Supplement to MECHANICAL PROPERTIES OF CROSS-LAMINATED AND COMPOSITE GLASS-FABRIC-BASE PLASTIC LAMINATES

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SUPPLEMENT TO

MECHANICAL PROPERTIES OF CROSS-LAMINATED AND COMPOSITE GLASS-FABRIC-BASE PLASTIC LAMINATES[1]

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Abstract

Methods of predicting the properties of cross laminates and composite parallel laminates were presented in Forest Products Laboratory Report No. 1821. Reported herein are the results of tests on additional composite parallel laminates, together with the results of application of the computation methods previously presented. The conclusions of the original report are reasonably confirmed by the results of the present study.

Introduction

It was the purpose of this study to supplement the data of the original report by tests on composite parallel laminates of a different type than that originally studied. In this study, facings of from 1 to 11 plies of a fine-weave fabric were applied to a core of a coarser-weave fabric. This type of construction might be employed where it was desired to impart a relatively smooth surface to a laminate made primarily of a coarse-weave fabric.

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

Material

One 1/4-inch-thick panel of each of three constructions was tested in this study. All panels were made with a core of 162-114 fabric with 1, 6, or 11 plies of 112-114 fabric on each face. The panels were laminated with resin 2, a laminating resin of the polyester (styrene-alkyd) type conforming with the requirements of types I, II, and III of U. S. Air Force Specification 12049. For all panels, the resin was catalyzed with 0.8 percent of benzoyl peroxide by weight.

Fabrication procedures were as described in the original report. Information on the make-up and physical properties of the various panels is given in table 11.

Before the composite panels were fabricated, an attempt was made to obtain 162-114 fabric from manufacturer A, who furnished the 162-114 fabric for the earlier panels.[3] The manufacturer did not have the fabric available at that time, so the material was purchased from manufacturer B. Both manufacturers stated that the 114 finishes were identical and that the fabrics, as obtained from either source, were considered to be the same. Subsequent tests, however, showed that this was not so. Therefore, a 162-114 control laminate was fabricated by using fabric from the same roll as that used in the composite laminates. Fabrication procedures were the same as those used for the composite laminates.

Testing

All test procedures were the same as those described in the original report

Presentation and Discussion of Results

Average miscellaneous data and test results are given in tables 11, 12, 13, 14, and 15. Control data for the 112-114 laminate and for the shear properties of the 162-114 laminate are from earlier tests of another study.[3] Tension, compression, and bending properties of the 162-114 laminate are from the control laminate made of the same fabric used in the composite laminate. Comparisons of test results with computed results are shown in tables 16 through 20.

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[3] Werren, Fred. Mechanical Properties of Plastic Laminates. Forest Products Laboratory Report No. 1820. February 1951.

Methods of computing the various properties of the composite laminates from the properties of the components are described in the original report and will not be repeated herein except for the equations.

Tension and Compression

Modulus of elasticity. --Modulus of elasticity of composite laminates may be computed from the equation:

$$E_a = \frac{1}{A} \sum_{i=1}^{i=n} E_i A_i \tag{1}$$

where E_a = modulus of elasticity of the composite laminate

A = cross-sectional area of the composite laminate

E_i = modulus of elasticity of the ith ply in the direction of stress

A_i = cross-sectional area of the ith ply.

Values of E_i were taken from the data for parallel laminates, tables 12 and 13. A comparison of computed and test results is shown in tables 16 and 17. Computed and test values for modulus of elasticity in tension and in compression generally agree within 10 percent.

Strength properties. --Three possible procedures for computing the tensile and compressive strength properties of composite laminates from those of the component materials are represented by the equations:

Method 1

$$S_a = \frac{S_1}{A} \left[A_1 + \frac{E_2}{E_1} A_2 \right] \tag{2}$$

Method 2

$$S_a = \frac{S_2}{A} \left[\frac{E_1}{E_2} A_1 + A_2 \right] \tag{3}$$

Method 3

$$S_a = \frac{1}{A} \sum_{i=1}^{i=n} S_i A_i \tag{4}$$

where S_a = strength property of composite laminate

S_1 = strength property of type 1 layers parallel to direction of stress

S_2 = strength property of type 2 layers parallel to direction of stress

S_i = strength property of the ith ply parallel to stress

E_1 = modulus of elasticity of type 1 layers parallel to direction of stress

E_2 = modulus of elasticity of type 2 layers parallel to direction of stress

A_1 = total cross-sectional area of type 1 layers

A_2 = total cross-sectional area of type 2 layers

A_i = cross-sectional area of the ith ply

A = total cross-sectional area.

In method 1, the computations were based on the properties of the 112 laminate; that is, S_1 equals the strength of the 112 laminate. In method 2, the computations were based on the strength of the 162 laminate.

Ratios of strength values computed by all three methods to strength values obtained by test are shown in tables 16 and 17.

As was to be expected from the results given in the original report, neither method 1 nor method 2 gives good correlation between computed and test values. By using method 3, there is reasonably good correlation between the tensile values. Compression values are also in reasonable agreement except for the composite laminate with facings of one ply of 112-114 fabric.

Properties in tension at a 45° angle. --Two methods of predicting the tensile properties of composite laminates at an angle of 45° to the warp direction were discussed in the original report. The first involved the use of the formulas of

Forest Products Laboratory Reports Nos. 1803 and 1803-A, with the tensile and shear properties of the composite laminates at angles of 0° and 90°. The second was based on using the weighted average of the 45° properties of the component parallel laminates. Parallel-laminate properties were weighted according to the proportion of the area occupied in the composite laminate. Results of both methods of computation are shown in table 20.

Both methods, except for stress at proportional limit, give reasonable correlation between computed and test results in tension, with the second method being somewhat better. The lack of correlation for stress at proportional limit may be attributed largely to difficulties in accurately locating the proportional limit.

Discussion of tensile properties. --Previous discussion has mentioned that a new panel of 162-114 fabric, parallel-laminated, was made to furnish control values for tension, compression, and bending tests. This was necessary because the laminates made from the 162-114 fabric from manufacturer B were appreciably lower in tensile properties than comparable laminates made with similar fabric from manufacturer A. Other mechanical properties were reasonably comparable.

In two other instances in tests of plastic laminates, laminates made with fabric from manufacturer B were appreciably lower in tensile properties than those made with fabric from manufacturer A. This may be seen by a comparison of items 1-3 and 1-13 (128-114 laminates) and items 1-8 and 1-20 (181-114 laminates) in Forest Products Laboratory Reports Nos. 1820[3] and 1820-A.[4] Examination of the data will also show that laminates made with fabric from manufacturer A were thinner, had a higher specific gravity, and had a lower resin content.

Analysis of these data indicates that there is apparently some difference between 114 finish fabrics furnished by the two manufacturers, even though the materials are supposed to be identical. This difference or variation, which might be in the finish, substantially affects the tensile properties of the laminate. Some differences might also be noted in tensile tests of the fabric, as are shown in the results of tests of 162-114 fabric, table 21.

Static Bending

Modulus of elasticity. --The modulus of elasticity in static bending may be computed from:

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[4]Werren, Fred. Supplement to Mechanical Properties of Plastic Laminates. Forest Products Laboratory Report No. 1820-A. February 1953.

$$E_a = \frac{1}{I} \sum_{i=1}^{i=n} E_i I_i \qquad (5)$$

where E_a = modulus of elasticity of the composite laminate

E_i = modulus of elasticity of the ith ply parallel to span

I_i = moment of inertia of the ith ply about the neutral plane of the laminate

I = moment of inertia of the laminate about its neutral plane.

A comparison of computed with test values is shown in table 18.

Strength properties. --Three possible methods of computing the static-bending-strength properties of the composite laminates from the strength properties of the component materials are represented by the equations:

Method 1

$$f_a = \frac{f_2}{I}\left[I_1 \frac{E_1}{E_2} + I_2\right] \qquad (6)$$

Method 2

$$f_a = \frac{f_1}{I}\left[1 - \frac{2t_f}{d}\right]\left[I_1 + \frac{E_2}{E_1} I_2\right] \qquad (7)$$

Method 3

$$f_a = \frac{1}{I} \sum_{i=1}^{i=n} f_i I_i \qquad (8)$$

where f_a = strength property of the composite laminate

f_1 = strength property of the type 1 layers parallel to span

f_2 = strength property of the type 2 layers parallel to span

f_i = strength property of the ith ply parallel to span

I_1 = sum of moments of inertia of the layers of type 1 about the neutral plane of the laminate

I_2 = sum of moments of inertia of the layers of type 2 about the neutral plane of the laminate

I_i = moment of inertia of the ith ply about the neutral plane of the laminate

I = moment of inertia of the composite laminate about its neutral plane

E_1 = modulus of elasticity of the layers of type 1 parallel to span

E_2 = modulus of elasticity of the layers of type 2 parallel to span

$\frac{t_f}{d}$ = ratio of thickness of surface layer to total thickness of laminate.

In method 1, computations were based on the strength of the 112 laminate; that is, f_2 equals the strength of the 112 laminate. In method 2, computations were based on the strength of the 162 laminate. The value of t_f was taken as the total thickness of each 112 facing. Results of computations by these methods are shown in table 18.

As was found in the original report, methods 1 and 2 do not give consistently good correlation between computed and test results. Method 3, however, gives generally good correlation except for stress at proportional limit.

Shear

The original report showed that reasonably good correlation between computed and test results in shear could be expected by use of the following equation:

$$F_a = \frac{1}{A} \sum_{i=1}^{i=n} F_i A_i \qquad (9)$$

where F_a = property of composite laminate

A = total cross-sectional area of composite laminate

F_i = property of ith ply

A_i = cross-sectional area of ith ply.

A comparison of computed and test results is given in table 19. In view of the small number of tests (two per laminate), the correlation is considered satisfactory.

Conclusions

The results of tests of three composite laminates made of 112-114 and 162-114 glass fabrics confirm reasonably well the conclusions of the original report.

The conclusions of the original report were:

(a) The properties of composite or cross laminates stressed in tension or compression parallel or perpendicular to the warp direction may be taken as the average of the properties of the component layers, parallel to stress, weighted according to the proportion of the area they occupy.

(b) The properties of cross laminates or composite laminates stressed in bending parallel or perpendicular to the warp direction may be taken as the average of the properties of the component layers, parallel to span, weighted according to the proportion they contribute to the moment of inertia of the laminate.

(c) The properties of cross laminates or composite laminates stressed in shear with the shear loads applied parallel and perpendicular to the warp direction may be taken as the average of the properties of the component plies when loaded in the same way, weighted according to the proportion of the area they occupy. For cross laminates, the properties are the same as for parallel laminates.

(d) The properties of cross laminates or composite laminates stressed in tension at 45° to the warp direction may be taken as the average of the properties of the component layers, parallel to stress, weighted according to the proportion of the area they occupy. For cross laminates, the properties are the same as for the parallel laminates.

(e) Since the laminates tested involve fabrics having a range of relative strength parallel and perpendicular to warp typical of the range used in aircraft applications, the relations developed should be applicable to any other glass fabrics now being used for aircraft laminates.

Table 11.--Miscellaneous data relative to composite parallel laminates made of 112-114 and 162-114 fabrics and resin 2

Panel No.	Number of plies[1] Total	112-114 fabric	162-114 fabric	Specific gravity	Resin content	Barcol hardness	Thickness
					Percent		In.
			112-114 Control Laminates				
5	84	[2]84	....	1.71	43.5	69	0.250
6	84	[2]84	....	1.70	43.4	69	.250
			162-114 Laminates--for Shear Controls				
52	17	....	[2]17	1.76	37.7	62	.252
53	17	....	[2]17	1.76	38.2	62	.254
			162-114 Laminate--for Tension, Compression, and Bending Controls				
223	16	....	[3]16	1.72	41.0	63	.257
			Composite Laminates				
217	18	[2]2	[3]16	1.73	41.1	69	.262
218	26	[2]12	[3]14	1.71	42.0	69	.264
219	34	[2]22	[3]12	1.71	42.0	69	.260

[1]Layers of 112-114 fabric formed a facing on a core of 162-114 fabric. One-half the number of plies of 112-114 fabric shown above at each face.

[2]Fabric from manufacturer A.

[3]Fabric from manufacturer B.

Table 12.--Results of tension tests of parallel laminates made of 112-114 and 162-114 fabrics and resin 2

Fabric	Layers of 112-114 fabric at each face	Direction of test	Modulus of elasticity: Initial	Modulus of elasticity: Secondary	Stress at -- Proportional limit: Initial	Stress at -- Proportional limit: Secondary	Stress at -- Ultimate
	No.	Degrees	1,000 p.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.	P.s.i.
Controls - Parallel-laminated							
112-114	....	0	2,690	2,390	11,800	29,500	42,700
		45	....	1,540	....	3,760	20,550
		90	2,640	2,240	9,800	27,050	38,650
162-114	....	0	2,760	2,440	7,940	19,750	37,600
		45	....	1,360	....	3,460	16,350
		90	1,960	1,520	4,560	10,200	20,600
Composite Laminates - Parallel-laminated							
112-114; 162-114	1	0	2,760	2,370	6,400	18,500	35,600
		45	....	1,450	....	2,580	16,000
		90	2,040	1,380	4,330	11,750	19,900
112-114; 162-114	6	0	2,670	2,250	8,120	20,950	36,050
		45	....	1,350	....	2,580	16,400
		90	1,960	1,400	4,660	12,850	22,400
112-114; 162-114	11	0	2,690	2,240	8,490	24,500	37,900
		45	....	1,530	....	2,380	16,200
		90	2,000	1,490	5,520	14,750	24,300

Table 13.--Results of compression tests of parallel laminates made of 112-114 and 162-114 fabrics and resin 2

Fabric	Layers of 112-114 fabric at each face	Direction of test	Modulus of elasticity	Stress at -- Proportional limit	Stress at -- 0.2 percent offset	Stress at -- Ultimate
	No.	Degrees	1,000 p.s.i.	P.s.i.	P.s.i.	P.s.i.
Controls - Parallel-laminated						
112-114	....	0	2,820	23,250	36,850	36,850
		90	2,630	21,600	32,900	32,900
162-114	....	0	2,850	11,250	19,100	19,100
		90	2,100	10,200	18,300	18,300
Composite Laminates - Parallel-laminated						
112-114; 162-114	1	0	2,810	16,950	23,900	23,900
		90	1,900	15,700	21,750	21,750
112-114; 162-114	6	0	2,660	16,450	22,100	22,100
		90	2,020	17,300	21,450	21,450
112-114; 162-114	11	0	2,810	16,750	23,400	23,400
		90	2,050	17,800	23,250	23,250

Table 14.--Results of static-bending tests of parallel laminates made of 112-114 and 162-114 fabrics and resin 2

Fabric	Layers of 112-114 fabric at each face	Direction of test	Modulus of elasticity	Stress at -- Proportional limit	Stress at -- 0.2 percent offset	Modulus of rupture
	No.	Degrees	1,000 p.s.i.	P.s.i.	P.s.i.	P.s.i.
			Controls - Parallel-laminated			
112-114	....	0	2,590	31,000	58,250	58,250
		90	2,400	26,450	48,350	48,350
162-114	....	0	2,470	17,200	32,550	35,000
		90	1,720	11,300	22,850	26,900
			Composite Laminates - Parallel-laminated			
112-114; 162-114	1	0	2,690	24,550	38,600	38,800
		90	2,000	12,200	26,250	28,800
112-114; 162-114	6	0	2,680	24,050	43,750	43,750
		90	2,110	15,250	33,750	33,750
112-114; 162-114	11	0	2,730	28,200	54,650	55,050
		90	2,270	14,950	36,800	37,800

Table 15.--Results of panel shear tests of parallel laminates made of 112-114 and 162-114 fabrics and resin 2

Fabric	Plies of 112-114 fabric at each face	Modulus of rigidity	Stress at --		
			Proportional limit	0.2 percent offset	Ultimate
	No.	1,000 p.s.i.	P.s.i.	P.s.i.	P.s.i.
			Controls - Parallel-laminated		
112-114	....	660	1,920	4,070	13,600
162-114	....	580	2,220	4,810	11,700
			Composite Laminates - Parallel-laminated		
112-114; 162-114	1	570	2,240	4,930	10,300
112-114; 162-114	6	560	2,160	4,580	10,850
112-114; 162-114	11	510	2,540	4,850	10,900

Table 16.--Ratios of computed tensile properties to properties obtained in test

Direction	Ratios									
	Modulus of elasticity		Stress at proportional limit						Ultimate stress		
			Initial			Secondary					
	Initial	Secondary	Method 1	Method 2	Method 3	Method 1	Method 2	Method 3	Method 1	Method 2	Method 3
Degrees											
				1 Ply of 112-114 Fabric on Each Face							
0	1.00	1.03	1.89	1.24	1.26	1.63	1.07	1.08	1.22	1.06	1.06
90	.97	1.12	1.69	1.06	1.08	1.58	.87	.90	1.34	1.05	1.06
				6 Plies of 112-114 Fabric on Each Face							
0	1.03	1.08	1.48	.98	1.05	1.43	.94	1.01	1.20	1.04	1.06
90	1.05	1.16	1.64	1.03	1.14	1.53	.85	.99	1.25	.98	1.04
				11 Plies of 112-114 Fabric on Each Face							
0	1.02	1.08	1.41	.93	1.06	1.22	.80	.91	1.14	.99	1.03
90	1.07	1.15	1.44	.90	1.08	1.40	.78	1.00	1.22	.96	1.05

Table 17.--Ratios of computed compressive properties to those obtained in test

Direction	Ratios									
	Modulus of elasticity	Stress at proportional limit			Stress at 0.2 percent offset			Stress at ultimate		
		Method 1	Method 2	Method 3	Method 1	Method 2	Method 3	Method 1	Method 2	Method 3
Degrees										
					1 Ply of 112-114 Fabric on Each Face					
0	1.01	1.38	0.66	0.68	1.56	0.80	0.82	1.56	0.80	0.82
90	1.11	1.39	.64	.67	1.53	.84	.86	1.53	.84	.86
					6 Plies of 112-114 Fabric on Each Face					
0	1.07	1.42	.68	.79	1.68	.86	.98	1.68	.86	.98
90	1.08	1.26	.59	.69	1.55	.85	.95	1.55	.85	.95
					11 Plies of 112-114 Fabric on Each Face					
0	1.01	1.40	.67	.86	1.59	.81	1.02	1.59	.81	1.02
90	1.10	1.22	.57	.75	1.43	.78	.96	1.43	.78	.96

Table 18.--Ratios of computed static-bending properties to properties obtained in test

Direction	Ratios									
	Modulus of elasticity	Stress at proportional limit			Stress at 0.2 percent offset			Modulus of rupture		
		Method 1	Method 2	Method 3	Method 1	Method 2	Method 3	Method 1	Method 2	Method 3
Degrees										
	1 Ply of 112-114 Fabric on Each Face									
0	0.92	1.21	0.68	0.74	1.44	0.83	0.89	1.44	0.88	0.95
90	.89	1.59	.93	1.01	1.36	.87	.94	1.24	.94	.99
	6 Plies of 112-114 Fabric on Each Face									
0	.94	1.25	.62	.93	1.29	.65	.97	1.29	.70	1.00
90	.94	1.42	.73	1.11	1.18	.66	.96	1.18	.78	1.04
	11 Plies of 112-114 Fabric on Each Face									
0	.93	1.08	.46	.91	1.05	.45	.89	1.04	.48	.89
90	.94	1.57	.69	1.37	1.17	.56	1.04	1.14	.65	1.06

Table 19.--Ratios of computed shear properties to properties obtained from test

Construction	Ratios			
	Modulus of rigidity	Stress at --		
		Proportional limit	0.2 percent offset	Ultimate
1 ply of 112-114 fabric on each face	1.02	0.99	0.97	1.14
6 plies of 112-114 fabric on each face	1.05	1.01	1.03	1.10
11 plies of 112-114 fabric on each face	1.18	.84	.95	1.12

Table 20.--Ratios of computed tensile properties, at 45° to warp, to properties obtained in test

Construction	Modulus of elasticity		Stress at			
			Proportional limit		Ultimate	
	Method 1	Method 2	Method 1	Method 2	Method 1	Method 2
1 ply of 112-114 fabric on each face	0.99	0.94	1.74	1.34	1.11	1.03
6 plies of 112-114 fabric on each face	1.06	1.03	1.67	1.36	1.15	1.03
11 plies of 112-114 fabric on each face	.89	.92	2.13	1.49	1.19	1.08

Table 21.--Physical properties of 162-114 glass fabric from two different manufacturers[1]

Properties	Samples from - Manufacturer A	Manufacturer B
Breaking strength (pounds per inch) (Grab method)		
Warp	459	398
Fill	277	253.4
Elongation (percent)		
Warp	8.0	7.3
Fill	4.0	4.5
Breaking strength of thread (pounds)		
Warp	17.0	17.5
Fill	18.1	15.9
Elongation of thread (percent)		
Warp	1.7	1.87
Fill	1.7	1.49
Thread count per inch		
Warp	28.5	28.5
Fill	16.5	16.5
Yarn ply		
Warp	5	5
Fill	5	5
Weave	(2)	(2)
Twist per inch (yarn)		
Warp	4.5	4.6
Fill	4.1	4.2

[1] Properties based on tests at the Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

[2] Plain, 1 up and 1 down.