Appendixes

A.1 WOVEN FABRIC TERMINOLOGY

Basic woven fabrics consist of two sets of yarns interlaced at right angles to create a single layer. Such biaxial or 0/90 fabrics are characterized by the following nomenclature:

1. *Yarn construction*: May include the strand count as well as the number of strands twisted and plied together to make up the yarn. In case of glass fibers, the strand count is given by the yield expressed in yards per pound or in TEX, which is the mass in grams per 1000 m. For example, if the yarn is designated as 150 2/3, its yield is 150 $\times$ 100 or 15,000 yd/lb. The 2/ after 150 indicates that the strands are first twisted in groups of two, and the /3 indicates that three of these groups are plied together to make up the final yarn. The yarns for carbon-fiber fabrics are called tows. They have little or no twist and are designated by the number of filaments in thousands in the tow. Denier (abbreviated as de) is used for designating Kevlar yarns, where 1 denier is equivalent to 1 g/9000 m of yarn.
2. *Count*: Number of yarns (ends) per unit width in the warp (lengthwise) and fill (crosswise) directions (Figure A.1.1). For example, a fabric count of 60 $\times$ 52 means 60 ends per inch in the warp direction and 52 ends per inch in the fill direction.
3. *Weight*: Areal weight of the fabric in ounces per square yard or grams per square meter.
4. *Thickness*: Measured in thousandths of an inch (mil) or in millimeters.
5. *Weave style*: Specifies the repetitive manner in which the warp and fill yarns are interlaced in the fabric. Common weave styles are shown in Figure A.1.2.
   (a) Plain weave, in which warp and fill yarns are interlaced over and under each other in an alternating fashion.
   (b) Basket weave, in which a group of two or more warp yarns are interlaced with a group of two or more fill yarns in an alternating fashion.
   (c) Satin weave, in which each warp yarn weaves over several fill yarns and under one fill yarn. Common satin weaves are crowfoot satin or four-harness satin, in which each warp yarn weaves over three and under one fill yarn, five-harness satin (over four, under one), and eight-harness satin (over seven, under one).

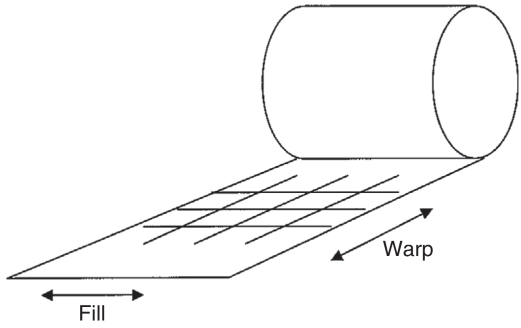

FIGURE A.1.1 Warp and fill directions of fabrics.

Plain weave fabrics are very popular in wet layup applications due to their fast wet-out and ease of handling. They also provide the least yarn slippage for a given yarn count. Satin weave fabrics are more pliable than plain weave fabrics and conform more easily to contoured mold surfaces.

In addition to the biaxial weave described earlier, triaxial (0/60/−60 or 0/45/90) and quadraxial (0/45/90/−45) fabrics are also commercially available. In these fabrics, the yarns at different angles are held in place by tying them with stitch yarns.

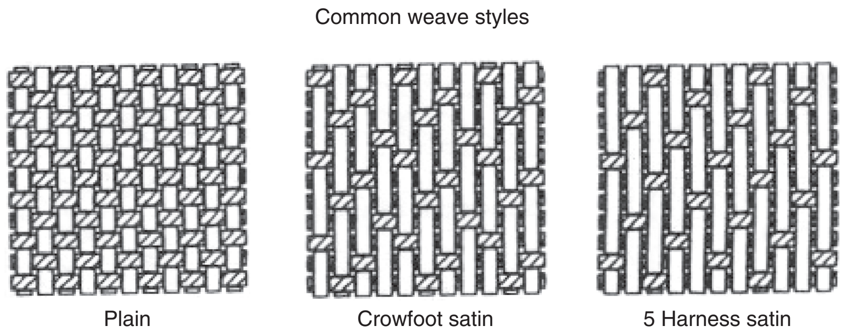

FIGURE A.1.2 Common weave styles. (Courtesy of Hexcel Corporation. With permission.)

A.2 RESIDUAL STRESSES IN FIBERS AND MATRIX IN A LAMINA DUE TO COOLING [1]

The following equations, derived on the basis of a composite cylinder model (Figure A.2.1), can be used to calculate the residual stresses in fibers and matrix in a unidirectional composite lamina developed due to differential thermal shrinkage as it cools down from the high processing temperature to the ambient temperature:

$$\sigma_{r\mathrm{m}} = A_1\left(1 - \frac{r_\mathrm{m}^2}{r^2}\right),$$

$$\sigma_{\theta\mathrm{m}} = A_1\left(1 + \frac{r_\mathrm{m}^2}{r^2}\right),$$

$$\sigma_{z\mathrm{m}} = A_2,$$

$$\sigma_{r\mathrm{f}} = \sigma_{\theta\mathrm{f}} = A_1\left(1 - \frac{r_\mathrm{m}^2}{r_\mathrm{f}^2}\right),$$

$$\sigma_{z\mathrm{f}} = A_2\left(1 - \frac{r_\mathrm{m}^2}{r_\mathrm{f}^2}\right),$$

where

r = radial distance from the center of the fiber

r_f = fiber radius

r_m = matrix radius in the composite cylinder model, which is equal to $(r_\mathrm{f}/\mathrm{v}_\mathrm{f}^{\frac{1}{2}})$

m,f = subscripts for matrix and fiber, respectively

r,θ,z = subscripts for radial, tangential (hoop), and longitudinal directions, respectively.

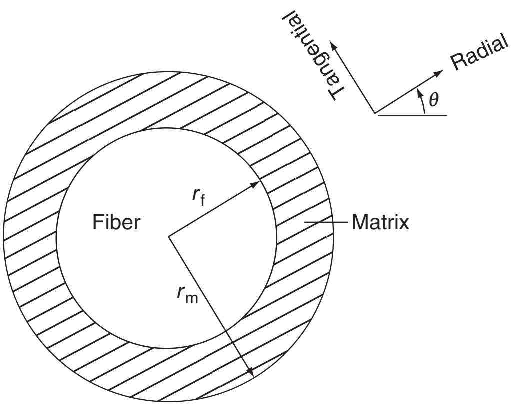

FIGURE A.2.1 Cross section of a composite cylinder model.

The constants A_1 and A_2 are given by the following expressions:

$$A_1 = \left[\frac{(\alpha_m - \alpha_{f1})\Delta_{22} - (\alpha_m - \alpha_{fr})\Delta_{12}}{\Delta_{11}\Delta_{22} - \Delta_{21}\Delta_{12}}\right]\Delta T$$
$$A_2 = \left[\frac{(\alpha_m - \alpha_{fr})\Delta_{11} - (\alpha_m - \alpha_{f1})\Delta_{21}}{\Delta_{11}\Delta_{22} - \Delta_{21}\Delta_{12}}\right]\Delta T$$

where

$$\Delta_{11} = 2\left(\frac{\nu_m}{E_m} + \frac{\nu_{f1}}{E_{fl}}\frac{v_m}{v_f}\right)$$
$$\Delta_{12} = -\left(\frac{v_m}{E_{fl}v_f} + \frac{1}{E_m}\right)$$
$$\Delta_{21} = -\left[\frac{(1-\nu_{fr})v_m}{E_{fr}v_f} + \frac{(1-\nu_m)}{E_m} + \frac{(1+\nu_m)}{E_m v_f}\right]$$
$$\Delta_{22} = \frac{1}{2}\Delta_{11}$$

ΔT = temperature change, which is negative for cooling
E = modulus
ν = Poisson's ratio
α = coefficient of linear thermal expansion
v = volume fraction
fl, fr, m = subscripts indicating fiber (longitudinal and radial) and matrix, respectively

Figure A.2.2 shows the variation of residual stresses for a carbon fiber–epoxy lamina with $v_f = 0.5$. The largest stress in the matrix is the longitudinal stress,

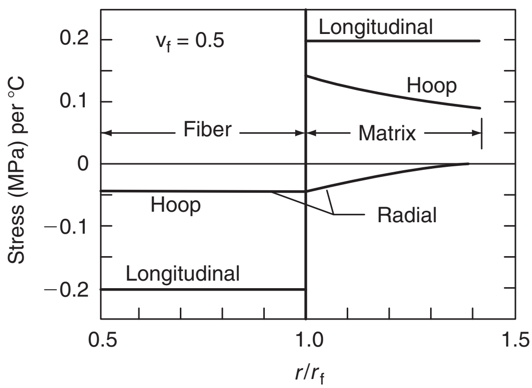

FIGURE A.2.2 Thermal stresses in the fiber and the matrix as a function of radial distance in a 50 vol% AS carbon fiber-reinforced epoxy matrix. (Adapted from Nairn, J.A., *Polym. Compos.*, 6, 123, 1985.)

which is tensile. If it is assumed that the lamina is cured from 177°C to 25°C, the magnitude of this stress will be 29.3 MPa, which is ~25% of the ultimate strength of the matrix. The hoop stress in the matrix is also tensile, while the radial stress is compressive.

REFERENCE

1. J.A. Nairn, Thermoelastic analysis of residual stresses in unidirectional high-performance composites, *Polym. Compos., 6*:123 (1985).

A.3 ALTERNATIVE EQUATIONS FOR THE ELASTIC AND THERMAL PROPERTIES OF A LAMINA

Property	Chamis [1]	Tsai–Hahn [2]
E_{11}	Same as Equation 3.36	Same as Equation 3.36
E_{22}	$\dfrac{E_f E_m}{E_f - \sqrt{v_f}(E_f - E_m)}$	$\dfrac{(v_f + \eta_{22} v_m) E_f E_m}{(E_m v_f + \eta_{22} v_m E_f)}$
G_{12}	$\dfrac{G_f G_m}{G_f - \sqrt{v_f}(G_f - G_m)}$	$\dfrac{(v_f + \eta_{12} v_m) G_f G_m}{(G_m v_f + \eta_{12} v_m G_f)}$
ν_{12}	Same as Equation 3.37	Same as Equation 3.37
α_{11}	Same as Equation 3.58	
α_{22}	$\alpha_{fT}\sqrt{v_f} + (1 - \sqrt{v_f})\left(1 + v_f \nu_m \dfrac{E_f}{E_{11}}\right)\alpha_m$	
K_{11}^*	$K_f v_f + K_m(1 - v_f)$	
K_{22}	$(1 - \sqrt{v_f})K_m + \dfrac{\sqrt{v_f} K_f K_m}{K_f - \sqrt{v_f}(K_f - K_m)}$	

Note: In Tsai–Hahn equations for E_{22} and G_{12}, η_{22} and η_{12} are called stress-partitioning parameters. They can be determined by fitting these equations to respective experimental data. Typical values of η_{22} and η_{12} for epoxy matrix composites are:

	Fiber Type		
	Carbon	**Glass**	**Kevlar-49**
η_{22}	0.5	0.516	0.516
η_{12}	0.4	0.316	0.4

* Thermal conductivity.

REFERENCES

1. C.C. Chamis, Simplified composite micromechanics equations for hygral, thermal and mechanical properties, *SAMPE Quarterly, 15*:14 (1984).
2. S.M. Tsai and H.T. Hahn, *Introduction to Composite Materials*, Technomic Publishing Co., Lancaster, PA (1980).

A.4 HALPIN–TSAI EQUATIONS

The Halpin–Tsai equations are simple approximate forms of the generalized self-consistent micromechanics solutions developed by Hill. The modulus values based on these equations agree reasonably well with the experimental values for a variety of reinforcement geometries, including fibers, flakes, and ribbons. A review of their developments is given in Ref. [1].

In the general form, the Halpin–Tsai equations for oriented reinforcements are expressed as

$$\frac{p}{p_{\mathrm{m}}} = \frac{1 + \zeta\eta \mathrm{v_r}}{1 - \eta \mathrm{v_r}}$$

with

$$\eta = \frac{(p_{\mathrm{r}}/p_{\mathrm{m}}) - 1}{(p_{\mathrm{r}}/p_{\mathrm{m}}) + \zeta}$$

where

p = composite property, such as E_{11}, E_{22}, G_{12}, G_{23}, and ν_{23}
p_{r} = reinforcement property, such as E_{r}, G_{r}, and ν_{r}
p_{m} = matrix property, such as E_{m}, G_{m}, and ν_{m}
ζ = a measure of reinforcement geometry, packing geometry, and loading conditions
$\mathrm{v_r}$ = reinforcement volume fraction

Reliable estimates for the ζ factor are obtained by comparing the Halpin–Tsai equations with the numerical solutions of the micromechanics equations [2–4]. For example,

$$\zeta = 2\frac{l}{t} + 40\mathrm{v_r^{10}} \quad \text{for } E_{11},$$

$$\zeta = 2\frac{w}{t} + 40\mathrm{v_r^{10}} \quad \text{for } E_{22},$$

$$\zeta = \left(\frac{w}{t}\right)^{1.732} + 40\mathrm{v_r^{10}} \quad \text{for } G_{12},$$

where l, w, and t are the reinforcement length, width, and thickness, respectively. For a circular fiber, $l = l_{\mathrm{f}}$ and $t = w = d_{\mathrm{f}}$, and for a spherical reinforcement, $l = t = w$. The term containing $\mathrm{v_r}$ in the expressions for ζ is relatively small up to $\mathrm{v_r} = 0.7$ and therefore can be neglected. Note that for oriented continuous fiber-reinforced composites, $\zeta \to \infty$, and substitution of η into the Halpin–Tsai equation for E_{11} gives the same result as obtained by the rule of mixture.

Nielsen [5] proposed the following modification for the Halpin–Tsai equation to include the maximum packing fraction, $\mathrm{v_r^*}$:

$$\frac{p}{p_m} = \frac{1 + \zeta\eta v_r}{1 - \eta\Phi v_r},$$

where $\Phi = 1 + \left(\frac{1 - v_r^*}{v_r^{*2}}\right) v_r$.

Note that the maximum packing fraction, v_r^*, depends on the reinforcement type as well as the arrangement of reinforcements in the composite. In the case of fibrous reinforcements,

1. $v_r^* = 0.785$ if they are arranged in the square array
2. $v_r^* = 0.9065$ if they are arranged in a hexagonal array
3. $v_r^* = 0.82$ if they are arranged in random close packing

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1. J.C. Halpin and J.L. Kardos, The Halpin–Tsai equations: a review, *Polym. Eng. Sci., 16*:344 (1976).
2. J.C. Halpin and S.W. Tsai, Environmental factors in composite materials design, U.S. Air Force Materials Laboratory Report, AFML-TR 67-423, June (1969).
3. J.C. Halpin and R.L. Thomas, Ribbon reinforcement of composites, *J. Compos. Mater., 2*:488 (1968).
4. J.C. Halpin, *Primer on Composite Materials*: *Analysis*, Chapter 6, Technomic Publishing Co., Lancaster, PA (1984).
5. L.E. Nielsen, *Mechanical Properties of Polymers and Composites*, Vol. 2, Marcel Dekker, New York (1974).

A.5 TYPICAL MECHANICAL PROPERTIES OF UNIDIRECTIONAL CONTINUOUS FIBER COMPOSITES

Property	Boron–Epoxy	AS Carbon–Epoxy	T-300–Epoxy	HMS Carbon–Epoxy	GY-70–Epoxy	Kevlar 49–Epoxy	E-Glass–Epoxy	S-Glass–Epoxy
Density, g/cm^3	1.99	1.54	1.55	1.63	1.69	1.38	1.80	1.82
Tensile properties								
Strength, MPa (ksi) 0°	1585 (230)	1447.5 (210)	1447.5 (210)	827 (120)	586 (85)	1379 (200)	1103 (160)	1214 (176)
90°	62.7 (9.1)	62.0 (9)	44.8 (6.5)	86.2 (12.5)	41.3 (6.0)	28.3 (4.1)	96.5 (14)	—
Modulus GPa (Msi) 0°	207 (30)	127.5 (18.5)	138 (20)	207 (30)	276 (40)	76 (11)	39 (5.7)	43 (6.3)
90°	19 (2.7)	9 (1.3)	10 (1.5)	13.8 (2.0)	8.3 (1.2)	5.5 (0.8)	4.8 (0.7)	—
Major Poisson's ratio	0.21	0.25	0.21	0.20	0.25	0.34	0.30	—
Compressive properties								
Strength, MPa (ksi), 0°	2481.5 (360)	1172 (170)	1447.5 (210)	620 (90)	517 (75)	276 (40)	620 (90)	758 (110)
Modulus, GPa (Msi), 0°	221 (32)	110 (16)	138 (20)	171 (25)	262 (38)	76 (11)	32 (4.6)	41 (6)
Flexural properties								
Strength, MPa (ksi), 0°	—	1551 (225)	1792 (260)	1034 (150)	930 (135)	621 (90)	1137 (165)	1172 (170)
Modulus, GPa (Msi), 0°	—	117 (17)	138 (20)	193 (28)	262 (38)	76 (11)	36.5 (5.3)	41.4 (6)
In-plane shear properties								
Strength, MPa (ksi)	131 (19)	60 (8.7)	62 (9)	72 (10.4)	96.5 (14)	60 (8.7)	83 (12)	83 (12)
Modulus, GPa (Msi)	6.4 (0.93)	5.7 (0.83)	6.5 (0.95)	5.9 (0.85)	4.1 (0.60)	2.1 (0.30)	4.8 (0.70)	—
Interlaminar shear strength, MPa (ksi) 0°	110 (16)	96.5 (14)	96.5 (14)	72 (10.5)	52 (7.5)	48 (7)	69 (10)	72 (10.5)

Source: From Chamis, C.C., *Hybrid and Metal Matrix Composites*, American Institute of Aeronautics and Astronautics, New York, 1977. With permission.

A.6 PROPERTIES OF VARIOUS SMC COMPOSITES

Property	SMC-R25	SMC-R50	SMC-R65	SMC-C20R30	XMC-3
Density, g/cm^3	1.83	1.87	1.82	1.81	1.97
Tensile strength, MPa (ksi)	82.4 (12)	164 (23.8)	227 (32.9)	289 (L) (41.9) 84 (T) (12.2)	561 (L) (81.4) 69.9 (T) (10.1)
Tensile modulus, GPa (Msi)	13.2 (1.9)	15.8 (2.3)	14.8 (2.15)	21.4 (L) (3.1) 12.4 (T) (1.8)	35.7 (L) (5.2) 12.4 (T) (1.8)
Strain-to-failure (%)	1.34	1.73	1.67	1.73 (L) 1.58 (L)	1.66 (T) 1.54 (T)
Poisson's ratio	0.25	0.31	0.26	0.30 (LT) 0.18 (TL)	0.31 (LT) 0.12 (TL)
Compressive strength, MPa (ksi)	183 (26.5)	225 (32.6)	241 (35)	306 (L) (44.4) 166 (T) (24.1)	480 (LT) (69.6) 160 (T) (23.2)
Shear strength, MPa (ksi)	79 (11.5)	62 (9.0)	128 (18.6)	85.4 (12.4)	91.2 (13.2)
Shear modulus, GPa (Msi)	4.48 (0.65)	5.94 (0.86)	5.38 (0.78)	4.09 (0.59)	4.47 (0.65)
Flexural strength, MPa (ksi)	220 (31.9)	314 (45.6)	403 (58.5)	645 (L) (93.6) 165 (T) (23.9)	973 (L) (141.1) 139 (T) (20.2)
Flexural modulus, GPa (Msi)	14.8 (2.15)	14 (2.03)	15.7 (2.28)	25.7 (L) (3.73) 5.9 (T) (0.86)	34.1 (L) (4.95) 6.8 (T) (1.0)
ILSS, MPa (ksi)	30 (4.3)	25 (3.63)	45 (6.53)	41 (5.95)	55 (7.98)
Coefficient of thermal expansion, $10^{-6}/°C$	23.2	14.8	13.7	11.3 (L) 24.6 (T)	8.7 (L) 28.7 (T)

Source: From Riegner, D.A. and Sanders, B.A., A characterization study of automotive continuous and random glass fiber composites, *Proceedings of the National Technical Conference*, Society of Plastics Engineers, 1979. With permission.

Note: All SMC composites in this table contain E-glass fibers in a thermosetting polyester resin. XMC-3 contains 50% by weight of continuous strands at ±7.5° to the longitudinal direction and 25% by weight of 25.4 mm (1 in.) long-chopped strands.

A.7 FINITE WIDTH CORRECTION FACTOR FOR ISOTROPIC PLATES

The hole stress concentration factor for an infinitely wide ($w \gg 2R$) isotropic plate is 3. If the plate has a finite width, the hole stress concentration factor (based on gross area) will increase with increasing hole radius. For $w > 8R$, the following equation is used to calculate the hole stress concentration factor of an isotropic plate.

$$\frac{K_{\mathrm{T}}(w)}{K_{\mathrm{T}}(\infty)} = \frac{2 + \left[1 - \left(\frac{2R}{w}\right)\right]^3}{3\left[1 - \left(\frac{2R}{w}\right)\right]},$$

where

$K_{\mathrm{T}}(w)$ = stress concentration factor of a plate of width w
$K_{\mathrm{T}}(\infty)$ = stress concentration factor of an infinitely wide plate
R = hole radius

A.8 DETERMINATION OF DESIGN ALLOWABLES

The statistical analysis for the determination of design allowables depends on the type of distribution used in fitting the experimental data.

A.8.1 Normal Distribution

If the experimental data are represented by a normal distribution, the A-basis and B-basis design allowables are calculated from the following equations:

$$\sigma_A = \bar{\sigma} - K_A s$$
$$\sigma_B = \bar{\sigma} - K_B s,$$

where

σ_A = A-basis design allowable
σ_B = B-basis design allowable
$\bar{\sigma}$ = mean strength
s = standard deviation
K_A = one-sided tolerance limit factor corresponding to a proportion at least 0.99 of a normal distribution and a confidence coefficient of 0.95
K_B = one-sided tolerance limit factor corresponding to a proportion at least 0.90 of a normal distribution and a confidence coefficient of 0.95

It should be noted that, for a given sample size, K_A is greater than K_B and both K_A and K_B decrease with increasing sample size. Tables of K_A and K_B are given in Ref. [1].

A.8.2 Weibull Distribution

If the experimental data are represented by a two-parameter Weibull distribution, the A-basis and B-basis design allowables are calculated from the following equation:

$$\sigma_{A,B} = \hat{\sigma}_0 \left[-2n \frac{\ln R}{\chi^2_{(2n,\gamma)}} \right]^{1/\alpha},$$

where

n = sample size
α = Weibull shape parameter
R = 0.99 for the A-basis design allowable and 0.90 for the B-basis design allowable
${\chi_{(2n,\gamma)}}^2$ = value from the χ^2 distribution table corresponding to $2n$ and a confidence limit of 0.95

$$\hat{\sigma}_0 = \left(\frac{1}{n} \sum_{i=1}^{n} \sigma_i^{\alpha} \right)^{1/\alpha}$$

REFERENCE

1. Metallic Materials and Elements for Aerospace Vehicles Structures, MIL-HDBK-5C, U.S. Department of Defense, Washington, D.C., September (1976).

A.9 TYPICAL MECHANICAL PROPERTIES OF METAL MATRIX COMPOSITES

Material	Tensile Strength, MPa (ksi)	Tensile Modulus, GPa (Msi)
6061-T6 aluminum alloy	306 (44.4)	70 (10)
T-300 carbon-6061 A1 alloy ($v_f = 35\%–40\%$)	1034–1276 (L) (150–185)	110–138 (L) (15.9–20)
Boron-6061 A1 alloy ($v_f = 60\%$)	1490 (L) (216)	214 (L) (31)
	138 (T) (20)	138 (T) (20)
Particulate SiC-6061-T6 A1 alloy ($v_f = 20\%$)	552 (80)	119.3 (17.3)
GY-70 Carbon-201 A1 alloy ($v_f = 37.5\%$)	793 (L) (115)	207 (L) (30)
Al_2O_3-A1 alloy ($v_f = 60\%$)	690 (L) (100)	262 (L) (38)
	172–207 (T) (25–30)	152 (T) (22)
Ti-6A1-4V titanium alloy	890 (129)	120 (17.4)
SiC-Ti alloy ($v_f = 35\%–40\%$)	820 (L) (119)	225 (L) (32.6)
	380 (T) (55)	—
SCS-6-Ti alloy ($v_f = 35\%–40\%$)[a]	1455 (L) (211)	240 (L) (34.8)
	340 (T) (49)	

[a] SCS-6 is a coated SiC fiber.

A.10 USEFUL REFERENCES

A.10.1 Text and Reference Books

1. R.M. Jones, *Mechanics of Composite Materials*, 2nd Ed., Taylor & Francis, Philadelphia, PA (1999).
2. C.T. Herakovich, *Mechanics of Fibrous Composites*, John Wiley & Sons, New York, NY (1998).
3. M.W. Hyer, *Stress Analysis of Fiber-Reinforced Composite Materials*, McGraw-Hill, New York, NY (1998).
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5. B.D. Agarwal, L.J. Broutman, and K. Chandrasekharan, *Analysis and Performance of Fiber Composites*, 3rd Ed., John Wiley & Sons, New York, NY (2006).
6. I.M. Daniel and O. Ishai, *Engineering Mechanics of Composite Materials*, 2nd Ed., Oxford University Press, London (2005).
7. A.K. Kaw, *Mechanics of Composite Materials*, 2nd Ed., CRC Press, Boca Raton, FL (2006).
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9. J.C. Halpin, *Primer on Composite Materials: Analysis*, Technomic Publishing Co., Lancaster, PA (1984).
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11. M.R. Piggott, *Load Bearing Fibre Composites*, 2nd Ed., Kluwer Academic Press, Dordrecht (2002).
12. K.H.G. Ashbee, *Fundamental Principles of Fiber Reinforced Composites*, Technomic Publishing Co., Lancaster, PA (1989).
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16. J.R. Vinson and R.L. Sierakowski, *The Behavior of Structures Composed of Composite Materials*, 2nd Ed., Kluwer Academic Publishers, Dordrecht (2002).
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20. S.G. Advani and E.M. Suzer, *Process Modeling in Composites Manufacturing*, Marcel Dekker, New York (2003).
21. G. Lubin (ed.), *Handbook of Composites*, Van Nostrand-Reinhold Co., New York (1982).
22. P.K. Mallick (ed.), *Composites Engineering Handbook*, Marcel Dekker, New York (1997).

A.10.2 Leading Journals on Composite Materials

1. *Journal of Composite Materials*, Sage Publications (www.sagepub.com)
2. *Journal of Reinforced Plastics and Composites*, Sage Publications (www.sagepub.com)
3. *Journal of Thermoplastic Composites*, Sage Publications (www.sagepub.com)
4. *Composites Part A: Applied Science and Manufacturing,* Elsevier (www.elsevier.com)
5. *Composites Part B: Engineering*, Elsevier (www.elsevier.com)
6. *Composites Science and Technology*, Elsevier (www.elsevier.com)
7. *Composite Structures*, Elsevier (www.elsevier.com)
8. *Polymer Composites*, Wiley Interscience (www.interscience.com)
9. *SAMPE Journal*, Society for the Advancement of Material and Process Engineering, Covina, CA

A.10.3 Professional Societies Associated with Conferences and Publications on Composite Materials

1. American Society for Composites (ASC) (www.asc-composites.org)
2. Society for the Advancement of Material and Process Engineering (SAMPE) (www.sampe.org)
3. Society of Plastics Engineers (SPE) (www.4spe.org)
4. American Society for Testing and Materials (ASTM International) (www.astm.org)
5. American Society for Aeronautics and Astronautics (AIAA) (www.aiaa.org)

A.11 LIST OF SELECTED COMPUTER PROGRAMS

Program Name	Program Description	Source
LAMINATOR	Analyzes laminated plates according to classical laminated plate theory. Calculates apparent laminate material properties, ply stiffness and compliance matrices, laminate "ABD" matrices, laminate loads and midplane strains, ply stresses and strains in global and material axes, and load factors for ply failure based on maximum stress, maximum strain, Tsai–Hill, Hoffman, and Tsai–Wu failure theories	1
ESAComp 3.4	Analysis capabilities include fiber–matrix micromechanics, classical laminate theory-based constitutive and thermal analysis of solid and sandwich laminates, first ply failure and laminate failure prediction, notched laminate analysis, probabilistic analysis, load response and failure of plates, stiffened panels, beams and columns, bonded and mechanical joint analysis in laminates. Has import–export interfaces to common finite element packages	2
SYSPLY	Capable of doing stress analysis, buckling analysis, thermomechanical analysis, large displacement and contact analysis of shell structures, and dynamic analysis of composite structures	3
LUSAS Composite	A finite element software capable of performing linear and nonlinear analysis, impact and contact analysis, and dynamic analysis of composite structures	4
GENOA	An integrated stand-alone structural analysis–design software, which uses micro- and macromechanics analysis of composite structures, finite element analysis, and damage evaluation methods. Capable of performing progressive fracture analysis under static, fatigue (including random fatigue), creep, and impact loads	5
MSC-NASTRAN	General purpose finite element analysis package; also performs static, dynamic, and buckling analysis of laminated composite structures; in addition to the in-plane stresses, computes the interlaminar-shear stresses between various laminas	6
ABAQUS	General purpose finite element package with capability of performing both linear and nonlinear analysis	7
LS-DYNA	General purpose finite element package with the capability of performing nonlinear analysis	8
ANSYS	General purpose finite element package with the capability of performing both linear and nonlinear analysis	9

Source:
1. www.thelaminator.net
2. www.componeering.com
3. www.esi-group.com
4. www.lusas.com
5. www.alphastarcorp.com
6. www.mscnastran.com
7. www.simulia.com
8. www.lsdyna.com
9. www.ansys.com