Chapter 14
Designing with Composites

Understanding how to design with composites, especially fiber reinforced composites, is very important because composite materials do not represent just another new class of materials. Although there have been, over the years, ongoing efforts by researchers to improve the properties of different materials such as new alloys, composite materials, especially fiber reinforced composites, represent a rather radical departure. Schier and Juergens (1983) analyzed the design impact of composites on fighter aircraft. The authors echoed the sentiments of many researchers and engineers in making the following statement: "Composites have introduced an extraordinary fluidity to design engineering, in effect forcing the designer-analyst to create a different material for each application. . ..." A single component made of a laminated composite can have areas of distinctively different mechanical properties. For example, the wing-skin of an F/A-18 airplane is made up of 134 plies. Each ply has a specific fiber orientation and geometric shape. Computer graphics allow us to define each ply "in place" as well as its relationship to other plies. The reader can easily appreciate that storage and transmission of such engineering data via computer makes for easy communication between design engineers and manufacturing engineers. In this chapter, we discuss some of the salient points in regard to this important subject of designing with composites.

14.1 General Philosophy

We will make a few general philosophical points about designing with composites before going into the specifics. First of all, the whole idea behind the composite materials is that, in principle, one can tailor-make a material for any desired function. Thus, one should start with a function, not a material. A suitable composite material, say to meet some mechanical and/or thermal loading conditions, can then be made. An important corollary that follows is that one must exploit the anisotropy

K.K. Chawla, *Composite Materials: Science and Engineering*,
DOI 10.1007/978-0-387-74365-3_14,

that is invariably present in fiber reinforced composites. Before discussing some specific design procedures, we review some of the advantages and fundamental characteristics of fiber reinforced composites that make them so different from conventional monolithic materials.

14.2 Advantages of Composites in Structural Design

The main advantages of using composites in structural design are as follows.

14.2.1 Flexibility

- Ply lay-up allows for variations in the local detail design.
- Ply orientation can be varied to carry combinations of axial and shear loads.

14.2.2 Simplicity

- Large one-piece structures can be made with attendant reductions in the number of components.
- Selective reinforcement can be used.

14.2.3 Efficiency

- High specific properties, i.e., properties on a per-unit-weight basis.
- Savings in materials and energy.

14.2.4 Longevity

- Generally, properly designed composites show better fatigue and creep behavior than their monolithic counterparts.

14.3 Some Fundamental Characteristics of Fiber Reinforced Composites

Composite materials come with some fundamental characteristics that are quite different from conventional materials. This is especially true of fiber reinforced composites. Among these important characteristics are the following:

- *Heterogeneity*. Composite materials, by definition, are heterogeneous. There is a large area of interface and the in situ properties of the components are different from those determined in isolation.
- *Anisotropy*. Composites in general, and fiber reinforced composites in particular, are anisotropic. For example, as we saw in Chap. 10, the modulus and strength are very sensitive functions of fiber orientation.
- *Coupling Phenomena*. Coupling between different loading modes, such as tension-shear, is not observed in conventional isotropic materials. We saw in Chap. 11 that in fiber reinforced composites such coupling phenomena can be very important. These coupling phenomena make designing with composites more complex, as we shall see in Sect. 14.4.
- *Fracture Behavior*. Monolithic, conventional isotropic materials show what is called a *self similar crack propagation*. This means that the damage mode involves the propagation of a single dominant crack; one can then measure the damage in terms of the crack length. In composites, one has a multiplicity of fracture modes. A fiber reinforced composite, especially in the laminated form, can sustain a variety of subcritical damage (cracking of matrix, fiber/matrix decohesion, fiber fracture, ply cracking, delamination). For example, in a [0/90] laminate, the 90° ply is likely to be weaker than the 0° ply, it will crack first. Such cracking of a ply, will result in a relaxation of stress in that ply, and with continued loading no further cracking occurs in that ply. Ply cracking could involve cracking in the matrix or along the fiber/matrix interface. Other damage accumulating mechanisms include the growth of existing cracks into interfaces leading to ply delamination.

14.4 Design Procedures with Composites

It is worth reemphasizing that composite materials, particularly fiber reinforced composite materials, are not just another kind of new material. When designing with composites, one must take into account their special characteristics delineated in the preceding section. First, composite materials are inherently heterogeneous at a microstructural level, consisting as they do of two components that have different elastic moduli, different strengths, different thermal expansion coefficients, and so on. We saw in the micromechanical analysis (Chap. 10) that the structural and physical properties of composites are functions of (a) component characteristics,

(b) geometric arrangement of one component in the other, and (c) interface characteristics. Even after selecting the two basic components, one can obtain a range of properties by manipulating the items (b) and (c). Second, the conventional monolithic materials are generally quite isotropic; that is, their properties do not show any marked preference for any particular direction, whereas fiber reinforced composites are highly anisotropic because of their fibrous nature. The analysis and design of composites should take into account this strong directionality of properties, or, rather, this anisotropy of fiber reinforced composites must be exploited to the fullest advantage by the designer. The reader is referred to some figures in previous chapters: Fig. 11.4 shows the marked influence of fiber orientation on the different elastic moduli of a composite. In a similar manner, Fig. 12.14 shows the acute dependence of the composite strength on fiber orientation. Figure 10.7 shows the marked influence of fiber orientation on the coefficient of thermal expansion of a fiber reinforced composite.

In laminated composites, the ply stacking sequence can affect the properties of a composite. Recall Fig. 5.20b, which showed tensile creep strain at ambient temperature as a function of time for two different stacking sequences (Sturgeon 1978). At a given stress level, the laminate with carbon fibers at $\pm 45°$ showed more creep strain than one containing plies at $0°/90°/\pm 45°$. The reason for this was that in the $\pm 45°$ sequence, the epoxy matrix had creep strain contributions from (a) tension in the loading direction, (b) shear in the $\pm 45°$ directions, and (c) rotation of the plies in a scissor-like action. As we saw in Chap. 11, the $0°$ and $90°$ plies do not contribute to the scissor-like rotation due to the absence of tension-shear coupling in these specially orthotropic laminae. Thus, the addition of $0°$ and $90°$ plies reduced the matrix shear deformation. Thus, for creep resistance, the $0°/90°/\pm 45°$ sequence is to be preferred over the $\pm 45°$ sequence.

For conventional materials, the designer needs only to consult a handbook or manual to obtain one unambiguous value of, say, modulus or any other property. For fiber reinforced composite laminates, however, the designer has to consult what are called *performance charts* or *carpet plots* representing a particular property of a given composite system. Such plots, sometimes also referred to as *parametric plots*, are made for fiber reinforced plies at $0°$, $\pm 45°$, and $90°$. Figure 14.1 shows such plots for Young's modulus and the tensile strength, both in the longitudinal direction, for a 65 % V_f carbon fiber/epoxy composite having a $0°/\pm 45°/90°$ ply sequence (Kliger 1979). A conventional material, say aluminum, would be represented by just one point on such graphs. The important and distinctive point is that, depending on the components, their relative amounts, and the ply stacking sequence, we can obtain a range of properties in fiber reinforced composite laminates. In other words, one can tailor-make a composite material as per the final objective. Figure 14.1 provides a good example of the versatility and flexibility of laminates. Say our material specifications require, for an application, a material with strength in the x direction, $\sigma_x = 500$ MPa and a stiffness in the y direction equal to that of aluminum, $E = 70$ GPa. We can then pick a material combination that gives us a composite with these characteristics. Using Fig. 14.1a, b, we can choose the following ply distribution:

60 % at 0°
20 % at 90°
20 % at ±45°

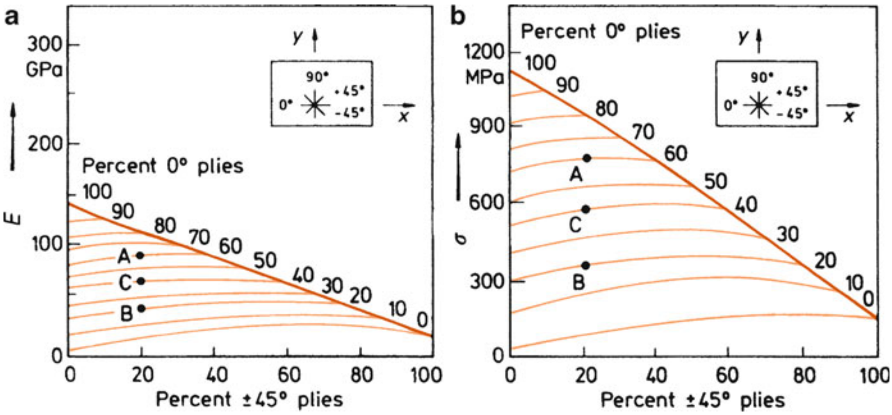

Fig. 14.1 Carpet plots for 65 % V_f carbon/epoxy with a 0°/±45°/90° stacking sequence: (**a**) Young's modulus, (**b**) tensile strength. [From Kliger (1979), used with permission]

Point A has a $\sigma_x = 725$ MPa and an $E_x = 90$ GPa. If we interchange the x and y coordinates and the amounts of the 0° and 90° plies, we get point B, which corresponds to a $\sigma_y = 340$ MPa and an $E_y = 40$ GPa. Thus, σ_x is now higher than required and E_y is too low. We now take some material from 0° and move it to 90°. Consider the following ply distribution:

40 % at 0°
40 % at 90°
20 % at ±45°

This is represented by point C, having $\sigma_x = 580$ MPa and $E_y = 70$ GPa. Reversing the x and y coordinates again gives point C with $\sigma_x = 580$ MPa and $E_y = 70$ GPa. Point C then meets our initial specifications.

Stacking sequences other than [0°/±45°/90°] can also satisfy one's requirements. A [0°/±30°/±60°/90°] arrangement gives quasi-isotropic properties in the plane. Carpet plots, however, work for three-ply combinations and the sequence [0°/±45°/90°] has some other advantages as described later. It should be pointed out that carpet plots for strengths in compression and shear, shear modulus, and thermal expansion coefficients can also be made. It is instructive to compare the expansion behavior of monolithic and fiber reinforced composites. Figure 14.2 compares the thermal expansion coefficients of some metals and composites as a function of fiber orientation (Fujimoto and Noton 1973). It should be recalled that cubic materials are isotropic in thermal properties, even in single crystal form. Noncubic monolithic materials in a polycrystalline form, with randomly distributed grains, will also be practically isotropic in thermal properties. Thus, titanium, steel, and aluminum are each represented by a single point on this figure. Not unexpectedly, fiber reinforced composites such as boron/epoxy and carbon/epoxy show highly anisotropic thermal expansion behavior. Both aramid and carbon fibers have negative expansion coefficients parallel to the fiber axis. One can exploit such anisotropy quite usefully to make components that show well-controlled expansion characteristics. Although aerospace applications of composite materials get much attention, one should appreciate the fact that composites, in one form or another, have been in use in the electrical and electronic industry for quite a long time. These applications range from cables to printed circuit boards. There are many applications of composites in the electronic packaging industry (Seraphim et al. 1986). An interesting example is that of the leadless chip carrier (LCC) that allows electronic designers to pack more electrical connections into less space than is possible with conventional flat packs or dual inline packages, which involve E-glass/epoxy resin laminates. Glass/epoxy laminate, however, is not very suitable for LCC as a substrate because it expands and contracts much more than the alumina chip carrier (the coefficient of expansion, α, of E-glass/epoxy can vary in the range of 14–17 $\times$ 10^{-6} K^{-1}, while that of alumina is ~8 $\times$ 10^{-6} K^{-1}). Aramid fiber (40–50 v/o)/epoxy composite provides the desired matching expansion characteristics with those of the alumina chip carrier. Thus, the thermal fatigue problem associated with the E-glass/epoxy composites and the ceramic chip carrier is avoided. It should be pointed out that, in general, thermal

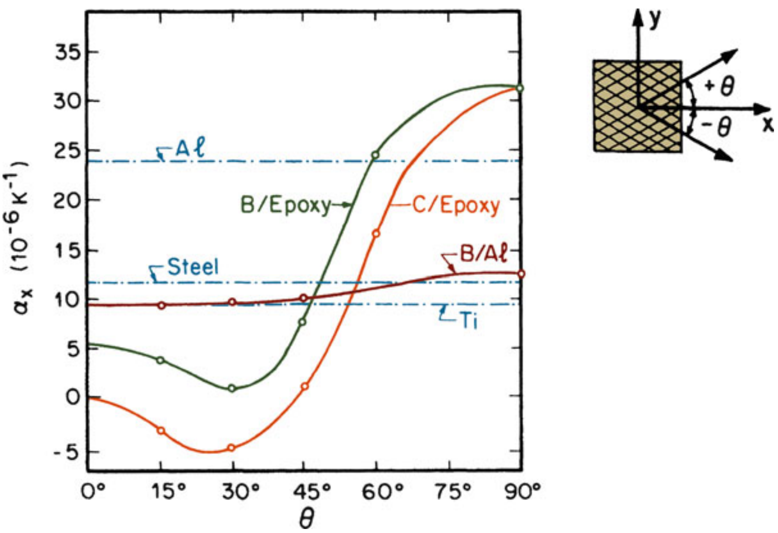

Fig. 14.2 Variation of thermal expansion coefficients with orientation θ. [From Fujimoto and Noton (1973), used with permission]

expansion of particulate composites, assuming an isotropic distribution of particles in the matrix, will be more or less isotropic.

We saw in Chap. 11 that laminated composites show coupling phenomena: tension-shear, tension-bending, and bending-twisting. We also saw in Chap. 11 that certain special ply sequences can simplify the analyses. Thus, using a balanced arrangement (for every $+\theta$ ply, there is a $-\theta$ ply in the laminate), we can eliminate shear coupling. In such an arrangement, the shear distortion of one layer is compensated by an equal and opposite shear distortion of the other layer. Yet another simplifying arrangement consists of stacking the plies in a symmetric manner with respect to the laminate midplane. Such a symmetric laminate gives $[B_{ij}]$ identically zero and thus eliminates stretching-bending and bending-torsion coupling. The phenomenon of edge effects, described in Sect. 11.7, should also be taken into account while arriving at a ply stacking sequence. Because of the edge effects, individual layers of different fiber orientation deform differently under tensile stress giving rise to out-of-plane tensile, compressive, shear and/or bending stresses in the neighborhood of the free edges. An arrangement that gives rise to compressive stresses in the thickness direction in the vicinity of the edges is to be preferred over one that gives rise to tensile stresses. Tensile stresses in the thickness direction near a free edge would tend to cause undesirable delamination in the composite. As an example, we show

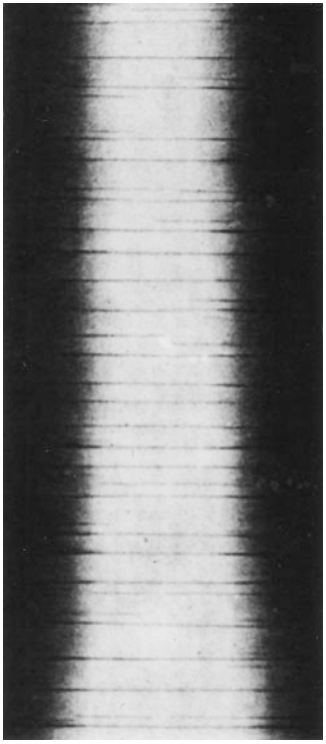

Fig. 14.3 Delaminations, as observed by contrast-enhanced X-ray radiography in a $[0°/\pm45°/90°]_s$ carbon/epoxy laminate upon fatigue testing. [From Bergmann (1985), used with permission]

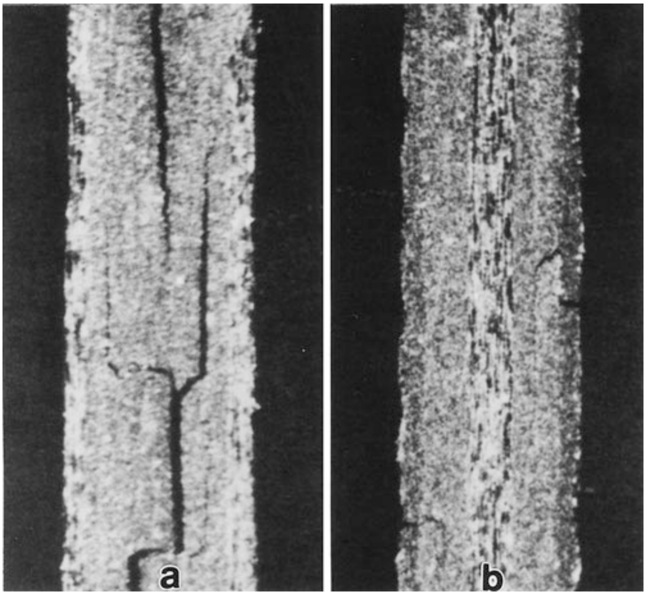

Fig. 14.4 Comparison of crack patterns at the free edges of a carbon/epoxy laminate: (**a**) $[0°/\pm45°/90°]_s$, (**b**) $[90°/\pm45°/0°]_s$. Note the greater severity of edge delaminations in (**a**) than in (**b**). [From Bergmann (1985), used with permission]

in Fig. 14.3 delaminations as observed by contrast enhanced X-ray radiography, in a $[0°/\pm45°/90°]_s$ carbon/epoxy laminate upon fatigue testing (Bergmann 1985). The delaminations proceed from both sides toward the specimen center. Mere stacking choice of the plies can make a big difference. This is shown in Fig. 14.4. The laminate with the sequence $[90°/\pm45°/0°]_s$ showed relatively less damage than the laminate with the sequence $[0°/\pm45°/90°]_s$. Figure 14.4 compares the crack patterns at the free edges of $[0°/\pm45°/90°]_s$ and $[90°/\pm45°/0°]_s$ laminates shortly before failure. Note the greater degree of delaminations in $[0°/\pm45°/90°]_s$ than in $[90°/\pm45°/0°]_s$. The reason for this different behavior of these laminates, identical in all respects except the stacking sequence, is due to the difference in the state of stress near the free edges. Finite element calculations showed (Bergmann 1985) that in the $[0°/\pm45°/90°]_s$ sequence there were large interlaminar tensile stresses in the thickness direction while in the $[90°/\pm45°/0°]_s$ sequence there were mostly compressive interlaminar stresses.

A little reflection will convince the reader that computer simulations involving complex finite element analyses can be used extensively in the design and analyses of laminated fiber composites. In view of the rather tedious matrix calculations involved, this should not be surprising at all. Computer codes can be very cost-effective in the analysis and design of fiber composite structures. Most codes specify, among other things, the interply layers, laminate failure stresses, laminate requirements at critical locations in the composite, etc. Many such codes are available commercially. An example of commercially available computer code is the FiberSIM suite of software tools that converts a CAD (computer-aided design) system into a composite design and manufacturing environment. Among its features are:

- Composite engineering environment: This allows engineers to work in their CAD environment with objects such as plies, cores, and tool surfaces. Forms and menus are used to enter and manage the geometry and other data required to define a composite part.
- Flat pattern/producibility: This module alerts the engineer to manufacturing problems such as wrinkling, bridging, and material width limitations. It also generates net flat patterns for woven and unidirectional complex curvature plies.
- Laminate properties: Exact fiber orientations are obtained for use in generating properties of a laminated composite.

14.5 Hybrid Composite Systems

An extra degree of flexibility in fiber composites can be obtained by making what are called *hybrid composites*, wherein one uses more than one type of fiber; see Fig. 14.5. Cost-performance effectiveness can be increased by judiciously using different reinforcement types and selectively placing them to get the highest strength in highly stressed locations and directions. For example, in a hybrid composite laminate, the cost can be minimized by reducing the carbon fiber content, while the performance is maximized by "optimal placement and orientation of the fiber." Figure 14.6 shows the increases in specific flexural modulus (curve *A*) and specific tensile modulus (curve *B*) with weight % of carbon fiber in a hybrid composite (Riggs 1985). Figure 14.7 shows the changes in flexural fatigue behavior as we go from 100 % unidirectional carbon fibers in polyester (curve *A*) to unidirectional carbon faces over chopped glass core (curve *B*) to 100 % chopped glass in polyester resin (curve *C*) (Riggs 1985); keeping the fiber volume fraction constant.

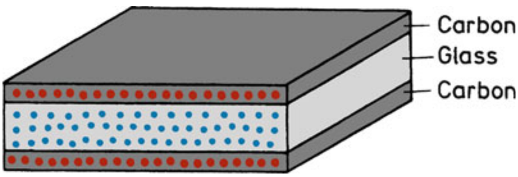

Fig. 14.5 Schematic of a hybrid laminate composite containing carbon and glass fibers

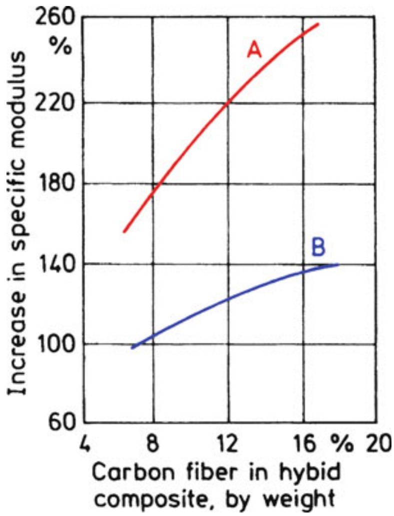

Fig. 14.6 Change in specific flexural modulus and specific tensile modulus with wt.% carbon fibers. [From Riggs (1985), reprinted by permission.] *A* = specific flexural modulus; *B* = specific tensile modulus

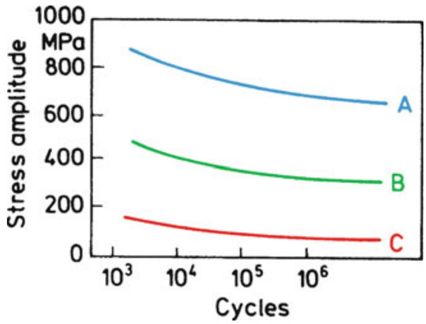

Fig. 14.7 Flexural fatigue behavior of 100 % carbon fiber composite (curve *A*), carbon fiber facings with chopped glass fiber core (curve *B*), and 100 % chopped glass fiber composite (curve *C*). [From Riggs (1985), reprinted by permission]

An extension of this concept is the so-called fiber metal laminates such as GLARE, an acronym for glass fiber/epoxy and aluminum laminates. GLARE consists of alternating layers of aluminum sheets and glass fiber reinforced epoxy composite. Such composites are used in the fuselage of the superjumbo aircraft A380 of Airbus. They show high strength, excellent fatigue, and fracture resistance combined with the advantages of metal construction such as formability, machinability, toughness, and impact resistance. We discuss this in Chap. 15.

References

Bergmann H (1985) Carbon fibres and their composites. Springer, Berlin, p 184
Fujimoto WT, Noton BR (1973) In: Proceedings of the 6th St. Louis symposium on composite material engineering & design. American Society for Metals, Metals Park, OH, p 335
Kliger HS (Dec. 6, 1979) Mach Des 51:150
Riggs JP (1985) Encyclopedia of polymer science & engineering, vol 2, 2nd edn. Wiley, New York, p 640
Schier JF, Juergens RJ (1983) Astronaut Aeronaut 44:44–49
Seraphim DP, Barr DE, Chen WT, Schmitt GP (1986) Advanced thermoset composites. Van Nostrand Reinhold, New York, p 110
Sturgeon JB (1978) In: Creep of engineering materials, a Journal of Strain Analysis Monograph, 175.

Further Reading

Chamis CC (ed) (1974) Structural design and analysis, Parts I and II. Academic, New York
Daniel IM, Ishai O (2005) Engineering mechanics of composite materials, 2nd edn. Oxford University Press, New York
Lubin G (ed) (1982) Handbook of composites. Van Nostrand Reinhold, New York
Swanson SR (1997) Introduction to design and analysis with advanced composite materials. Prentice Hall, Upper Saddle River, NJ

Problems

14.1. Following are the data for a 60 % V_f, unidirectionally reinforced, carbon fiber/epoxy composite:

$$\begin{aligned} \text{Longitudinal tensile strength} &= 1,200\,\text{MPa} \\ \text{Longitudinal compressive strength} &= 1,000\,\text{MPa} \\ \text{Transverse tensile strength} &= 50\,\text{MPa} \\ \text{Transverse compressive strength} &= 250\,\text{MPa} \end{aligned}$$

Calculate F_{11}, F_{22}, F_{66}, F_1, F_2, and F_{12}^*. Take $F_{12}^* = -0.5$. Compute the focal points plot the failure envelope for this composite.

14.2. For a carbon/epoxy composite, the strength parameters are:

$$
\begin{gathered}
F_{11}(\mathrm{GPa})^{-2} = 0.45 \\
F_{22}(\mathrm{GPa})^{-2} = 101 \\
F_{12}(\mathrm{GPa})^{-2} = -3.4 \\
F_{66}(\mathrm{GPa})^{-2} = 215 \\
F_{1}(\mathrm{GPa})^{-1} = 0 \\
F_{2}(\mathrm{GPa})^{-1} = 21.
\end{gathered}
$$

Compute the off axis uniaxial strengths of this composite for different θ and obtain a plot of σ_x vs. θ.