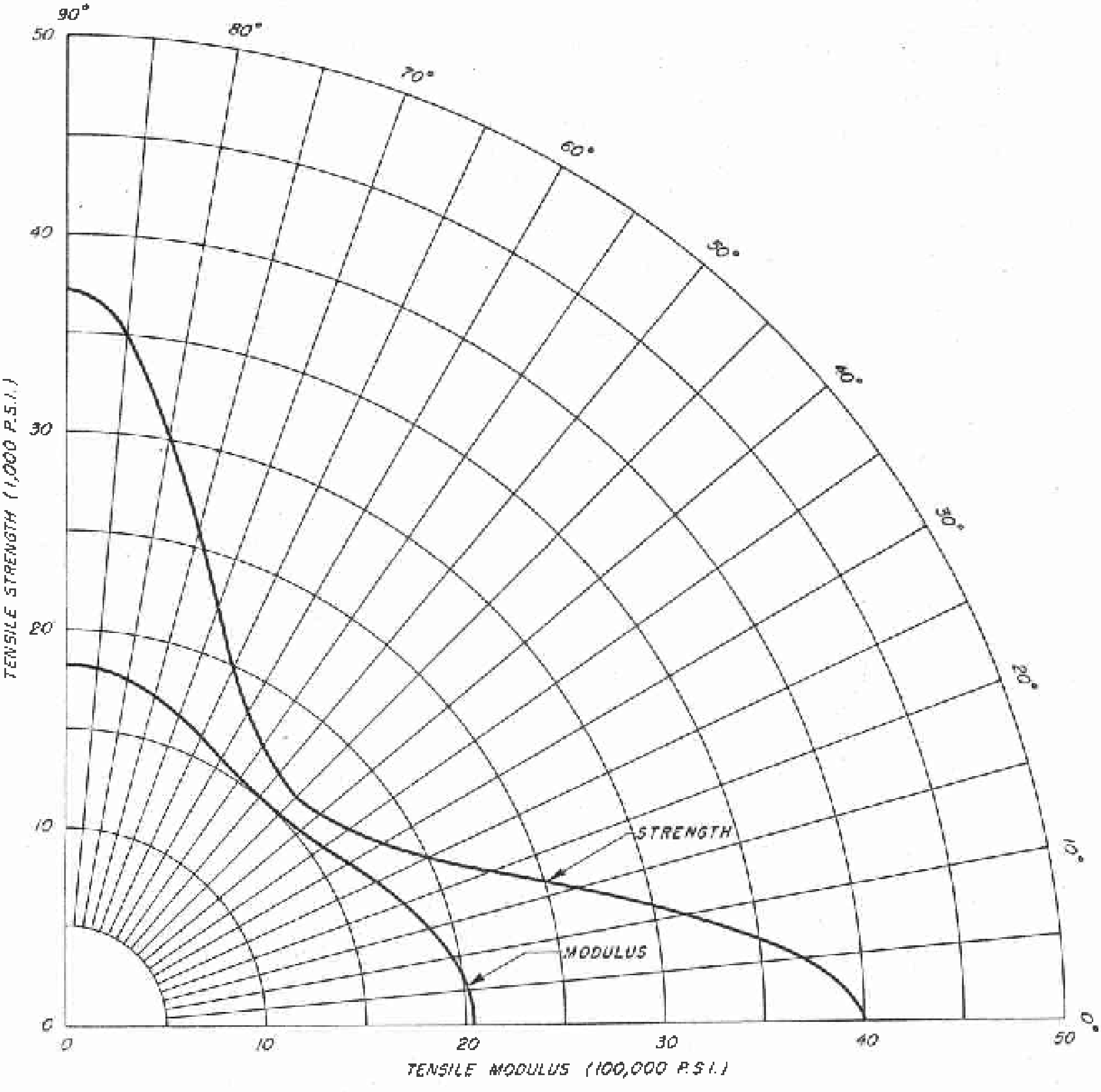

Figure 51. --Directional properties in tension of parallel-laminated 183 glass-fabric laminate made with polyester resin (MIL-R-7575).

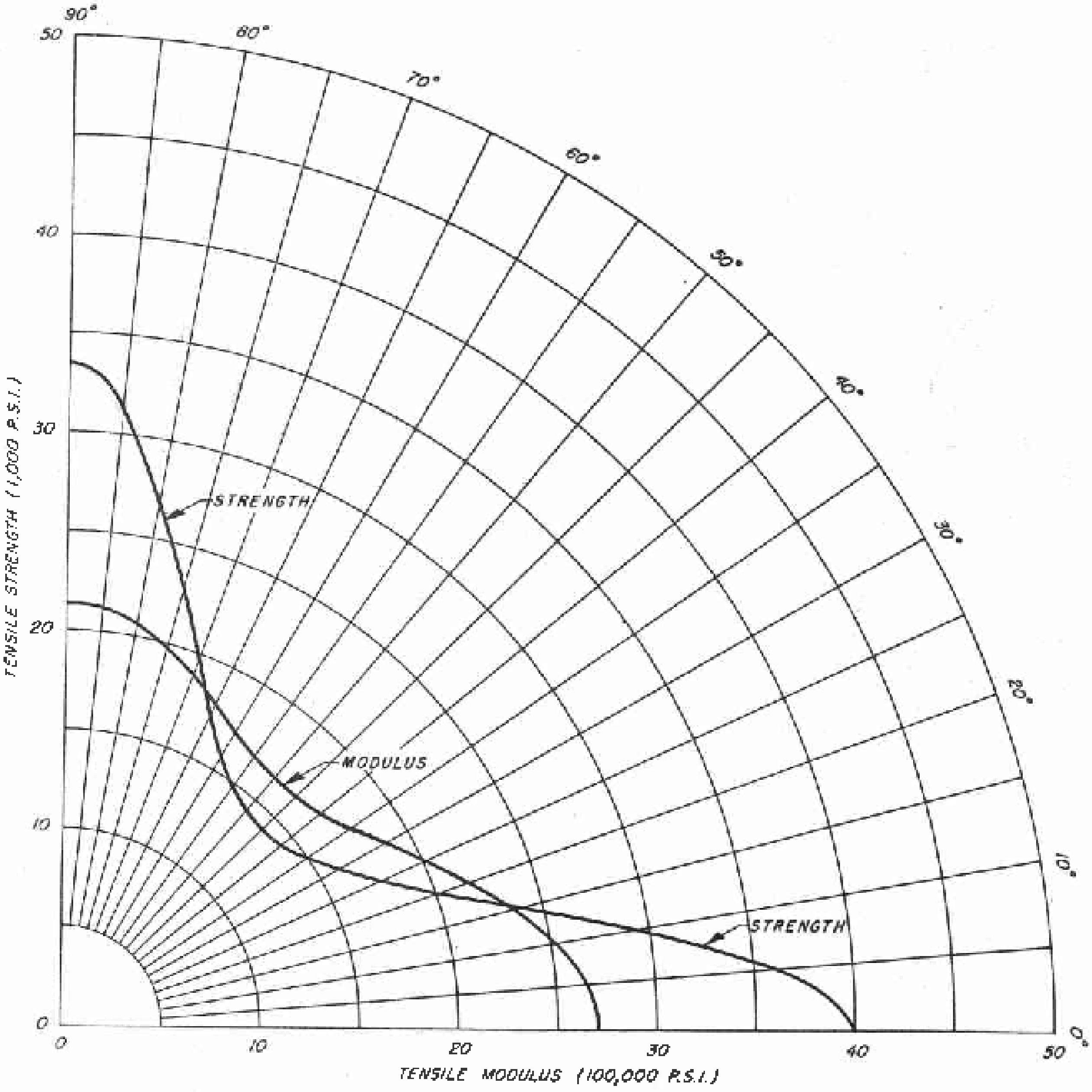

Figure 32. --Directional properties in tension of parallel-laminated 184 glass-fabric laminate made with polyester resin (MIL-R-7575).

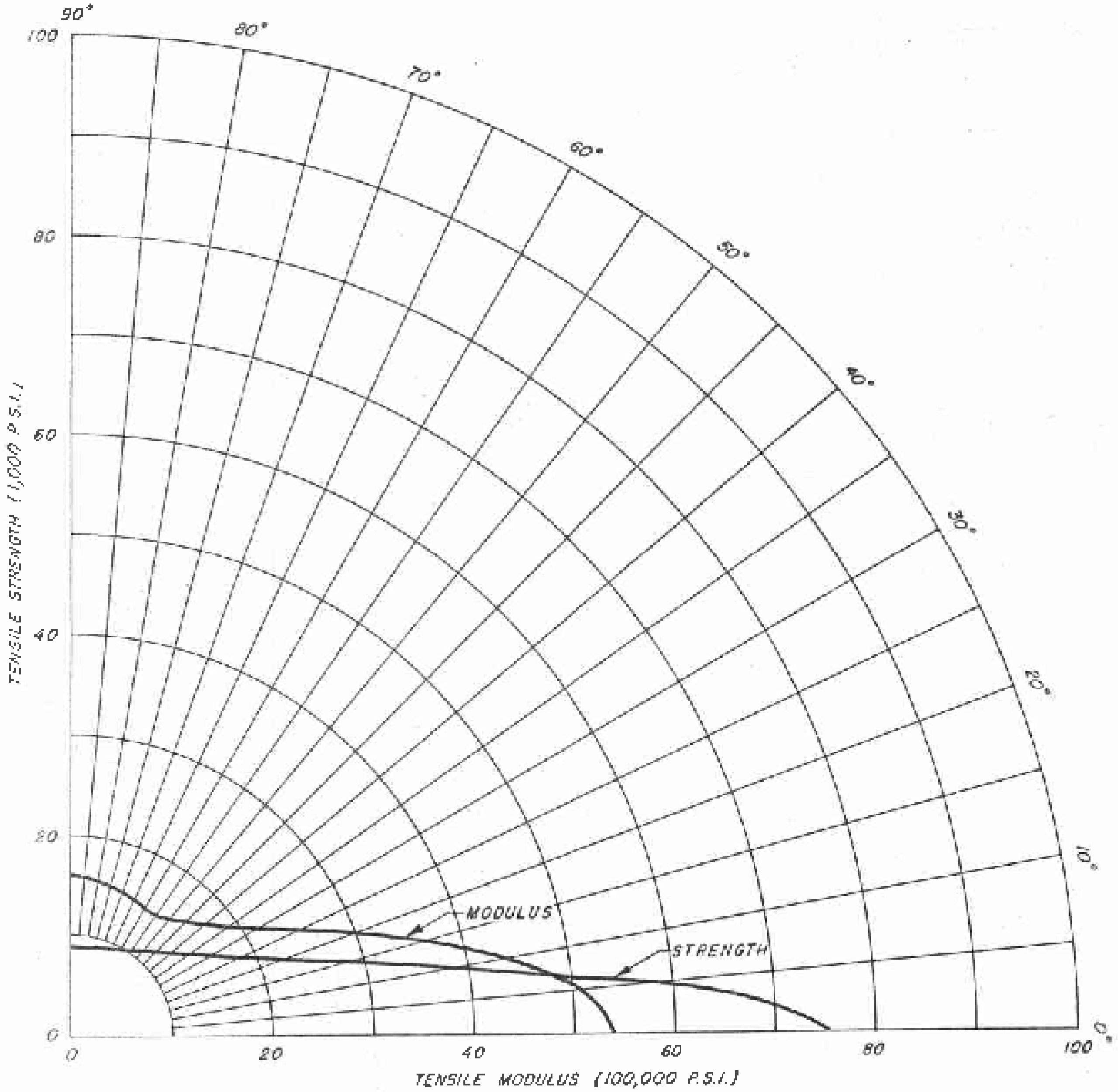

Figure 53. --Directional properties in tension of parallel-laminated 143 glass-fabric laminate made with polyester resin (MIL-R-7575).

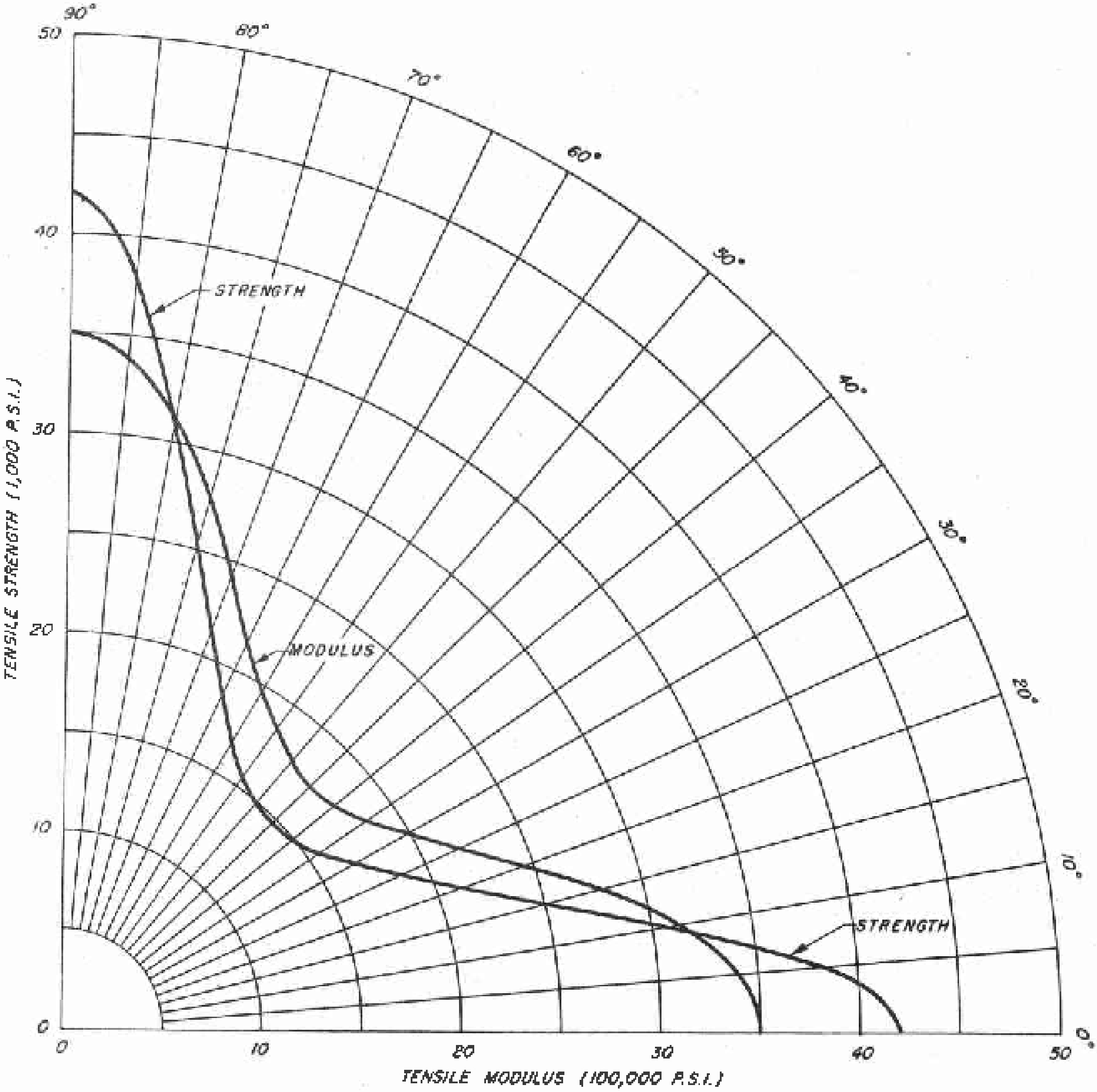

Figure 54. --Directional properties in tension of cross-laminated 143 glass-fabric laminate made with polyester resin (MIL-R-7575).

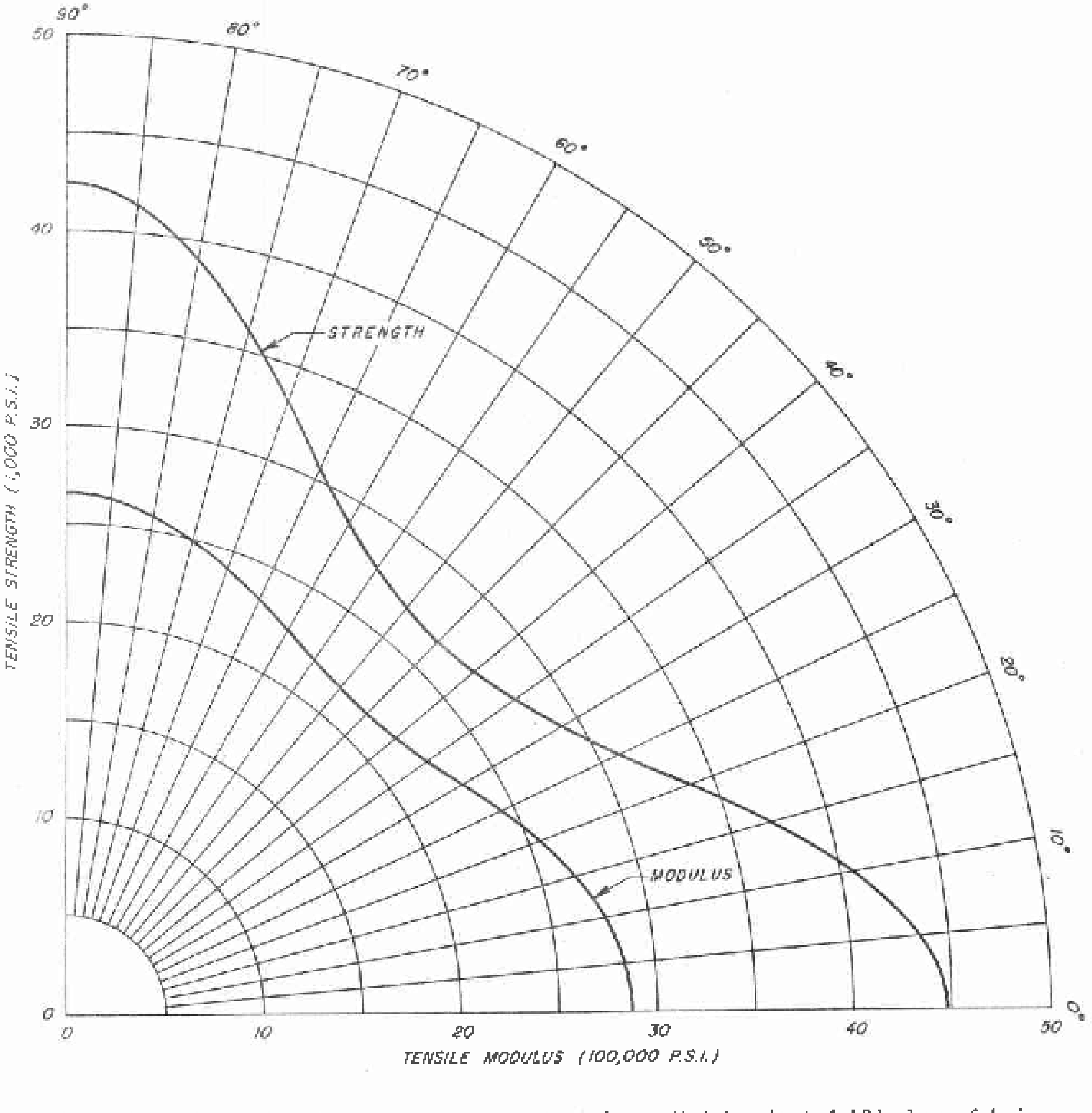

Figure 55. --Directional properties in tension of parallel-laminated 181 glass-fabric laminate made with epoxide resin (MIL-R-9300).

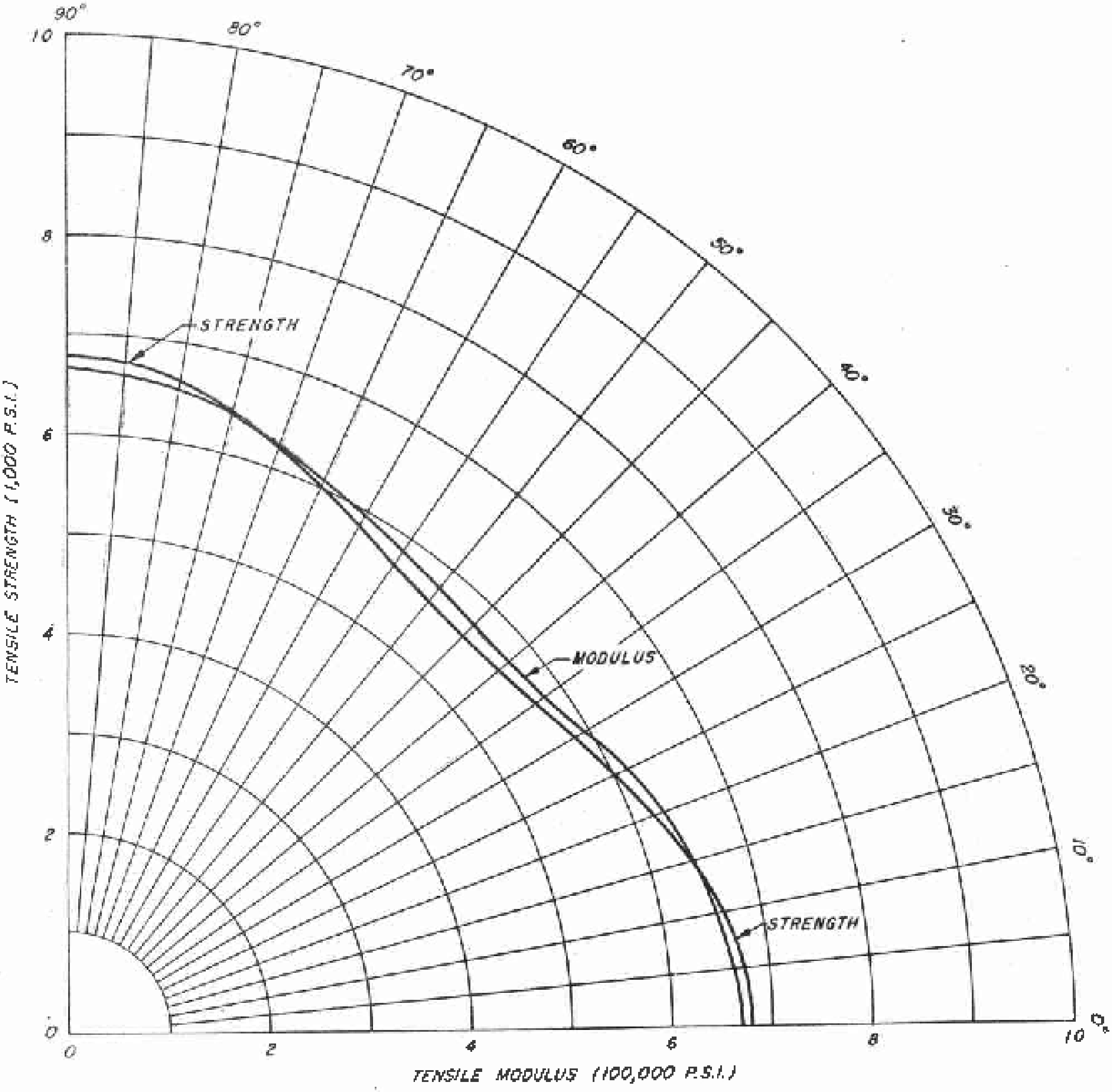

Figure 56. --Directional properties in tension of parallel-laminated cotton-fabric laminate made with phenolic resin (AMS-3605, MIL-P-8655).

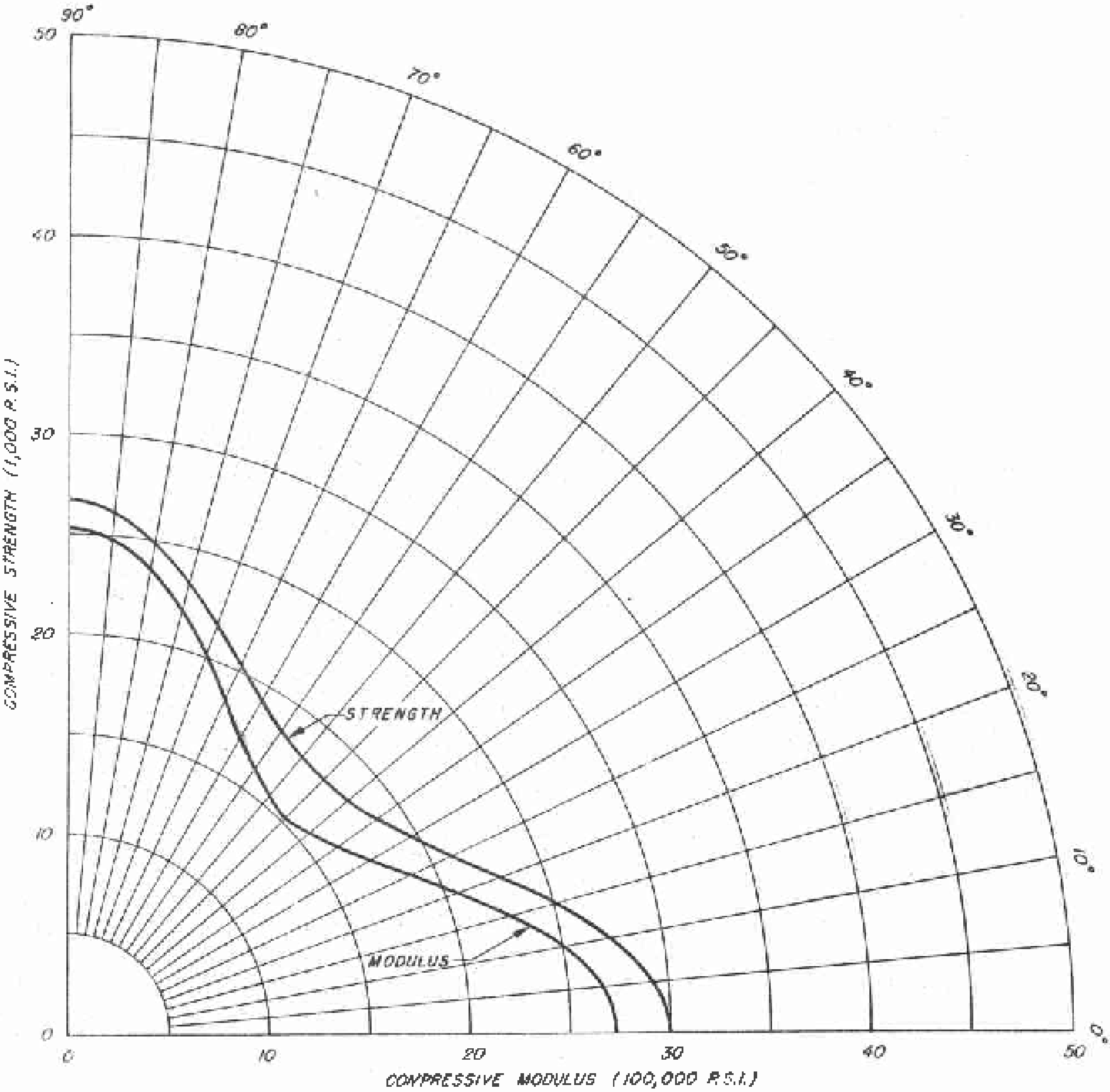

Figure 57. --Directional properties in compression of parallel-laminated 112 glass-fabric laminate made with polyester resin (MIL-R-7575).

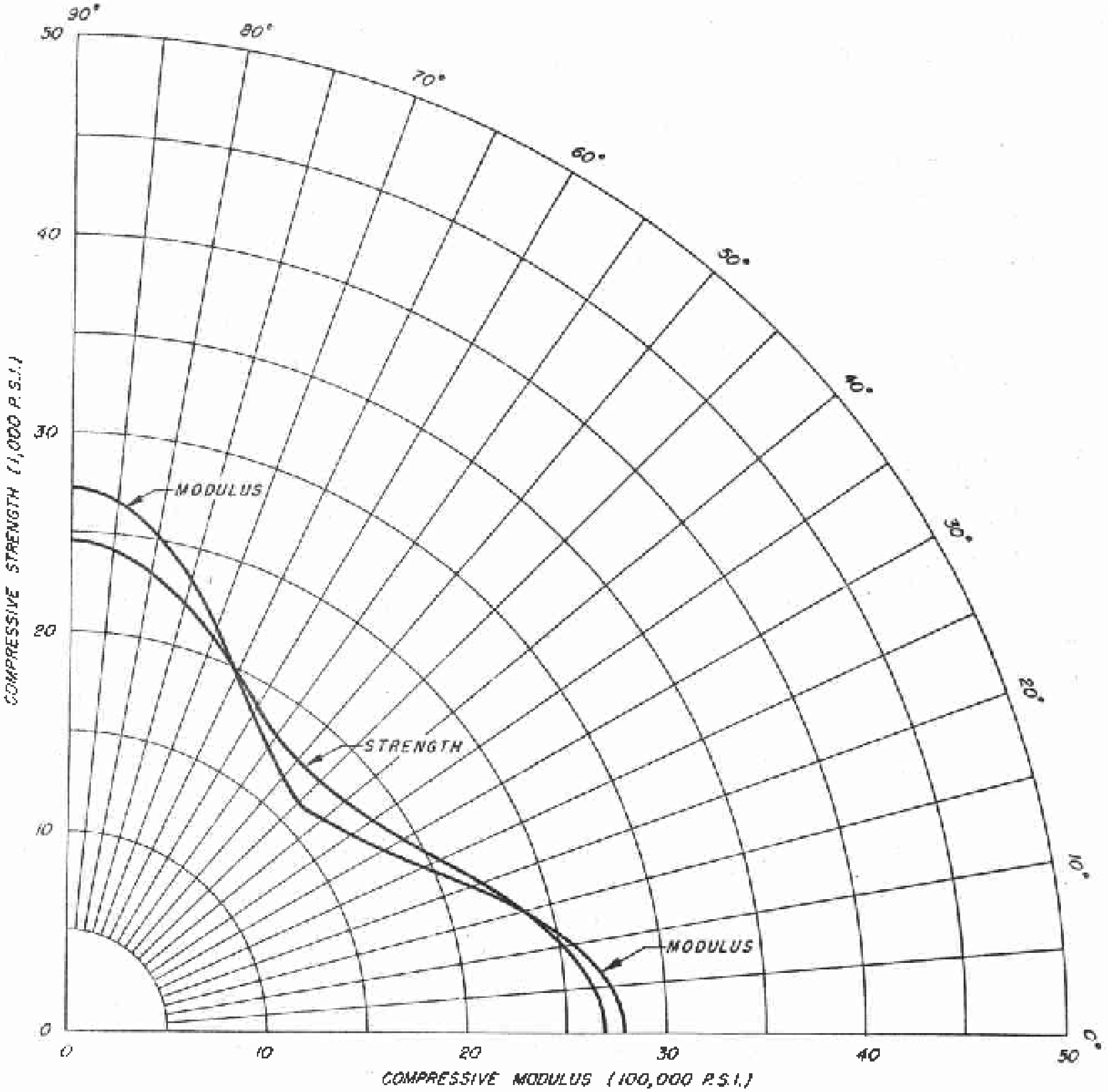

Figure 58. --Directional properties in compression of parallel-laminated 116 glass-fabric laminate made with polyester resin (MIL-R-7575).

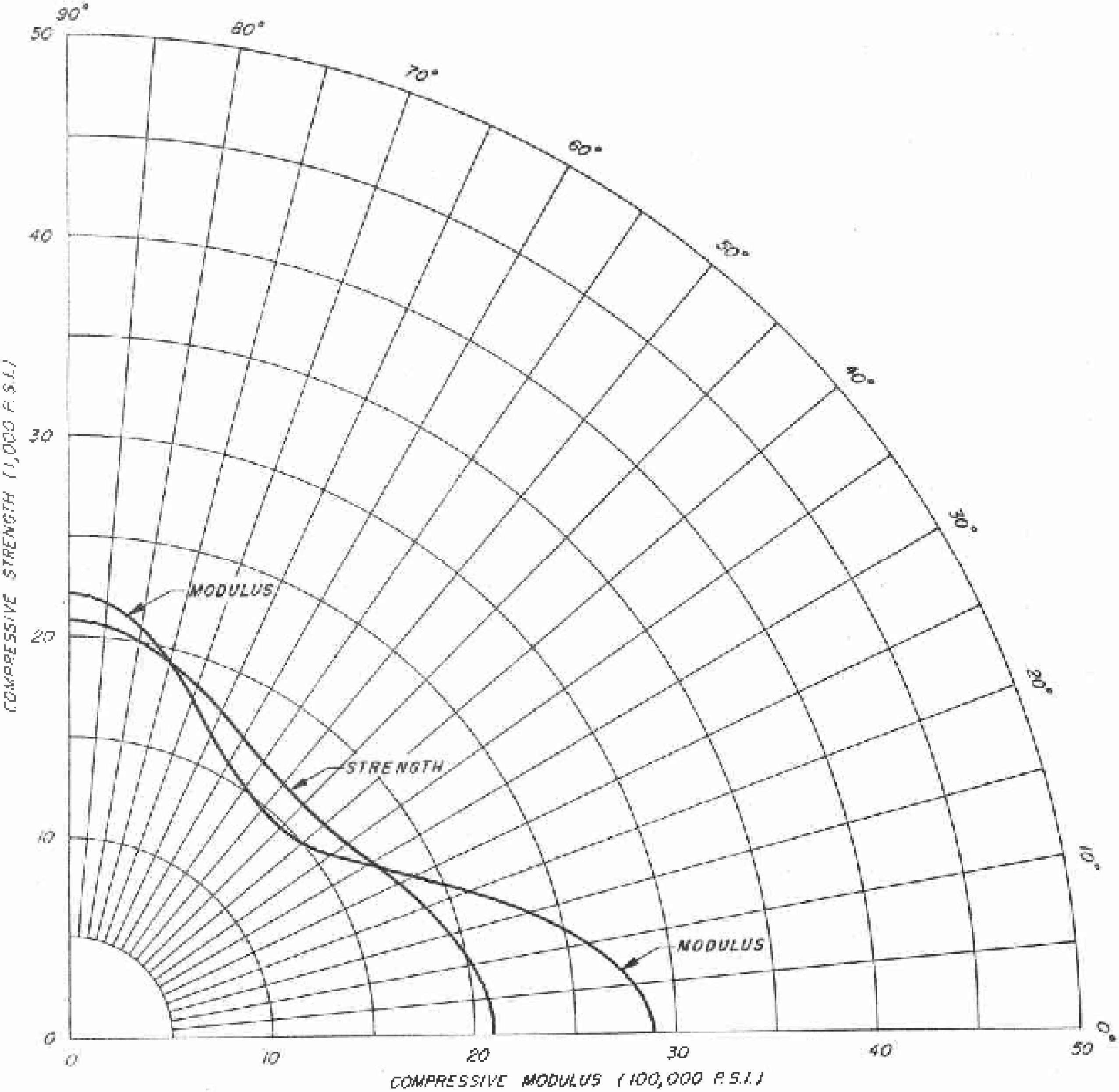

Figure 59. --Directional properties in compression of parallel-laminated 128 glass-fabric laminate made with polyester resin (MIL-R-7575).

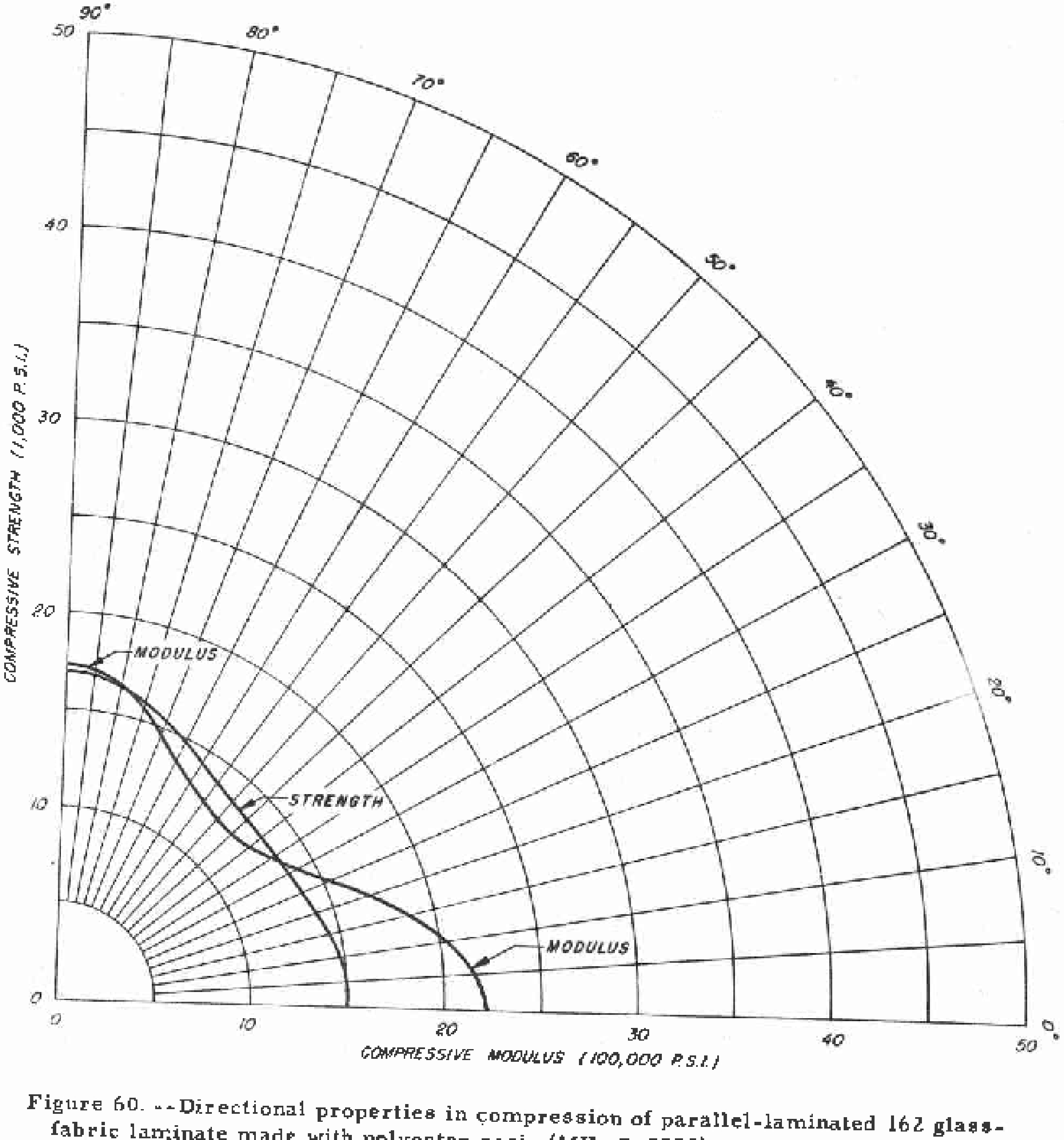

Figure 60. --Directional properties in compression of parallel-laminated 162 glass-fabric laminate made with polyester resin (MIL-R-7575).

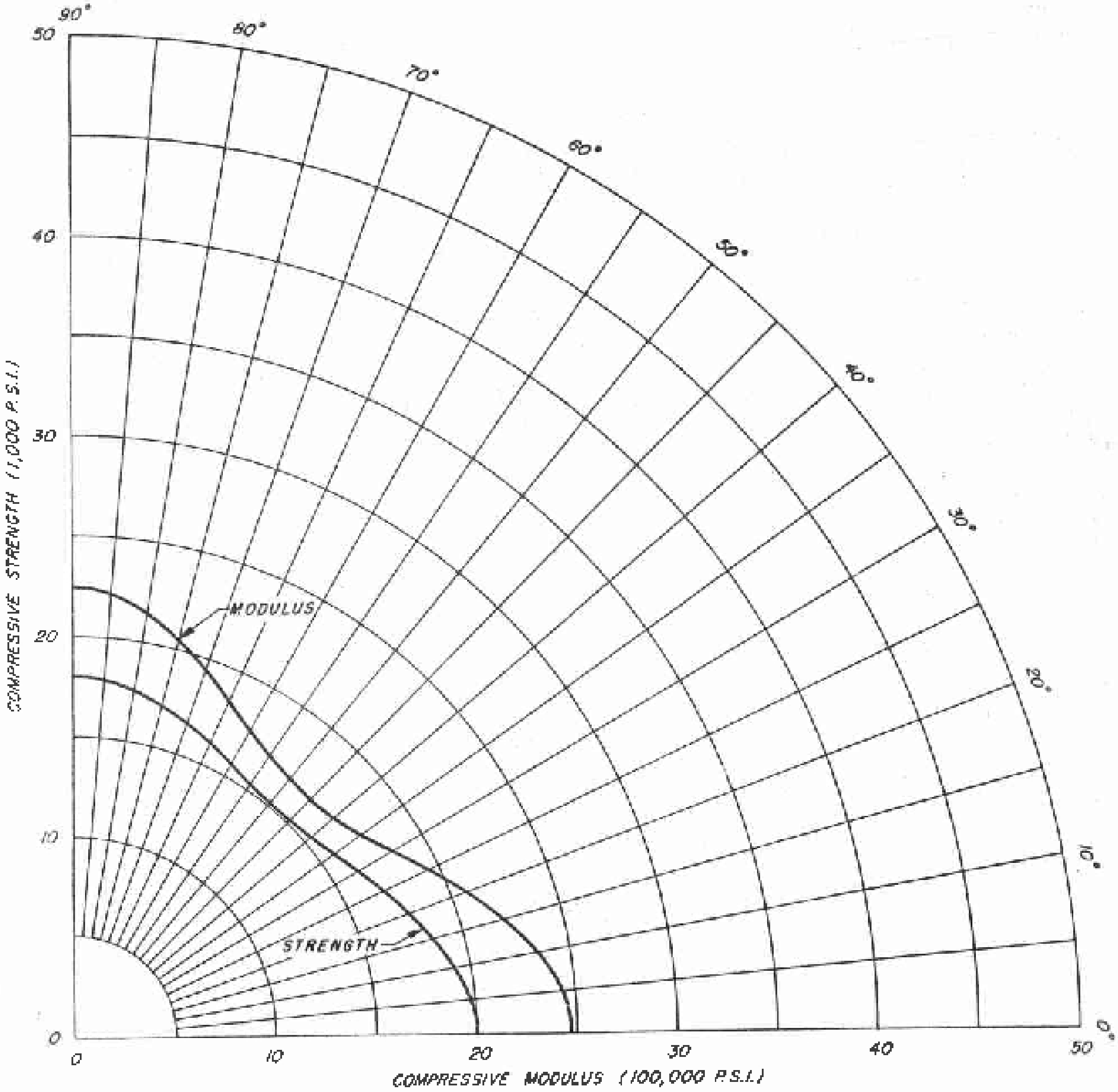

Figure 61. --Directional properties in compression of parallel-laminated 164 glass-fabric laminate made with polyester resin (MIL-R-7575).

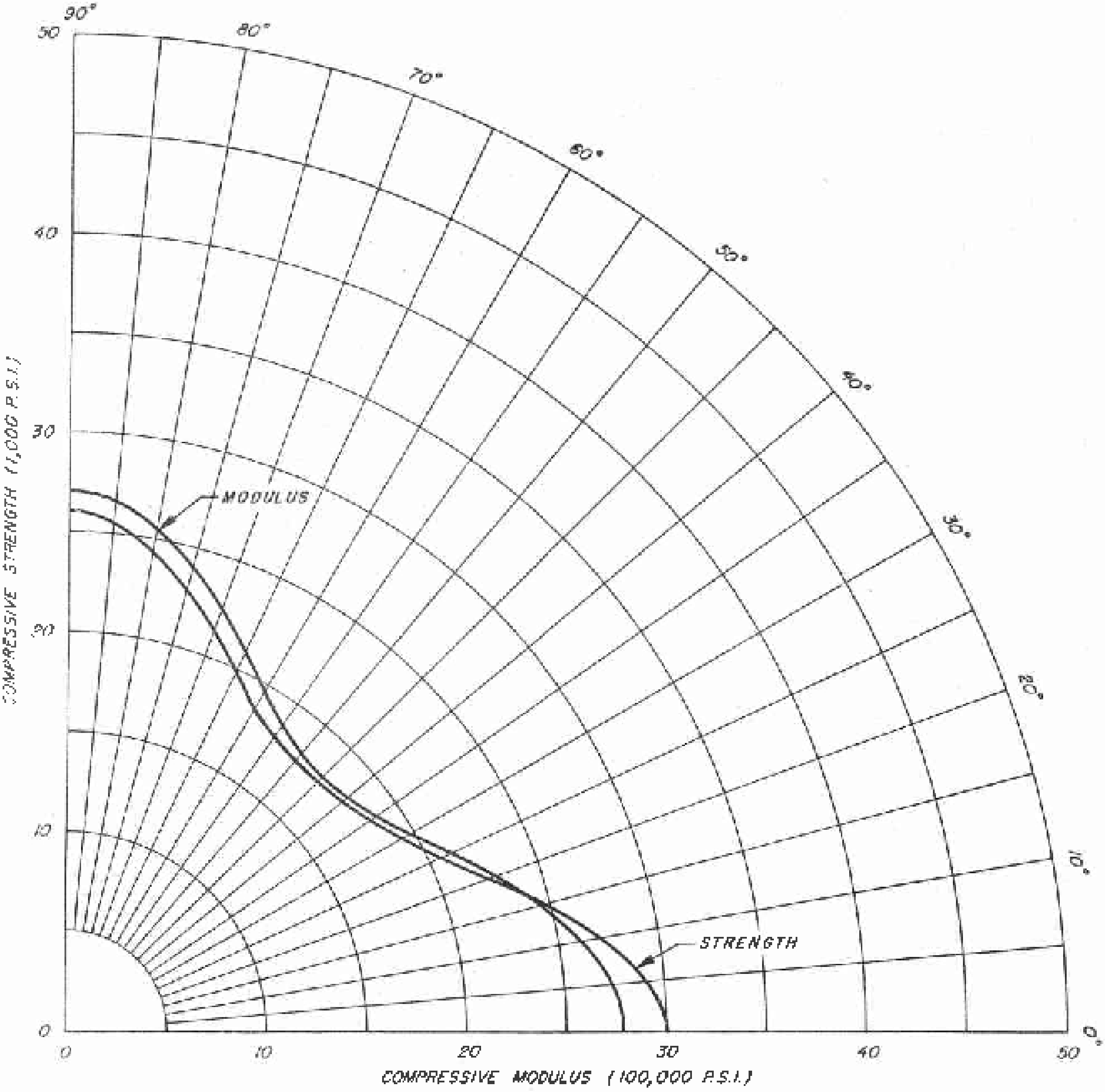

Figure 62. --Directional properties in compression of parallel-laminated 120 glass-fabric laminate made with polyester resin (MIL-R-7575).

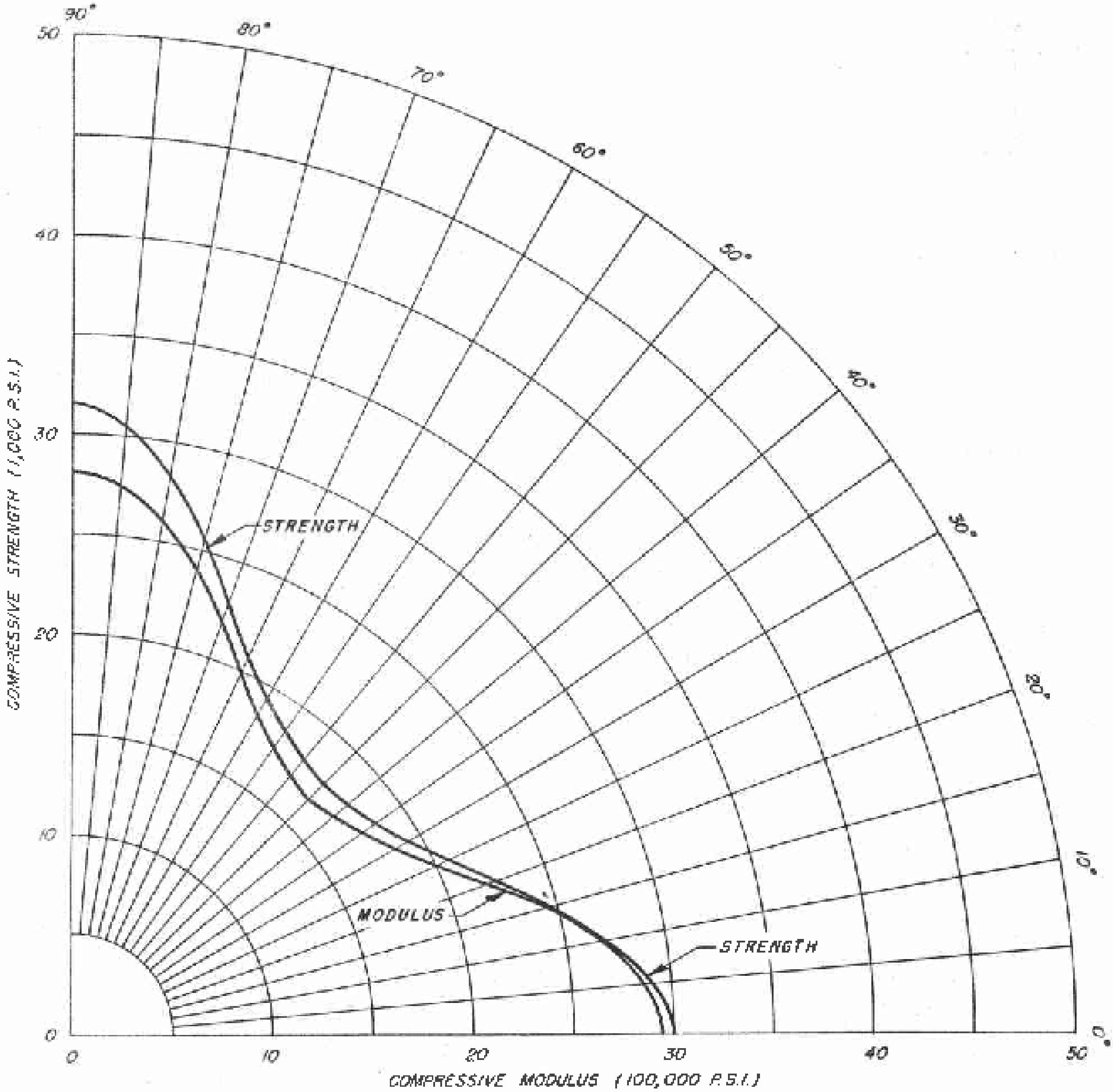

Figure 63. --Directional properties in compression of parallel-laminated 181 glass-fabric laminate made with polyester resin (MIL-R-7575).

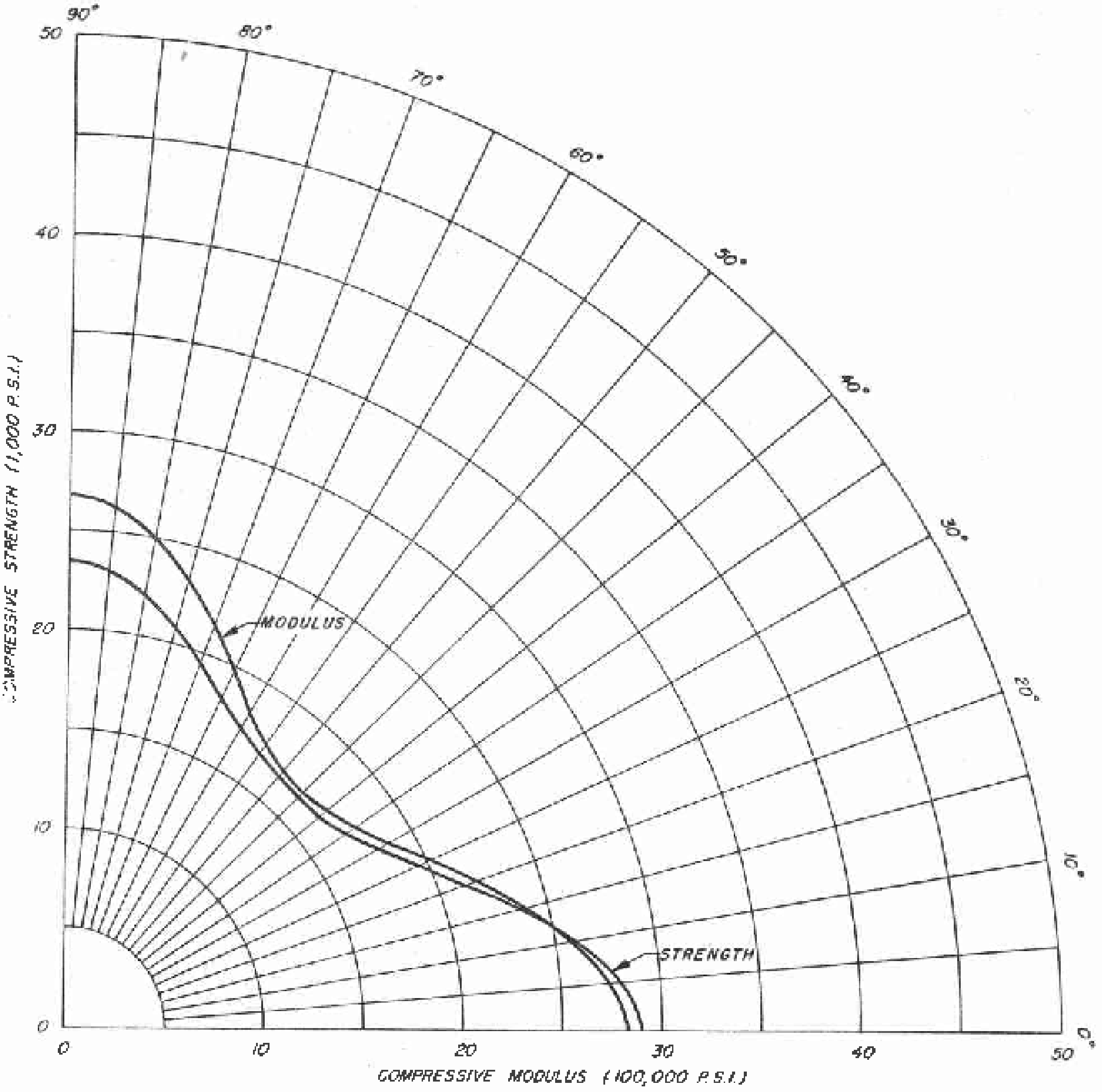

Figure 64. --Directional properties in compression of parallel-laminated 182 glass-fabric laminate made with polyester resin (MIL-R-7575).

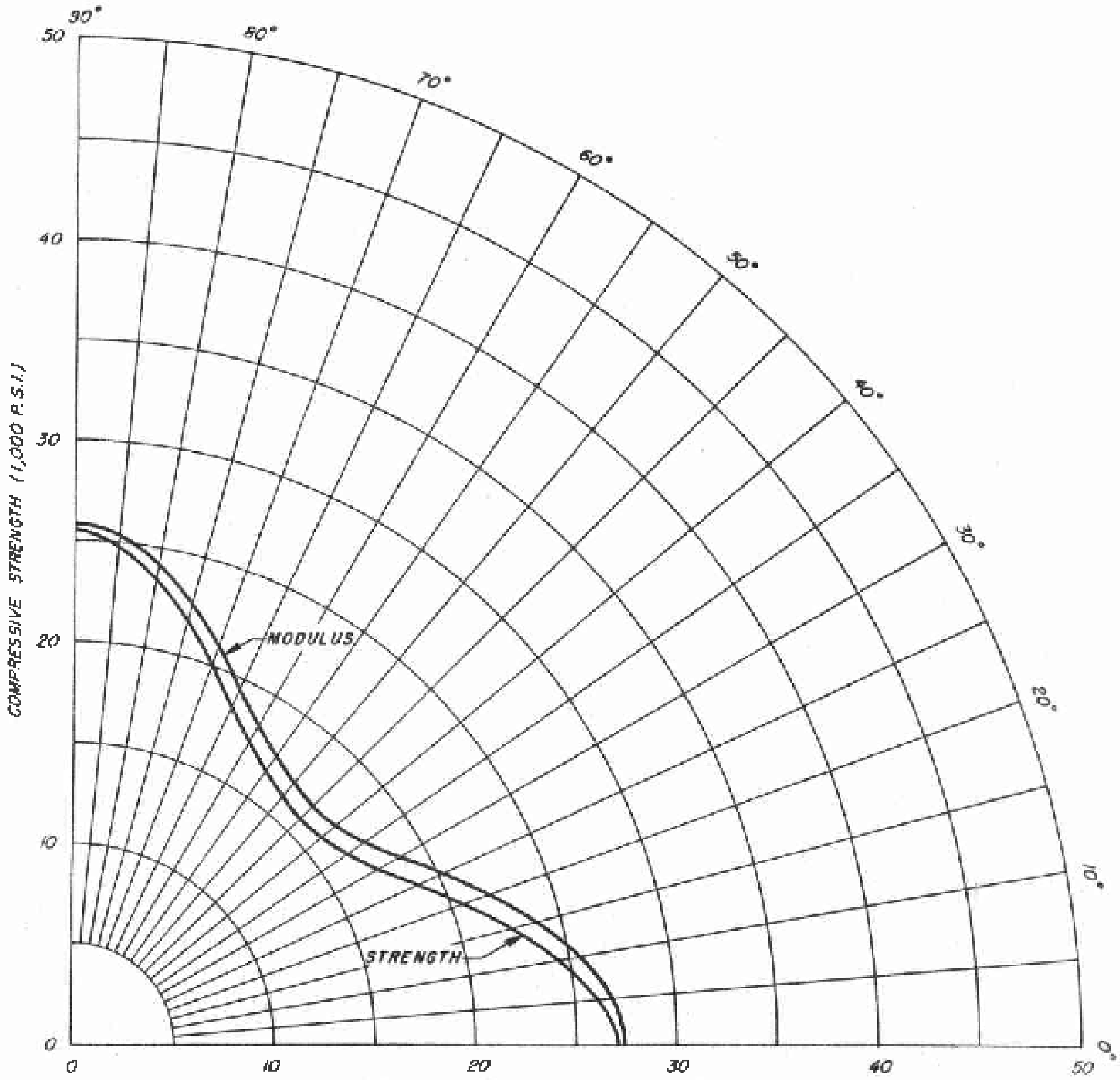

Figure 65. --Directional properties in compression of parallel-laminated 183 glass-fabric laminate made with polyester resin (MIL-R-7575).

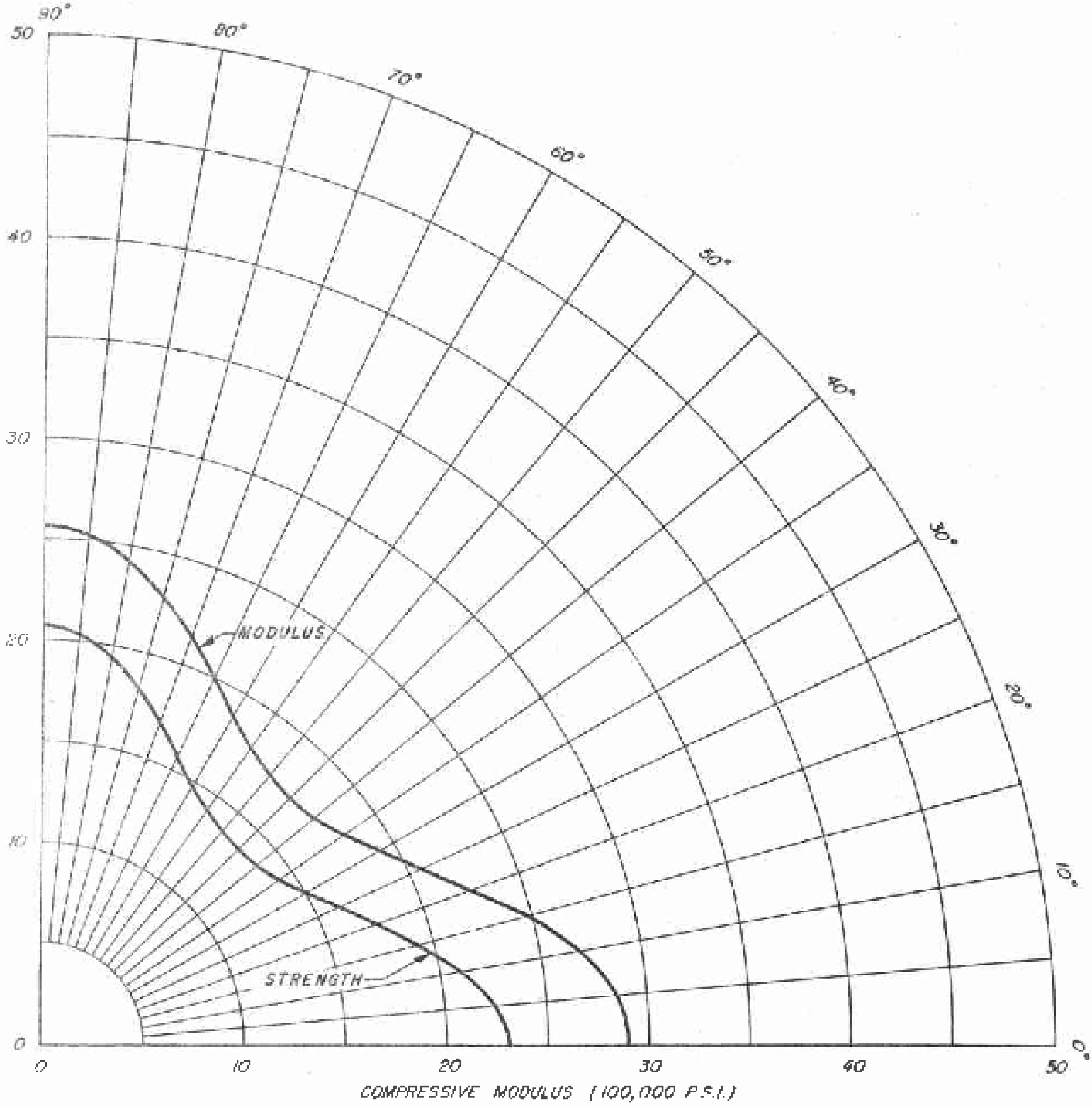

Figure 66. --Directional properties in compression of parallel-laminated 184 glass-fabric laminate made with polyester resin (MIL-R-7575).

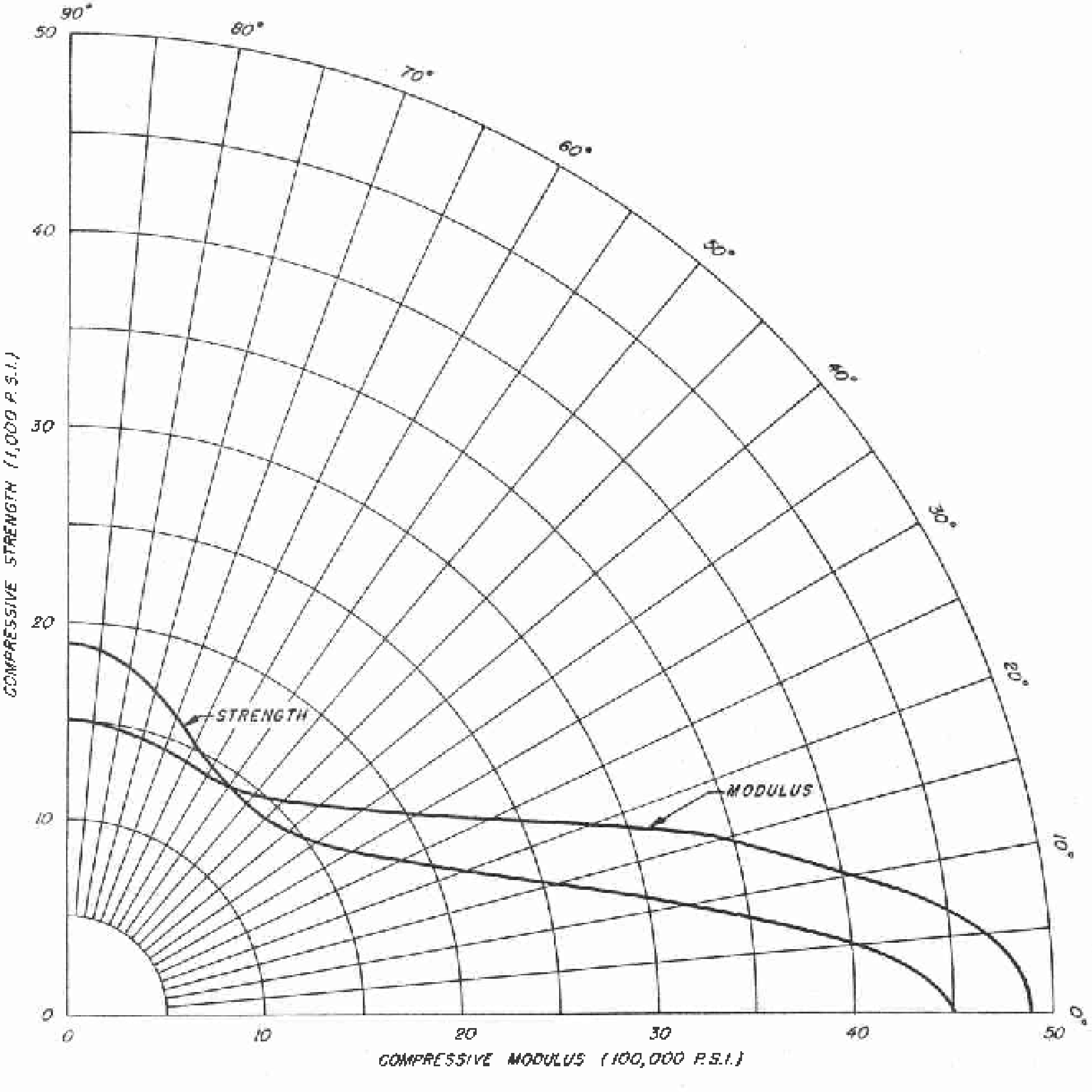

Figure 67. --Directional properties in compression of parallel-laminated 143 glass-fabric laminate made with polyester resin (MIL-R-7575).

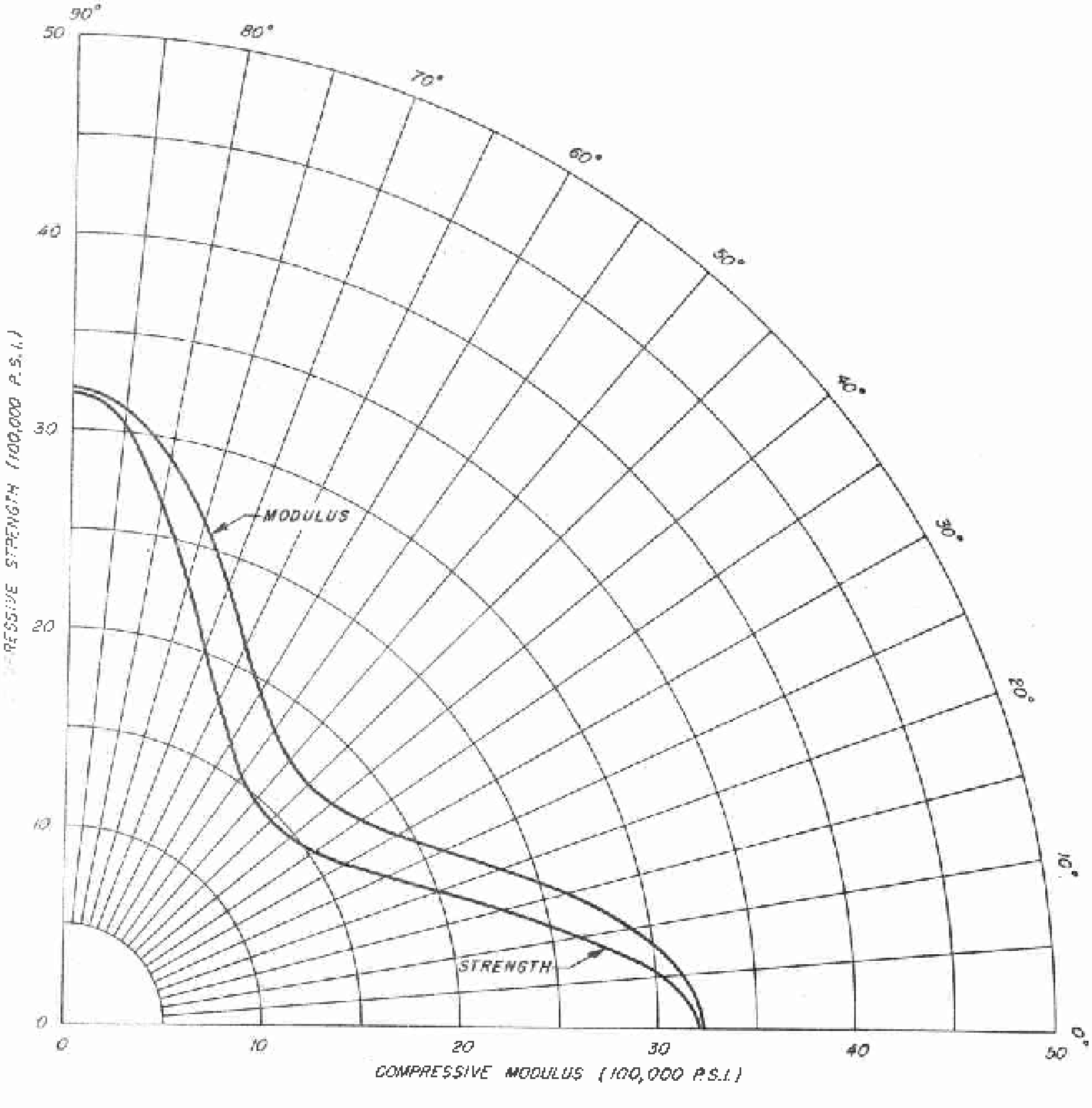

Figure 68. --Directional properties in compression of cross-laminated 143 glass-fabric laminate made with polyester resin (MIL-R-7575).

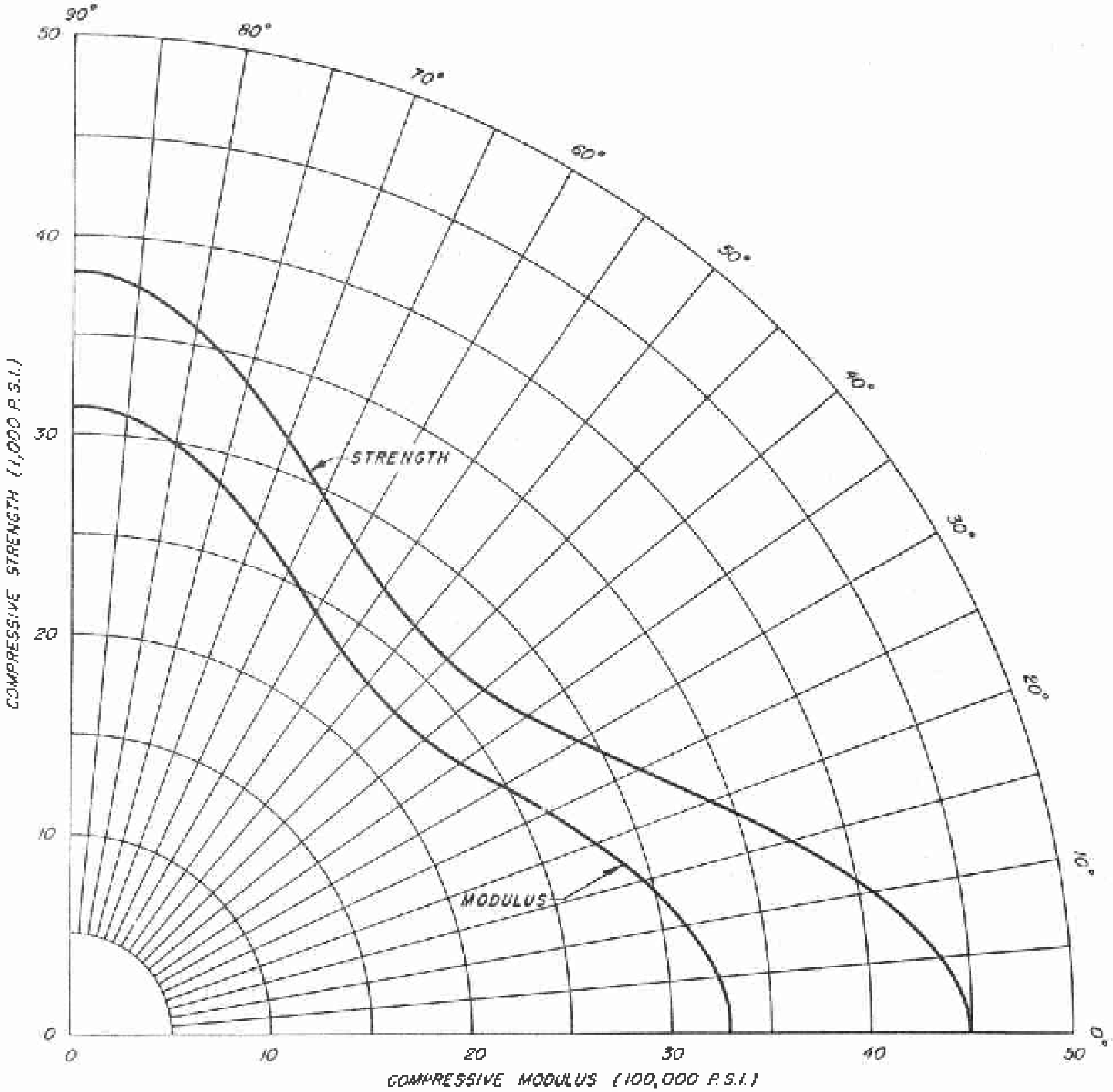

Figure 69. --Directional properties in compression of parallel-laminated 181 glass-fabric laminate made with epoxide resin (MIL-R-9300).

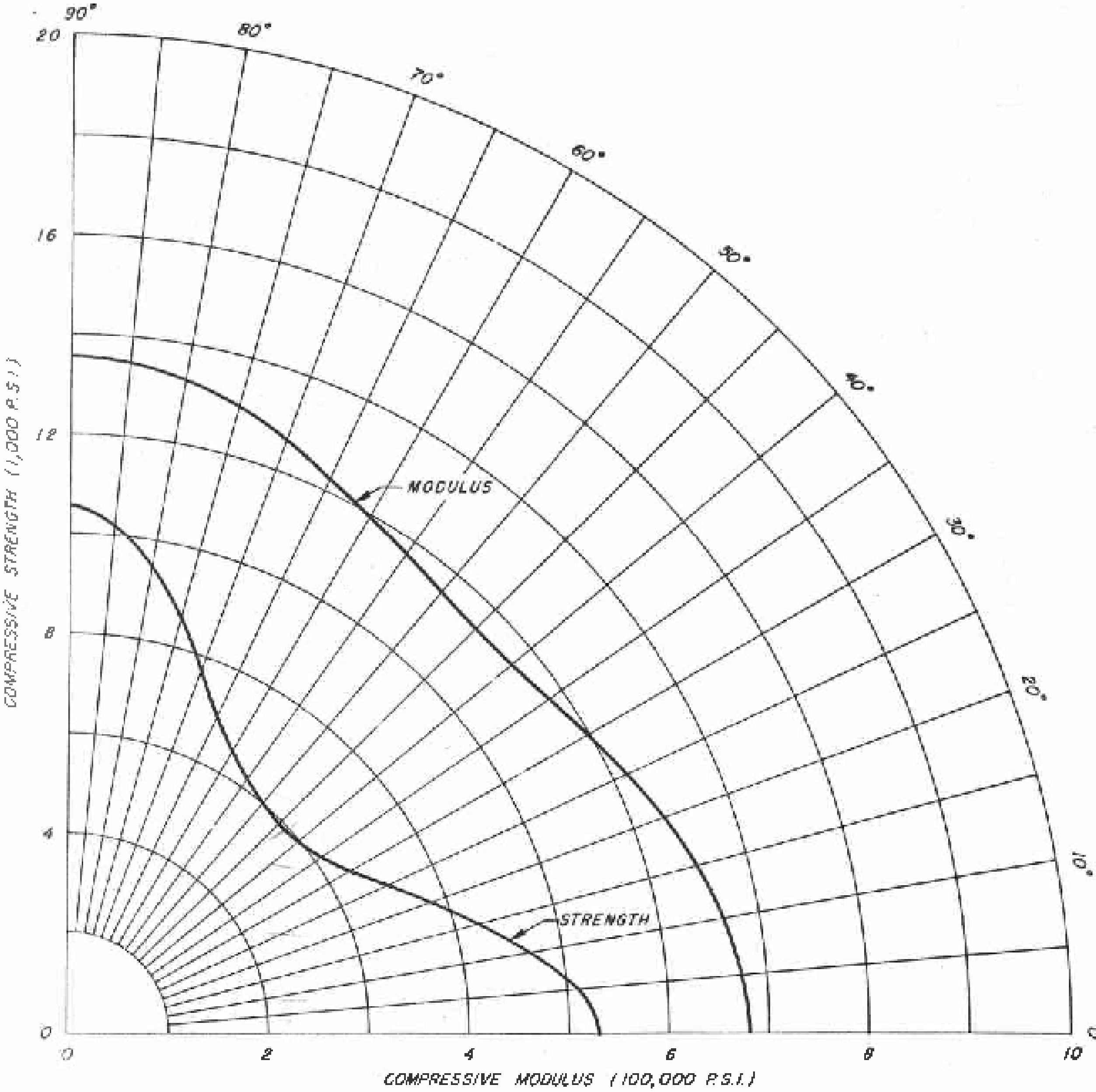

Figure 70. --Directional properties in compression of parallel-laminated cotton-fabric laminate made with phenolic resin (AMS-3605, MIL-P-8655).

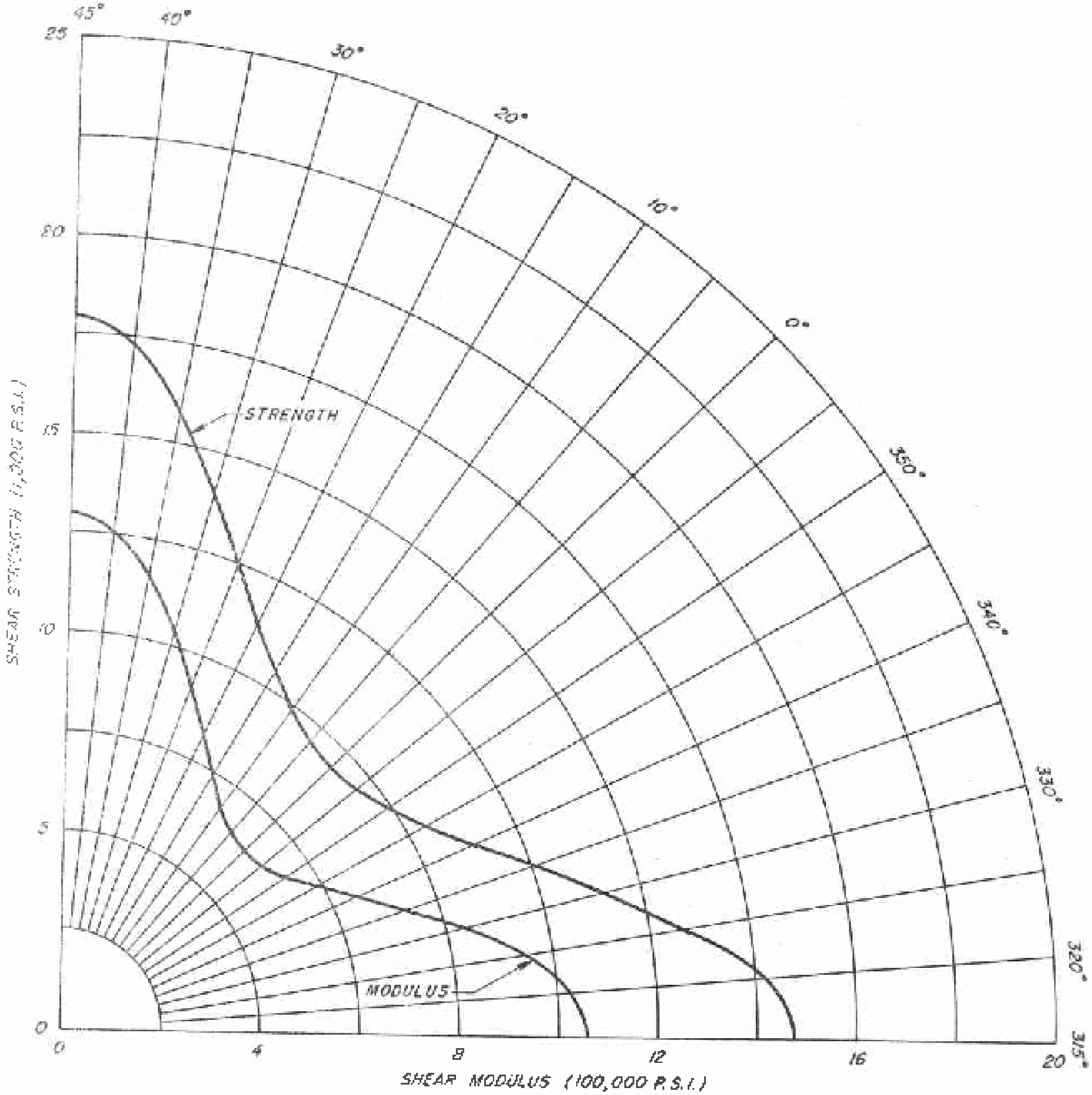

Figure 71. --Directional properties in shear of parallel-laminated 112 glass-fabric laminate made with polyester resin (MIL-R-7575).

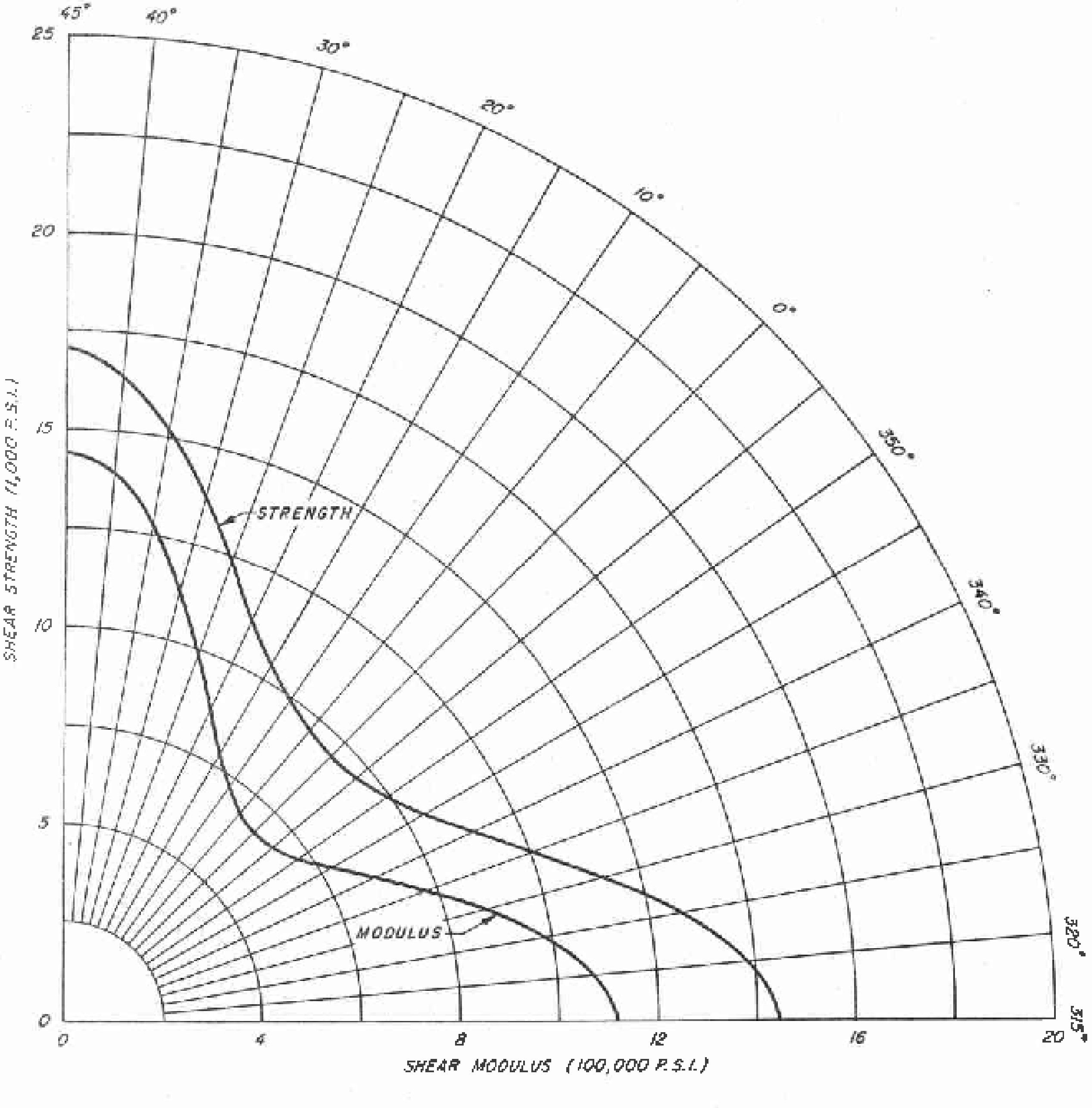

Figure 72. --Directional properties in shear of parallel-laminated 116 glass-fabric laminate made with polyester resin (MIL-R-7575).

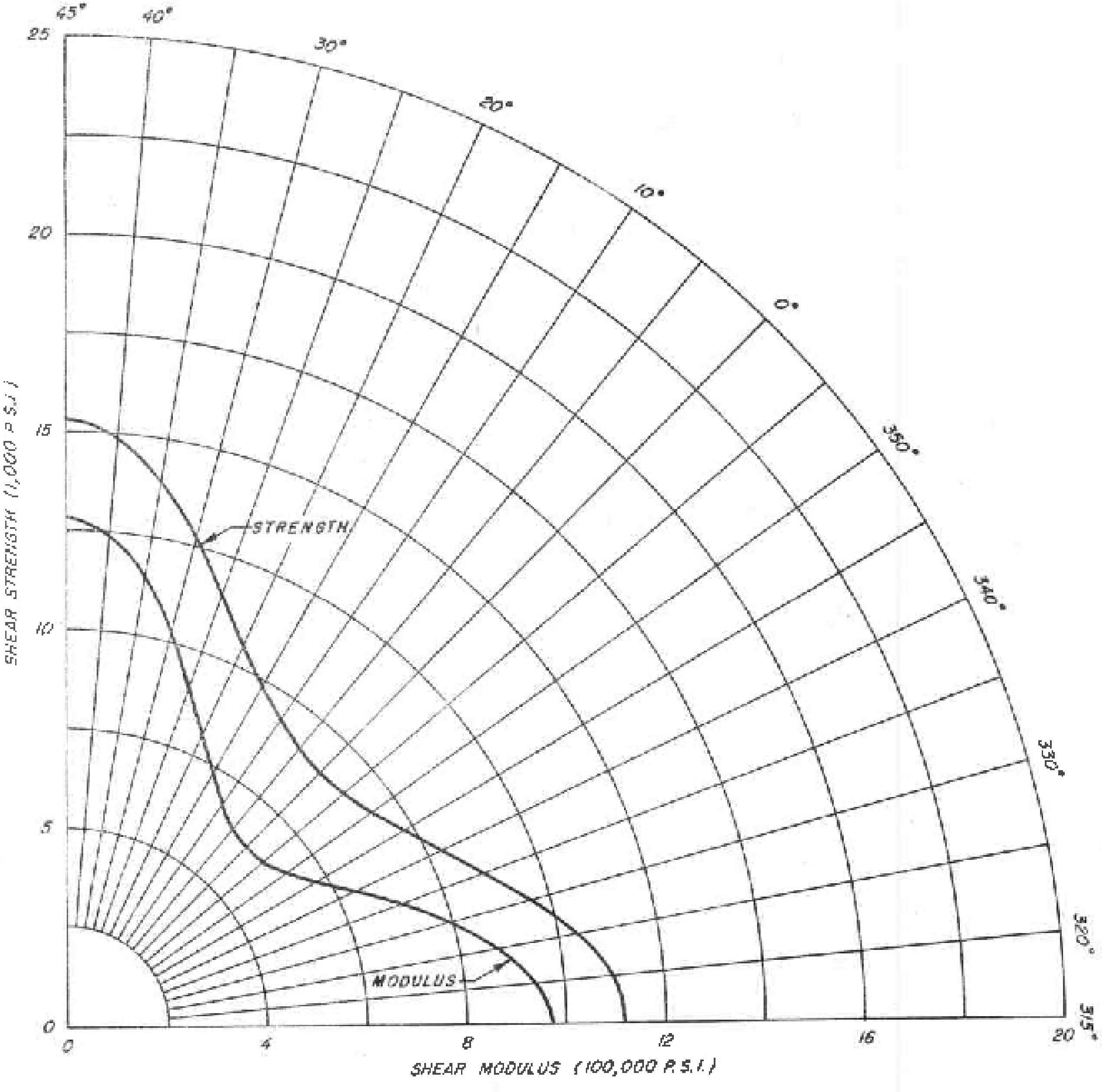

Figure 73. --Directional properties in shear of parallel-laminated 128 glass-fabric laminate made with polyester resin (MIL-R-7575).

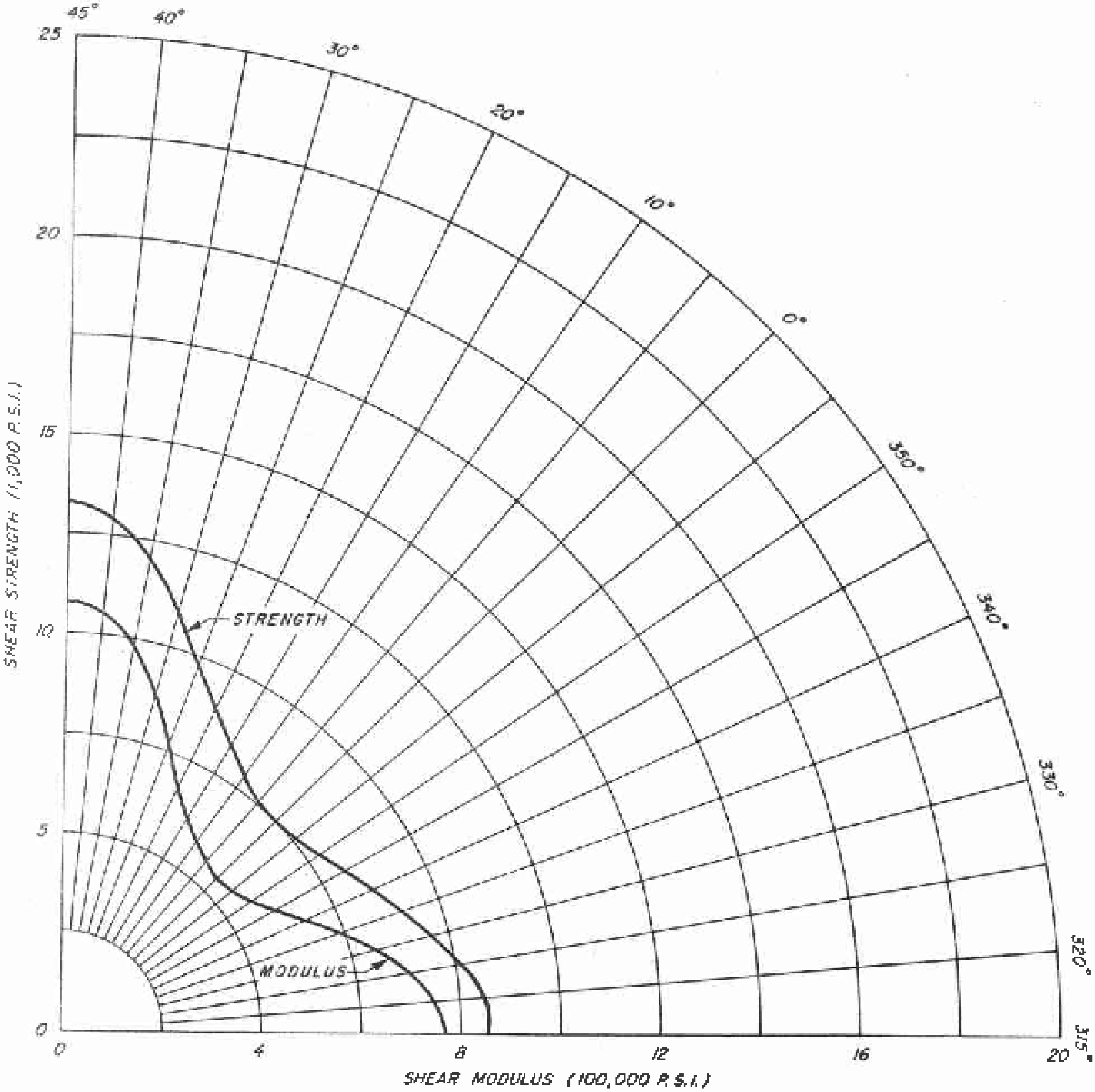

Figure 74. --Directional properties in shear of parallel-laminated 162 glass-fabric laminate made with polyester resin (MIL-R-7575).

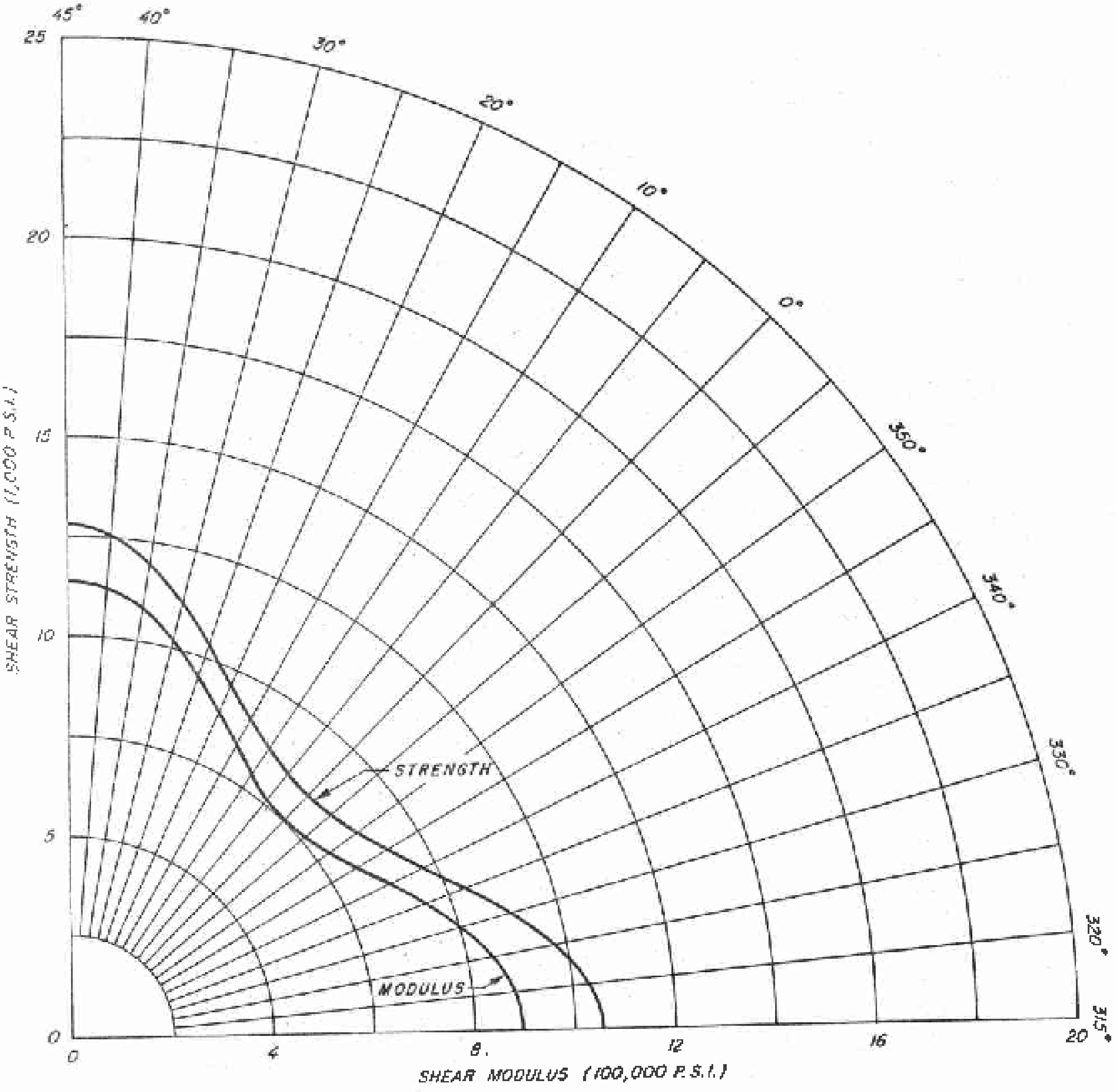

Figure 75. --Directional properties in shear of parallel-laminated 164 glass-fabric laminate made with polyester resin (MIL-R-7575).

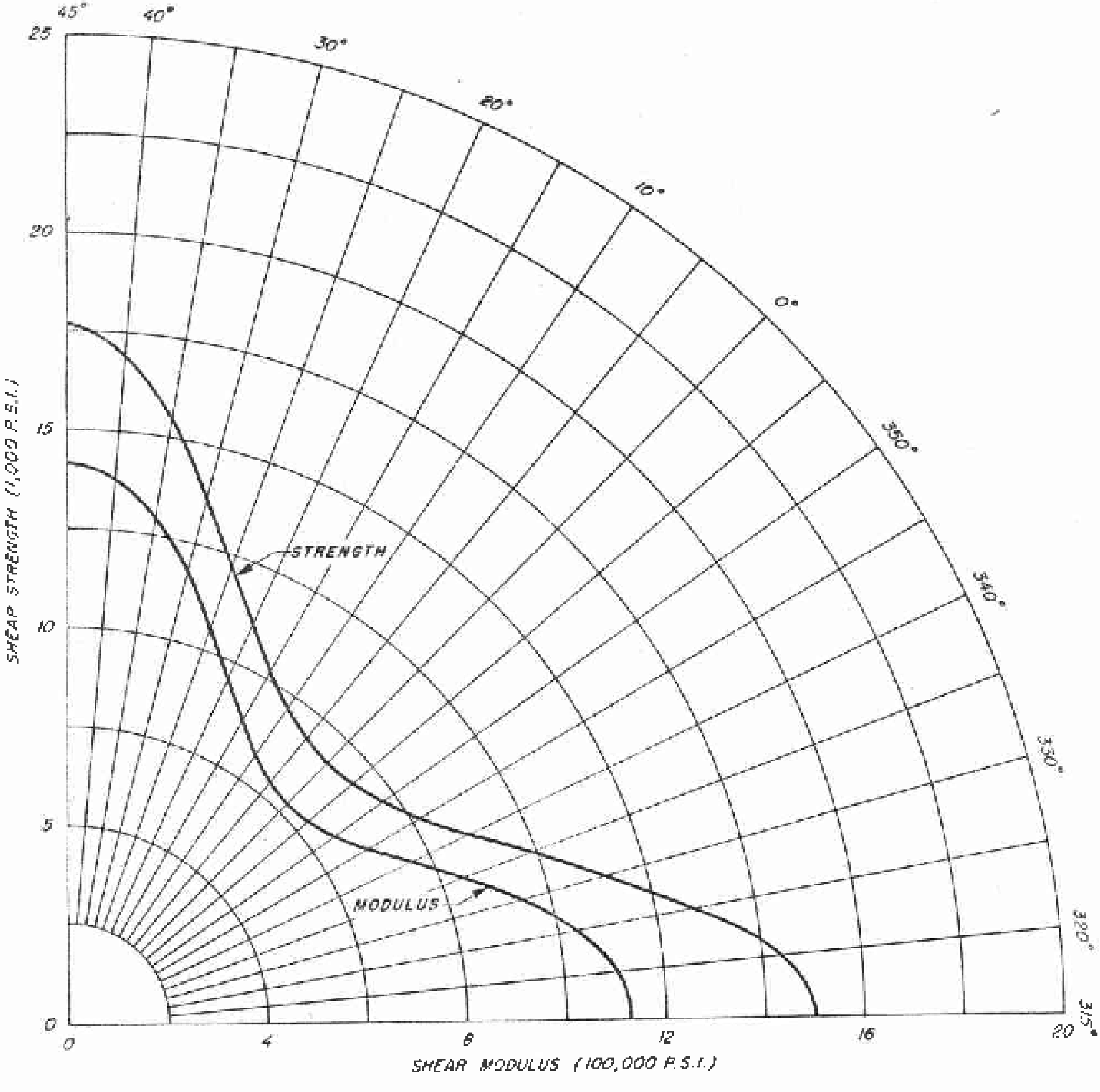

Figure 76. --Directional properties in shear of parallel-laminated 120 glass-fabric laminate made with polyester resin (MIL-R-7575).

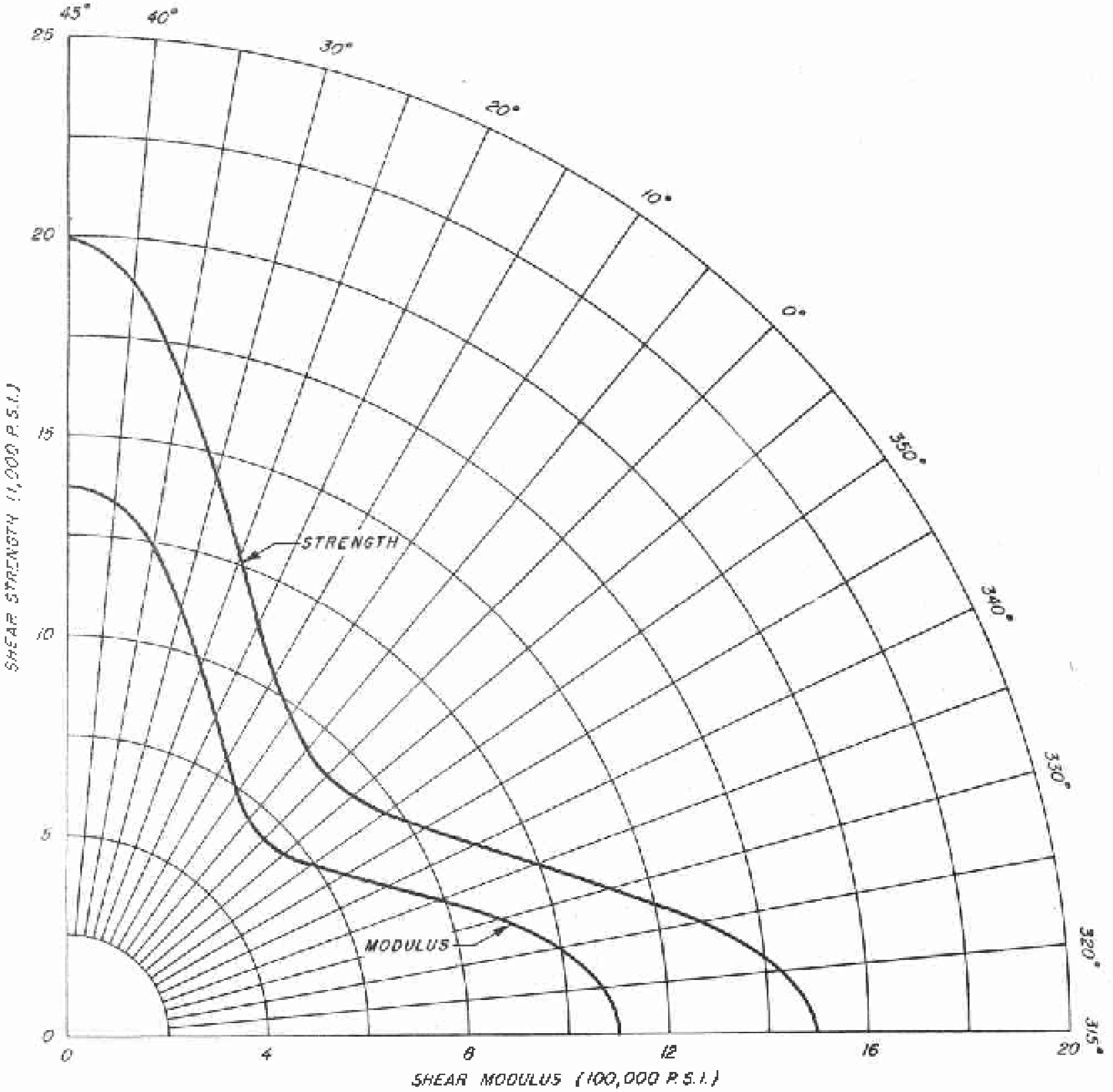

Figure 77. --Directional properties in shear of parallel-laminated 181 glass-fabric laminate made with polyester resin (MIL-R-7575).

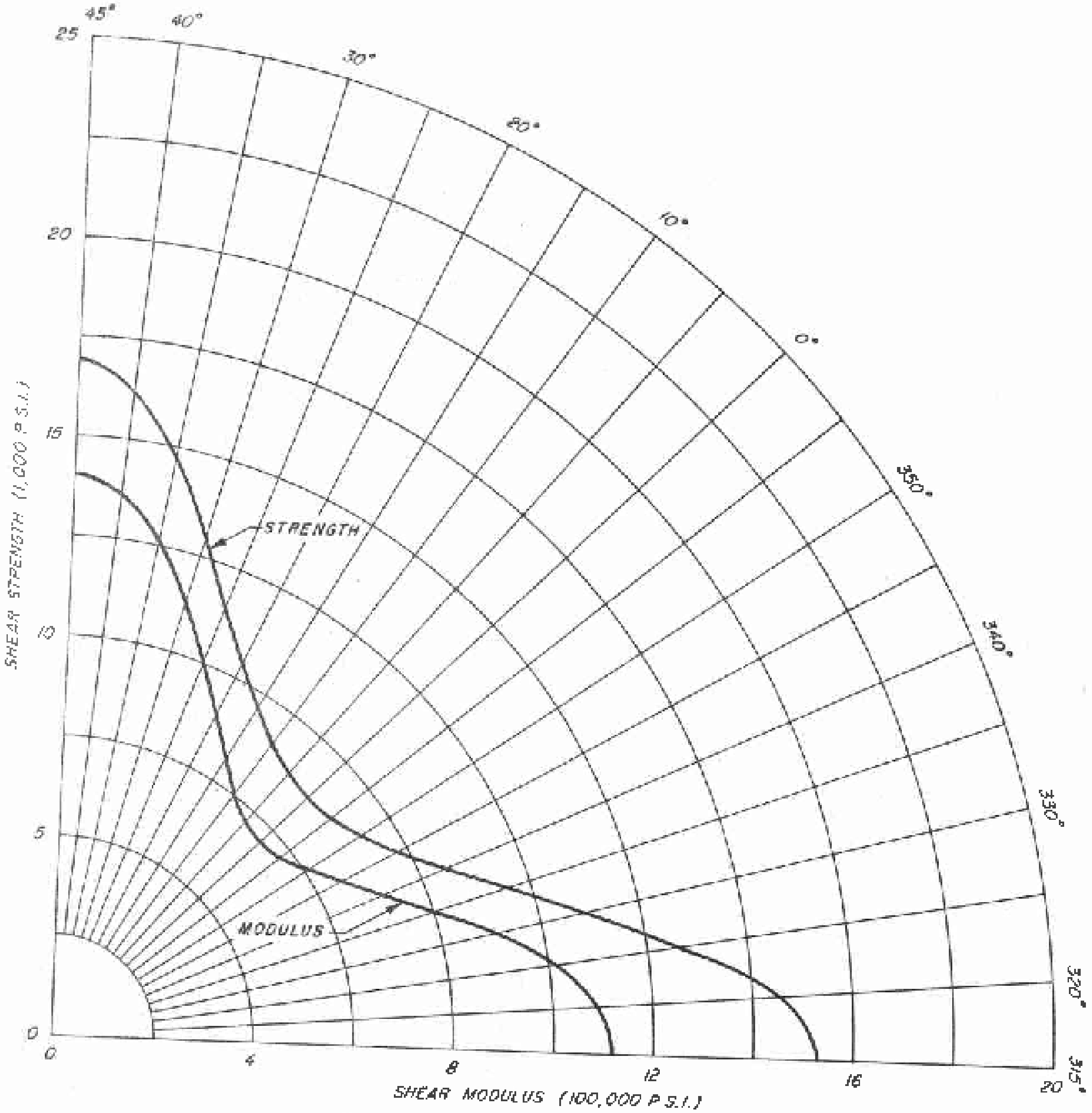

Figure 78. --Directional properties in shear of parallel-laminated 182 glass-fabric laminate made with polyester resin (MIL-R-7575).

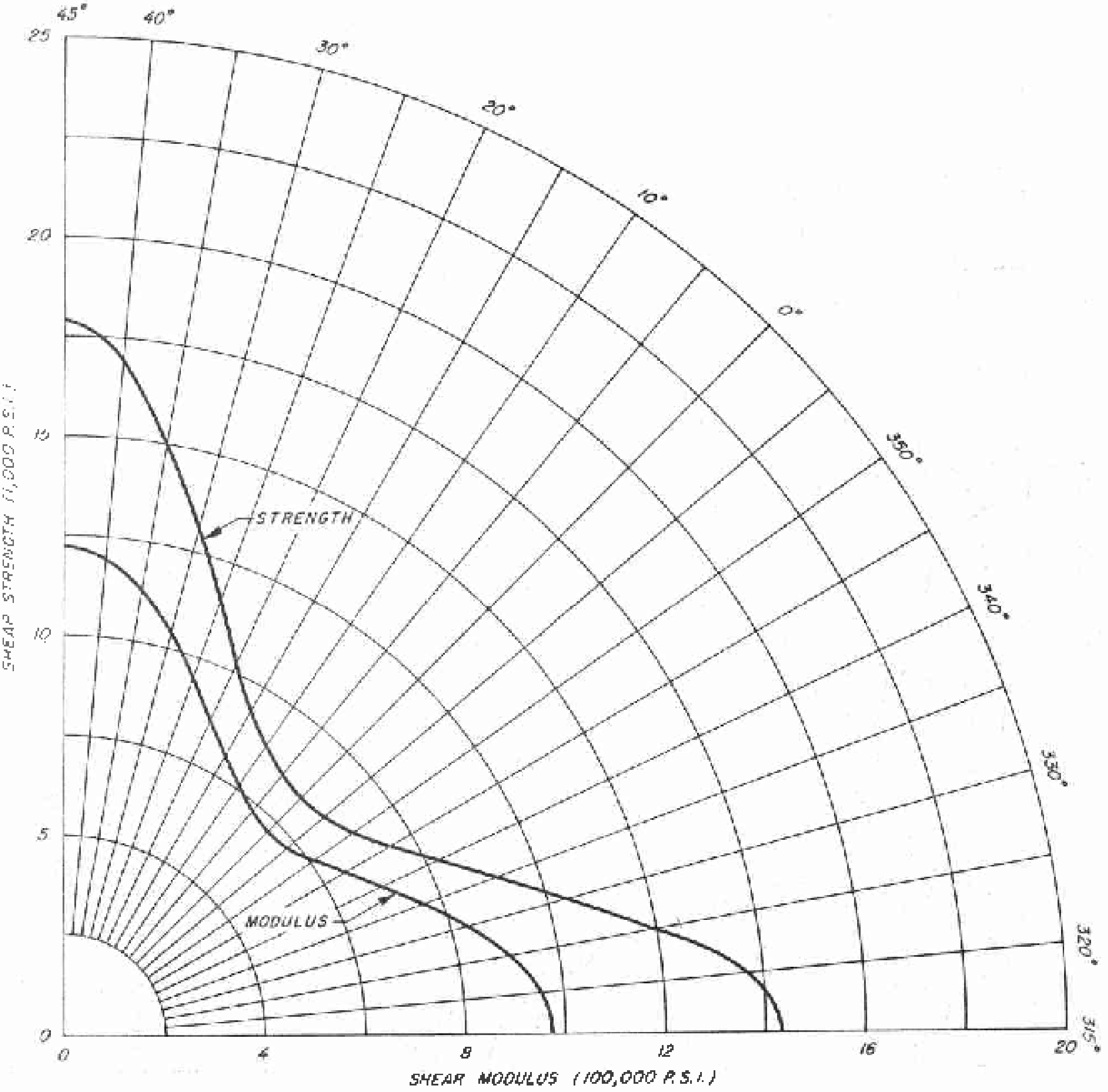

Figure 79. --Directional properties in shear of parallel-laminated 183 glass-fabric laminate made with polyester resin (MIL-R-7575).

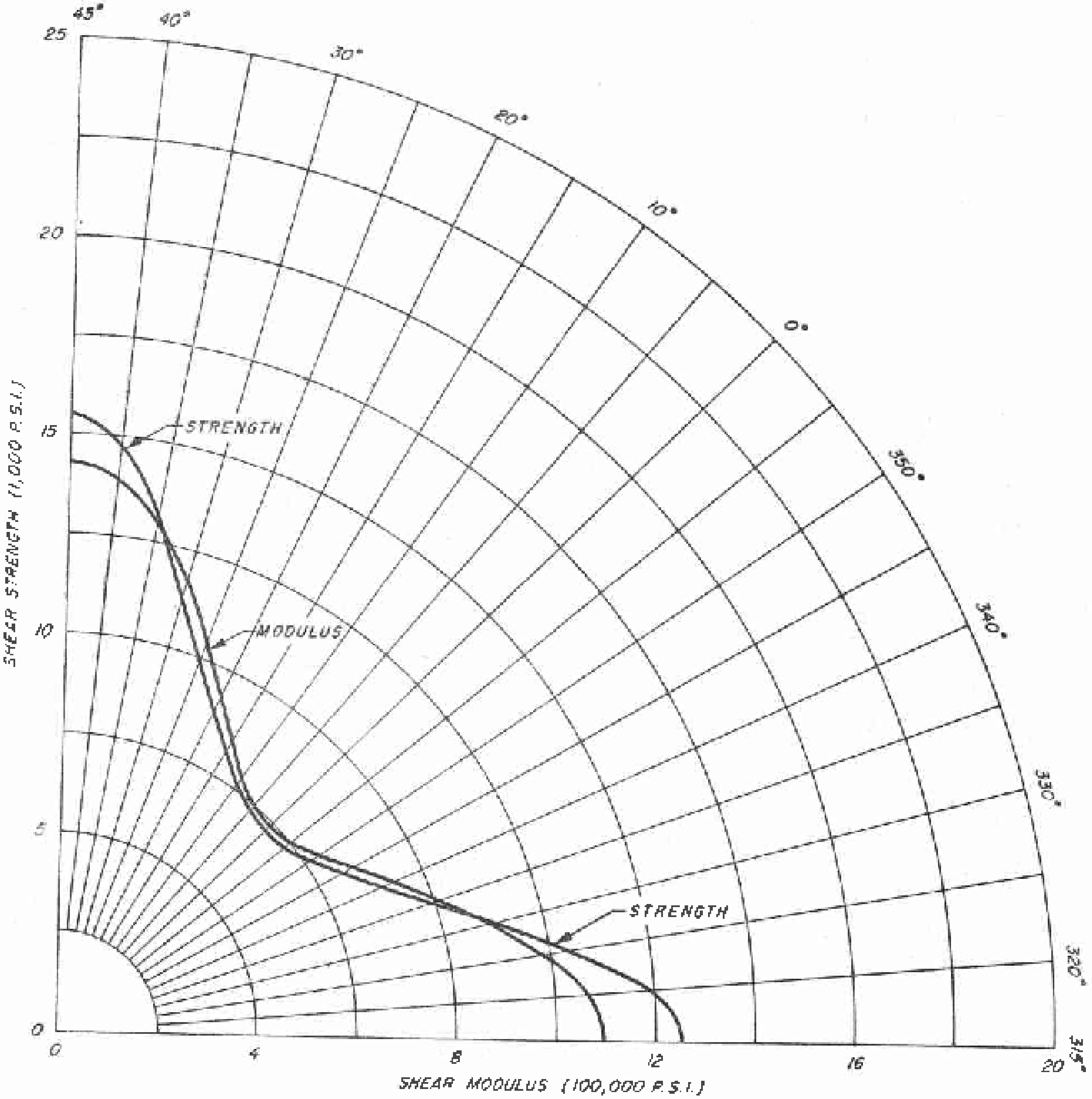

Figure 80. --Directional properties in shear of parallel-laminated 184 glass-fabric laminate made with polyester resin (MIL-R-7575).

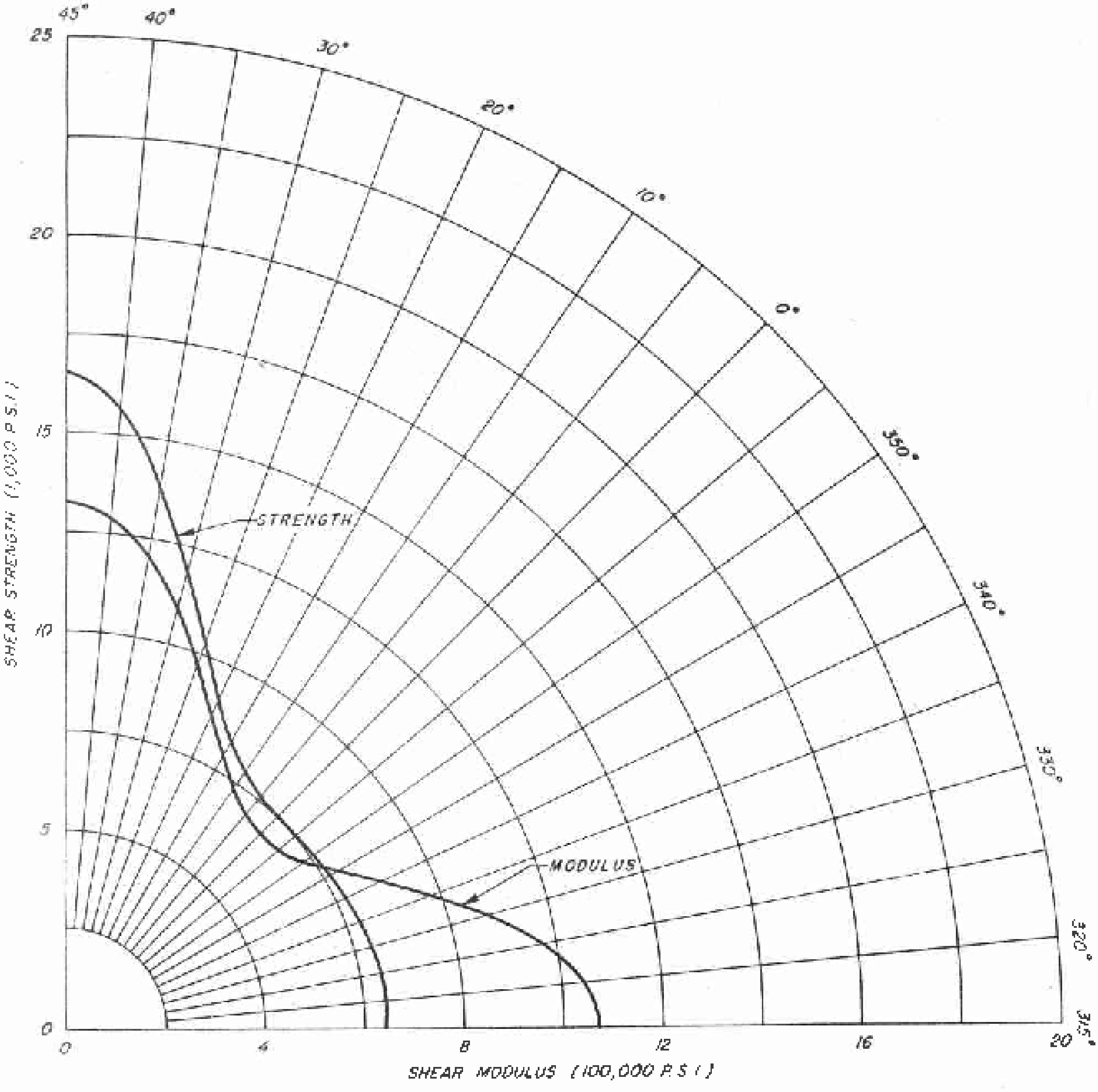

Figure 81. --Directional properties in shear of parallel-laminated 143 glass-fabric laminate made with polyester resin (MIL-R-7575).

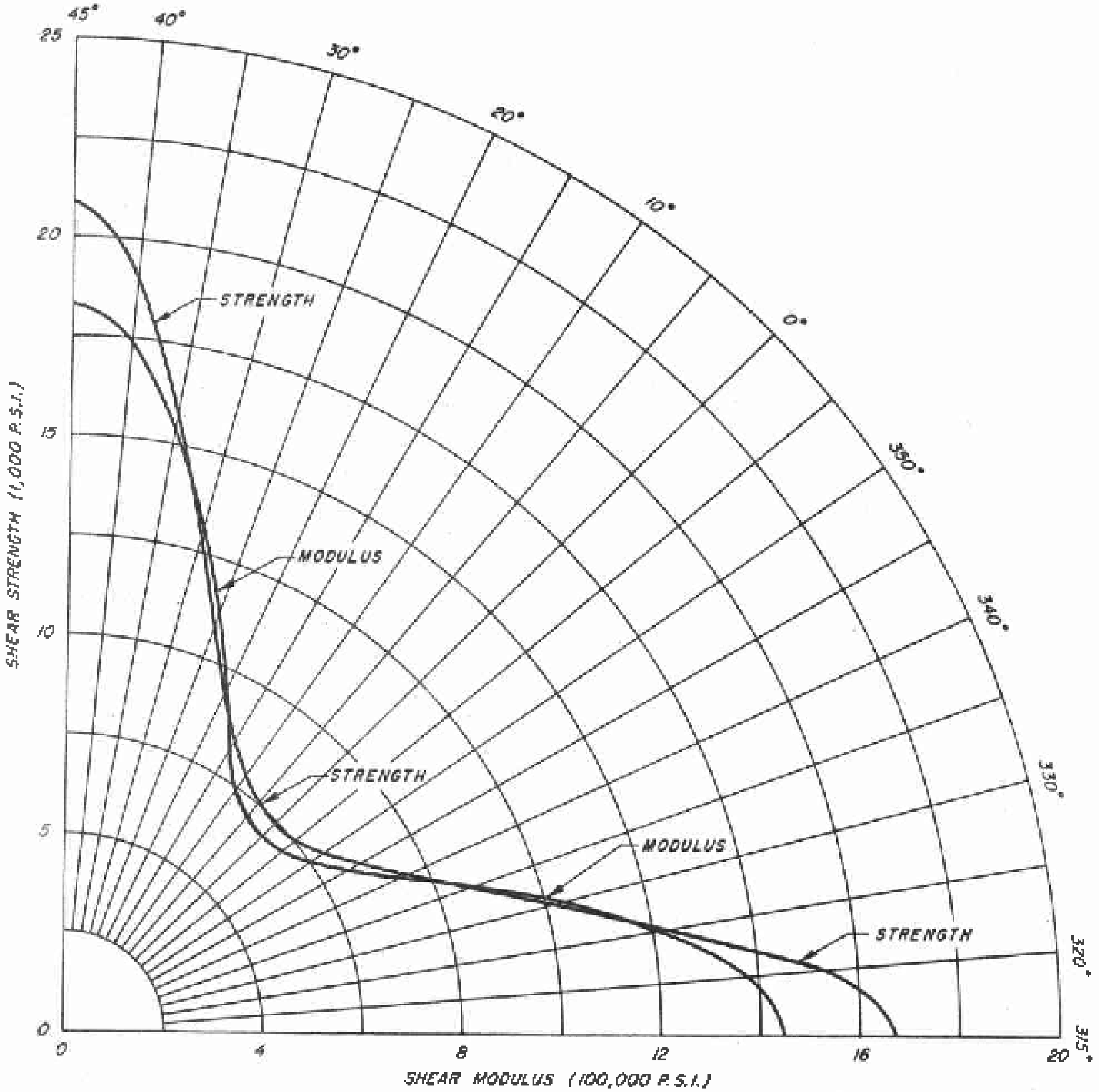

Figure 82. --Directional properties in shear of cross-laminated 143 glass-fabric laminate made with polyester resin (MIL-R-7575).

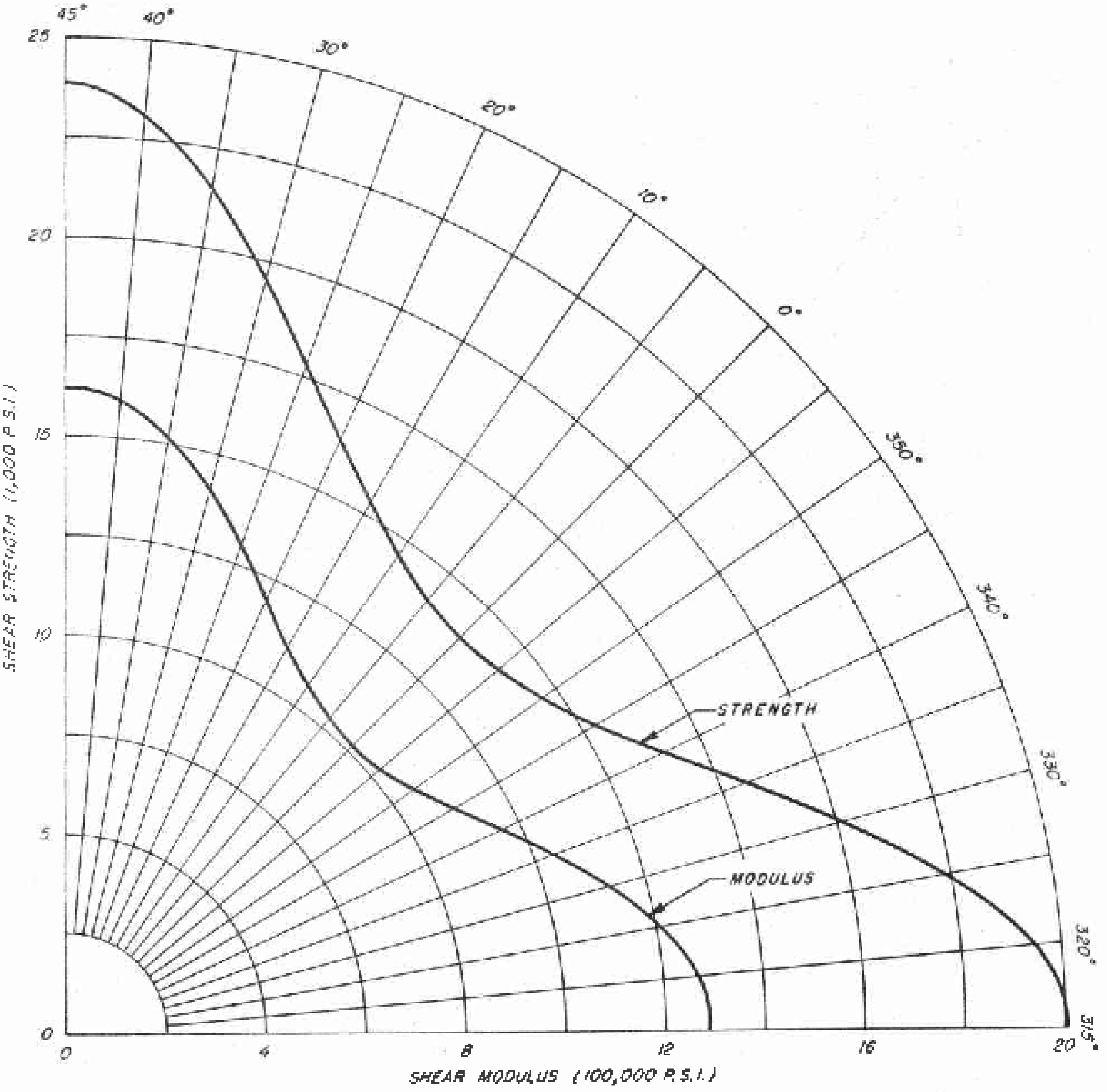

Figure 83. --Directional properties in shear of parallel-laminated 181 glass-fabric laminate made with epoxide resin (MIL-R-9300).

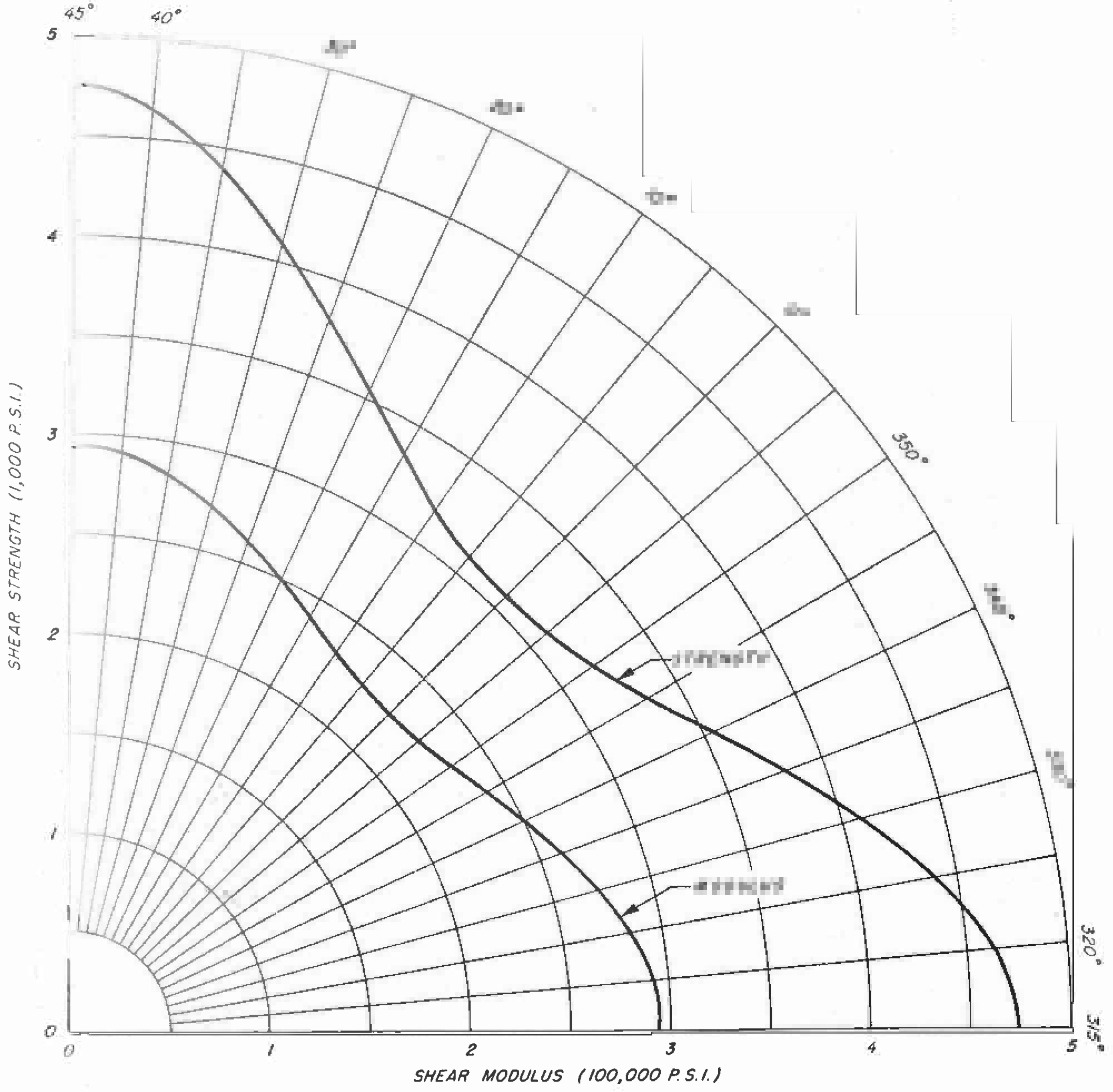

Figure 84. --Directional properties in shear of parallel-laminated cotton-fabric laminate made with phenolic resin (AMS-3605, MIL-P-8655).