MECHANICAL PROPERTIES OF FIBER REINFORCED COMPOSITES

Dr. Osama Mohammed Elmardi Suleiman Khayal
Department of Mechanical Engineering, Faculty of Engineering and Technology, Nile Valley University, Atbara – Sudan
E – mail address: osamakhayal66@nilevalley.edu.sd

Abstract
This research article introduces basic concepts of stiffness and strength underlying the mechanics of fiber reinforced advanced composite materials. This aspect of composite materials technology is sometimes termed as micromechanics, because it deals with the relations between macroscopic engineering properties and the microscopic distribution of the material constituents, namely the volume fraction of fiber. This research paper will deal primarily with unidirectional reinforced continuous fiber composites, and with properties measured along and transverse to the fiber direction.
Keywords: fiber, reinforced lamina, stiffness, strength, micromechanics, macro mechanics

1. Introduction

Composite materials have many mechanical characteristics, which are different from those of conventional engineering materials such as metals. More precisely, composite materials are often both inhomogeneous and non-isotropic. Therefore, and due to the inherent heterogeneous nature of composite materials, they can be studied from a micromechanical or a macro-mechanical point of view. In micromechanics, the behaviour of the inhomogeneous lamina is defined in terms of the constituent materials; whereas in macro-mechanics the material is presumed homogeneous and the effects of the constituent materials are detected only as averaged apparent macroscopic properties of the composite material. This approach is generally accepted when modeling gross response of composite structures. The micromechanics approach is more convenient for the analysis of the composite material because it studies the volumetric percentages of the constituent materials for the desired lamina stiffnesses and strengths, i.e. the aim of micromechanics is to determine the moduli of elasticity and strength of a lamina in terms of the moduli of elasticity, and volumetric percentage of the fibers and the matrix. To explain further, both the fibers and the matrix are assumed homogeneous, isotropic and linearly elastic. The fibers may be oriented randomly within the material, but it is also possible to arrange for them to be oriented preferentially in the direction expected to have the highest stresses. Such a material is said to be anisotropic (i.e. different properties in different directions), and control of the anisotropy is an important means of optimizing the material for specific applications. At a microscopic level, the properties of these composites are determined by the orientation and distribution of the fibers, as well as by the properties of the fiber and matrix materials.

2. Materials

The term composite could mean almost anything if taken at face value, since all materials are composed of dissimilar subunits if examined at close enough detail. But in modern materials engineering, the term usually refers to a matrix material that is reinforced with fibers. For instance, the term FRP (i.e. Fiber Reinforced Plastic) usually indicates a thermosetting polyester matrix containing glass fibers, and this particular composite has the lion share of today commercial market. Fig. 1 shows a laminate fabricated by cross plying unidirectional reinforced layers in a 0^o-90^o stacking sequence [1] – [8].

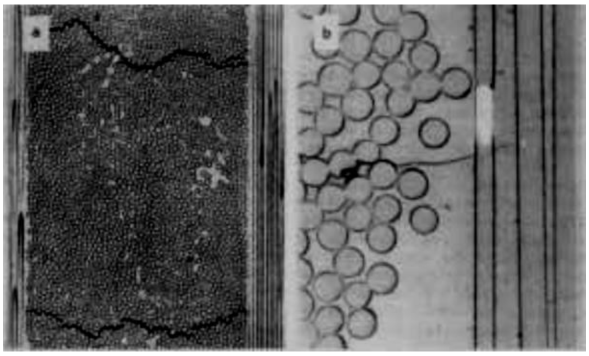

Fig. 1 A cross plied FRP laminate, showing non uniform fiber packing and micro cracking (from Harris, 1986)

Many composites used today are at the leading edge of materials technology, with performance and costs appropriate to ultra-demanding applications such as spacecraft. But heterogeneous materials combining the best aspects of dissimilar constituents have been used by nature for millions of years. Ancient society, imitating nature, used this approach as well: the Book of Exodus speaks of using straw to reinforce mud in brickmaking, without which the bricks would have almost no strength. Here in Sudan, people from ancient times dated back to Merowe civilization, and up to now used zibala mixed with mud as a strong building material [9] – [18].

As seen in Table 1 [8], the fibers used in modern composites have strengths and stiffnesses far above those of traditional bulk materials. The high strengths of the glass fibers are due to processing that avoids the internal or surface flaws which normally weaken glass, and the strength and stiffness of the polymeric aramid fiber is a consequence of the nearly perfect alignment of the molecular chains with the fiber axis.

Table 1 Properties of Composite Reinforcing Fibers

Material	E (GPa)	σ_b (GPa)	ϵ_b (%)	ρ (Mg/m^3)	E/ρ (MJ/kg)	σ_b/ρ (MJ/kg)	cost ($/kg)
E-glass	72.4	2.4	2.6	2.54	28.5	0.95	1.1
S-glass	85.5	4.5	2.0	2.49	34.3	1.8	22–33
aramid	124	3.6	2.3	1.45	86	2.5	22–33
boron	400	3.5	1.0	2.45	163	1.43	330–440
HS graphite	253	4.5	1.1	1.80	140	2.5	66–110
HM graphite	520	2.4	0.6	1.85	281	1.3	220–660

Of course, these materials are not generally usable as fibers alone, and typically they are impregnated by a matrix material that acts to transfer loads to the fibers, and also to protect the fibers from abrasion and environmental attack. The matrix dilutes the properties to some degree, but even so very high specific (weight-adjusted) properties are available from these materials. Metal and glass are available as matrix materials, but these are currently very expensive and largely restricted to R&D laboratories. Polymers are much more commonly used, with unsaturated styrene-hardened polyesters having the majority of low-to-medium performance applications and epoxy or more sophisticated thermosets having the higher end of the market. Thermoplastic matrix composites are increasingly attractive materials, with processing difficulties being perhaps their principal limitation.

3. Stiffness

The fibers may be oriented randomly within the material, but it is also possible to arrange for them to be oriented preferentially in the direction expected to have the highest stresses. Such a material is said to be anisotropic (different properties in different directions), and control of the anisotropy is an important means of optimizing the material for specific applications. At a microscopic level, the properties of these composites are determined by the orientation and distribution of the fibers, as well as by the properties of the fiber and matrix materials. The topic known as composite micromechanics is concerned with developing estimates of the overall material properties from these parameters [8] – [13].

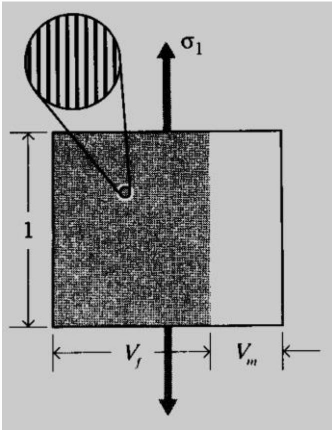

Fig. 2 Loading parallel to the fibers

Consider a typical region of material of unit dimensions, containing a volume fraction V_f of fibers all oriented in a single direction. The matrix volume fraction is then $V_m = 1 - V_f$. This region can be idealized as shown in Fig. 2 by gathering all the fibers together, leaving the matrix to occupy the remaining volume, this is sometimes called the "slab model." If a stress σ_1 is applied along the fiber direction, the fiber and matrix phases act in parallel to support the load. In these parallel connections the strains in each phase must be the same, so the strain ε_1 in the fiber direction can be written as:

$$\epsilon_f = \epsilon_m = \epsilon_1$$

The forces in each phase must add to balance the total load on the material. Since the forces in each phase are the phase stresses times the area (here numerically equal to the volume fraction), we have

$$\sigma_1 \models \sigma_f V_f + \sigma_m V_m = E_f \epsilon_1 V_f + E_m \epsilon_1 V_m$$

The stiffness in the fiber direction is found by dividing by the strain as shown in equation 1 below:

$$E_1 = \frac{\sigma_1}{\epsilon_1} = V_f\, E_f + V_m\, E_m$$

This relation is known as a rule of mixtures prediction of the overall modulus in terms of the moduli of the constituent phases and their volume fractions.

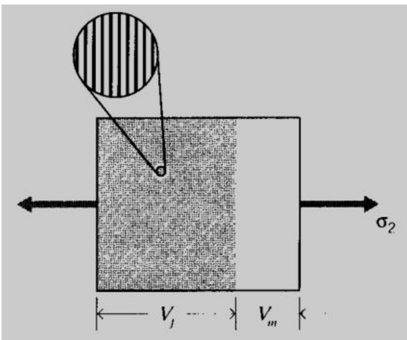

Fig. 3 Loading perpendicular to the fibers

If the stress is applied in the direction transverse to the fibers as depicted in Fig. 3, the slab model can be applied with the fiber and matrix materials acting in series. In this case the stress in the fiber and matrix are equal (an idealization), but the deflections add to give the overall transverse deflection as in equation 2 below.

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m}$$

Fig. 4 below shows the functional form of the parallel (equation 1) and series (equation 2) predictions for the fiber and transverse direction moduli.

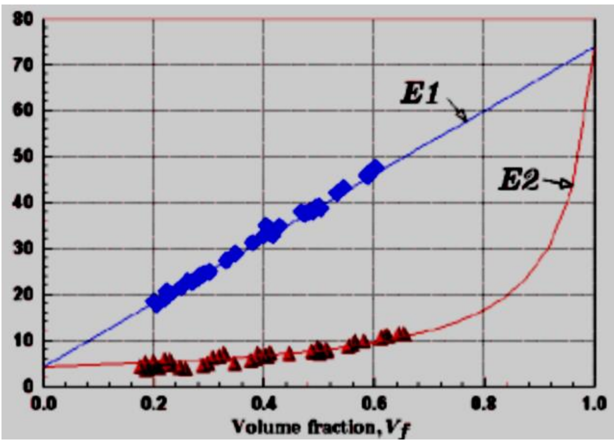

Fig. 4 Rule-of-mixtures predictions for longitudinal (E_1) and transverse (E_2) modulus, for glass-polyester composite (E_f = 73.7 MPa, E_m = 4 GPa). Experimental data taken from Hull (1996)

The prediction of transverse modulus given by the series slab model (equation 2) is considered unreliable, in spite of its occasional agreement with experiment. Among other deficiencies the assumption of uniform matrix strain being untenable; both analytical and experimental studies have shown substantial non uniformity in the matrix strain. Fig. 5 shows the photo elastic fringes in the matrix caused by the perturbing effect of the stiffer fibers.

In more complicated composites, for instance those with fibers in more than one direction or those having particulate or other non-fibrous reinforcements, equation 1 provides an upper bound to the composite modulus, while equation 2 is a lower bound (see Fig. 4). Most practical cases will be somewhere between these two values, and the search for reasonable models for these intermediate cases has occupied considerable attention in the composites research community. Perhaps the most popular model is an empirical one known as the Halpin-Tsai equation 3, which can be written in the form [2]:

$$E = \frac{E_m[E_f + \xi(V_f E_f + V_m E_m)]}{V_f E_m + V_m E_f + \xi E_m}$$

Here ζ is an adjustable parameter that results in series coupling for ζ = 0 and parallel averaging for very large ζ. [8] – [11].

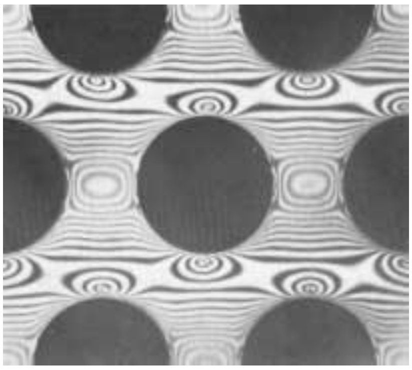

Fig. 5 Photo elastic (isochromatic) fringes in a composite model subjected to transverse tension (from Hull, 1996)

4. Strength

Rule of mixtures estimates for strength proceed along lines similar to those for stiffness. For instance, consider a unidirectional reinforced composite that is strained up to the value at which the fibers begin to break. Denoting this value ε_{fb}, the stress transmitted by the composite is given by multiplying the stiffness (equation 1):

$$\sigma_b = \epsilon_{fb} E_1 = V_f \sigma_{fb} + (1 - V_f)\sigma^*$$

The stress $\sigma*$ is the stress in the matrix, which is given by $\varepsilon_{fb}E_m$. This relation is linear in V_f, rising from $\sigma*$ to the fiber breaking strength $\sigma_{fb} = E_f\ \varepsilon_{fb}$. However, this relation is not realistic at low fiber concentration, since the breaking strain of the matrixε_{mb} is usually substantially greater than ε_{fb}. If the matrix had no fibers in it, it would fail at a stress $\sigma_{mb} = E_m\varepsilon_{mb}$. If the fibers were considered to carry no load at all, having broken at $\varepsilon = \varepsilon_{fb}$ and leaving the matrix to carry the remaining load, the strength of the composite would fall off with fiber fraction according to:

$$\sigma_b = (1 - V_f)\sigma_{mb}$$

Since the breaking strength actually observed in the composite is the greater of these two expressions, there will be a range of fiber fraction in which the composite is weakened by the addition of fibers. These relations are depicted in Fig. 6. [14] – [18].

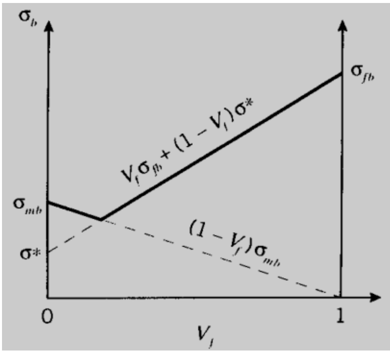

Fig. 6 Strength of unidirectional composite in fiber direction

5. Conclusions

The micromechanical approach is not responsible for the many defects which may arise in fibers, matrix, or lamina due to their manufacturing. These defects, if they exist include misalignment of fibers, cracks in matrix, non-uniform distribution of the fibers in the matrix, voids in fibers and matrix, delaminated regions, and initial stresses in the lamina as a result of its manufacture and further treatment. The above mentioned defects tend to propagate as the lamina is loaded causing an accelerated rate of failure. The experimental and theoretical results in this case tend to differ. Hence, due to the limitations necessary in the idealization of the lamina components, the properties estimated on the basis of micromechanics should be proved experimentally. The proof includes a very simple physical test in which the lamina is considered homogeneous and orthotropic. In this test, the ultimate strength and modulus of elasticity in a direction parallel to the fiber direction can be determined experimentally by loading the lamina longitudinally. When the test results are plotted, the required properties may then be evaluated. Similarly, the properties of the lamina in a perpendicular to the fiber-direction direction can be evaluated in the same procedure. The properties of a composite laminate depend on the geometrical arrangement and the properties of its constituents. The exact analysis of such structure – property relationship is rather complex because of many variables involved. Therefore, a few simplifying assumptions regarding the structural details and the state of stress within the composite have been introduced. It has been observed, that the concept of representative volume element and the selection of appropriate boundary conditions are very important in the discussion of micromechanics. The composite stress and strain are defined as the volume averages of the stress and strain fields, respectively, within the representative volume element. By finding relations between the composite stresses and the composite strains in terms of the constituent properties expressions for the composite moduli could be derived. In addition, it has been shown that, the results of advanced methods can be put in a form similar to the rule of mixtures equations. Prediction of composite strengths is rather difficult because there are many unknown variables and also because failure critically depends on defects. However, the effects of constituents including fiber – matrix interface on composite strengths can be qualitatively explained. Certainly, failure modes can change depending on the material combinations. Thus, an analytical model developed for one material combination cannot be expected to work for a different one. Ideally a truly analytical model will be applicable to material combination. However, such an analytical model is not available at present. Therefore, it has been chosen to provide models each of which is applicable only to a known failure mode.

References

[1] F.P. Gerstle, "Composites," Encyclopedia of Polymer Science and Engineering, Wiley, New York, 1991.

[2] J.C.. Halpin and J.L. Kardos, Polymer Engineering and Science, Vol. 16, May 1976, pp. 344–352.

[3] Ashton, J.E., J.C. Halpin and P.H. Petit, Primer on Composite Materials: Analysis, Technomic Press, Westport, CT, 1969.

[4] Harris, B., Engineering Composite Materials, The Institute of Metals, London, 1986.

[5] Hull, D. and T.W. Clyne, An Introduction to Composites Materials, Cambridge University Press, 1996.

[6] Jones, R.M., Mechanics of Composite Materials, McGraw-Hill, New York, 1975.

[7] Powell, P.C, Engineering with Polymers, Chapman and Hall, London, 1983.

[8] Roylance, D., Mechanics of Materials, Wiley & Sons, New York, 1996.

[9] Osama Mohammed Elmardi Suleiman Khayal , September (2016). ANALYSIS OF COMPOSITE LAMINATED PLATES, International Journal of Advances in Scientific Research and Engineering (IJASRE), Vol. 02, Issue 08, ISSN: 2454-8006, www.ijasre.net, PP. 24 – 41.

[10] Osama Mohammed Elmardi Suleiman Khayal, Mahmoud Yassin Osman & Tagelsir Hassan, (2018). BIAXIAL BUCKLING OF THIN LAMINATED COMPOSITE PLATES, International Journal of Bridge Engineering (IJBE), Vol. 6, No. 3, PP. 19 – 44.

[11] Mahmoud Yassin Osman & Osama Mohammed Elmardi Suleiman, March (2017). Buckling Analysis of Thin Laminated Composite Plates using Finite Element Method, International Journal of Engineering Research And Advanced Technology (IJERAT), Volume. 03 Issue.3, ISSN:2454 – 6135.

[12] Osama Mohammed Elmardi Suleiman Khayal, October (2016). Convergence and Accuracy of Dynamic Relaxation Technique in Determination of Central Deflection of Composite Rectangular Laminates, International Journal of Scientific Research Engineering & Technology (IJSRET), ISSN 2278 – 0882, Volume 5, Issue 10, PP. 502 – 509.

[13] Osama Mohammed Elmardi Suleiman, August (2016). Deflection and Stress Analysis of Fibrous Composite Laminates, International Journal of Advanced Research in Computer Science and Software Engineering, ISSN: 2277 128X, Volume 6, Issue 8, Available online at: www.ijarcsse.com, PP. 105 – 115.

[14] Osama Mohammed Elmardi Suleiman, April (2017). Deflection of Laminated Composite Plates Using Dynamic Relaxation Method, International Journal of Physical Sciences and Engineering, e-ISSN : 2550-6943, p-ISSN : 2550-6951, Vol. 1 No. 1, PP. 40 – 53.

[15] Osama Mohammed Elmardi Suleiman Khayal, February (2017). Literature review on imperfection of composite laminated plates, Journal of Microscopy and Ultrastructure, Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license, 5, PP. 119 – 122.

[16] Osama Mohammed Elmardi Suleiman Khayal, (2017). MECHANICAL PROPERTIES OF COMPOSITE LAMINATED DECKS PLATES, International Journal of Bridge Engineering (IJBE), Vol. 1, No. 1, PP. 01 – 41.

[17] Osama Mohammed Elmardi Suleiman, October (2016). Theories of Composite Plates and Numerical Methods Used on Bending and Buckling of Laminated Plates, International Journal of Engineering Research And Advanced Technology (IJERAT), ISSN: 2454-6135, Volume. 02, Issue.10, PP. 1 – 12.

[18] Osama Mohammed Elmardi, (2014). Verification of Dynamic Relaxation (DR) Method in Isotropic, Orthotropic and Laminated Plates using Small Deflection Theory, International Journal of Advanced Science and Technology, http://dx.doi.org/10.14257/ijast.2014.72.04, Vol.72, PP. 37 – 48.

Author

Osama Mohammed Elmardi Suleiman Khayal was born in Atbara, Sudan in 1966. He received his diploma degree in mechanical engineering from Mechanical Engineering College, Atbara, Sudan in 1990. He also received a bachelor degree in mechanical engineering from Sudan University of science and technology – Faculty of engineering in 1998, and a master degree in solid mechanics from Nile valley university (Atbara, Sudan) in 2003, and a PhD in structural engineering in 2017. He contributed in teaching some subjects in other universities such as Red Sea University (Port Sudan, Sudan), Kordofan University (Obayed, Sudan), Sudan University of Science and Technology (Khartoum, Sudan), Blue Nile University (Damazin, Sudan) and Kassala University (Kassala, Sudan). In addition, he supervised more than hundred and fifty under graduate studies in diploma and B.Sc. levels and about fifteen master theses. The author wrote about forty engineering books written in Arabic language, and fifteen books written in English language and more than hundred research papers in fluid mechanics, thermodynamics, internal combustion engines and analysis of composite structures. He authored more than thousands of lectures notes in the fields of mechanical, production and civil engineering He is currently an associated professor in Department of Mechanical Engineering, Faculty of Engineering and Technology, Nile Valley University Atbara, Sudan. His research interest and favorite subjects include structural mechanics, applied mechanics, control engineering and instrumentation, computer aided design, design of mechanical elements, fluid mechanics and dynamics, heat and mass transfer and hydraulic machinery. The author also works as a technical manager and superintendent of Al – Kamali mechanical and production workshops group which specializes in small, medium and large automotive overhaul maintenance and which situated in Atbara town in the north part of Sudan, River Nile State.