Mechanical Properties of Composite Laminated Plates

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ABSTRACT

A composite material can be defined as a combination of two or more materials that gives better properties than those of the individual components used alone. In contrast to metallic alloys, each material retains its separate chemical, physical, and mechanical properties. The two constituents are reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness combined with low density when compared to classical materials. Micromechanical approach is found to be more suitable for the analysis of composite materials because it studies the volume proportions of the constituents for the desired lamina stiffness and strength.

Keywords: Glass and Carbon fibers, Composite laminates, Micromechanical approach, Stiffness and Strength.

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1. INTRODUCTION

Composites were first considered as structural materials a little more than half a century ago. From that time to now, they have received increasing attention in all aspects of material science, manufacturing technology, and theoretical analysis.

The term composite could mean almost anything if taken at face value, since all materials are composites of dissimilar subunits if examined at close enough details. But in modern materials engineering, the term usually refers to a matrix material that is reinforced with fibers. For instance, the term "FRP" which refers to Fiber Reinforced Plastic usually indicates a thermosetting polyester matrix containing glass fibers, and this particular composite has the lion's share of today commercial market.

Many composites used today are at the leading edge of materials technology, with performance and costs appropriate to ultra-demanding applications such as space craft. But

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heterogeneous materials combining the best aspects of dissimilar constituents have been used by nature for millions of years. Ancient societies, imitating nature, used this approach as well: The book of Exodus speaks of using straw to reinforce mud in brick making, without which the bricks would have almost no strength. Here in Sudan as stated by Osama Mohammed Elmardi [1], people from ancient times dated back to Meroe civilization, and up to now used *zibala*(i.e. animals' dung) mixed with mud as a strong building material.

As seen in table(1) below, which is cited by David Roylance [2], Stephen et al. [3]and Turvey et al. [4],the fibers used in modern composites have strengths and stiffnesses far above those of traditional structural materials. The high strengths of the glass fibers are due to processing that avoids the internal or external textures flaws which normally weaken glass, and the strength and stiffness of 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 (GN/m^2)	$\dagger_b$ (GN/m^2)	V_b (%)	… (Mg/m^3)	E / … (MN.m/kg)	$\dagger_b$ / … (MN.m/kg)
E-glass	72.4	2.4	2.6	2.54	28.5	0.95
S-glass	85.5	4.5	2.0	2.49	34.3	1.8
Aramid	124	3.6	2.3	1.45	86	2.5
Boron	400	3.5	1.0	2.45	163	1.43
H S graphite	253	4.5	1.1	1.80	140	2.5
H M graphite	520	2.4	0.6	1.85	281	1.3

Where E is Young's modulus, $\dagger_b$ is the breaking stress, V_b is the breaking strain, and … is the mass density.

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. 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

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composites are increasingly attractive materials, with processing difficulties being perhaps their principal limitation.

Recently, composite materials are increasingly used in many mechanical, civil, and aerospace engineering applications due to two desirable features: the first one is their high specific stiffness (stiffness per unit density) and high specific strength (strength per unit density),and the second is their properties that can be tailored through variation of the fiber orientation and stacking sequence which gives the designers a wide spectrum of flexibility. The incorporation of high strength, high modulus and low-density filaments in a low strength and a low modulus matrix material is known to result in a structural composite material with a high strength to weight ratio. Thus, the potential of a two-material composite for use in aerospace, under-water, and automotive structures has stimulated considerable research activities in the theoretical prediction of the behaviourof these materials. One commonly used composite structure consists of many layers bonded one on top of another to form a high-strength laminated composite plate. Each lamina is fiber reinforced along a single direction, with adjacent layers usually having different filament orientations. For these reasons, composites are continuing to replace other materials used in structures such as conventional materials. In fact composites are the potential structural materials of the future as their cost continues to decrease due to the continuous improvements in production techniques and the expanding rate of sales.

2. STRUCTURE OF COMPOSITES.

There are many situations in engineering where no single material will be suitable to meet a particular design requirement. However, two materials in combination may possess the desired properties and provide a feasible solution to the materials selection problem. A composite can be defined as a material that is composed of two or more distinct phases, usually a reinforced material supported in a compatible matrix, assembled in prescribed amounts to achieve specific physical and chemical properties.

In order to classify and characterize composite materials, distinction between the following two types is commonly accepted;see Vernon [5], Jan Stegmann and Erik Lund [6], and David Roylance [2], Osama Mohammed Elmardi Suleiman {[7]– [15] }.

1. Fibrous composite materials: Which consist of high strength fibers embedded in a matrix. The functions of the matrix are to bond the fibers together to protect them from damage, and to transmit the load from one fiber to another. {Seefig. (1) Below}.

2. Particulate composite materials: This composed of particles encased within a tough matrix, e.g. powders or particles in a matrix like ceramics.

Fig. (1) Structure of a fibrous composite

In this thesis the focus will be on fiber reinforced composite materials, as they are the basic building element of a rectangular laminated plate structure. Typically, such a material consists of stacks of bonded-together layers (i.e. laminas or plies)made from fiber reinforced material. The layers will often be oriented in different directions to provide specific and directed strengths and stiffnesses of the laminate. Thus, the strengths and stiffnesses of the laminated fiber reinforced composite material can be tailored to the specific design requirements of the structural element being built.

2.1. Mechanical properties of a fiber reinforced lamina

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 forthe 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 moduliof

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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.

2.1.1. Stiffness and strength of a lamina

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.

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 by gathering all the fibers together, leaving the matrix to occupy the remaining volume. If a stress $\dagger_l$ is applied along the fiber direction, the fiber and matrix phases act in parallel to support the load. In these parallel connectionsthe strains in each phase must be the same, so the strain v_l in the fiber direction can be written as:

$$v_l = v_f = v_m \tag{1}$$

Where the subscripts *L, f* and *m* denote the lamina, fibers and matrix respectively.
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

$$\dagger_l = \dagger_f V_f + \dagger_m V_m = E_f v_l V_f + E_m v_l V_m \tag{2}$$

The stiffness in the fiber direction is found by dividing the stress by the strain:

$$E_l = \frac{\dagger_l}{v_l} = E_f V_f + E_m V_m \tag{3}$$

(Where E is the longitudinal Young's modulus)
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.

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 fiber begins to fracture. If the matrix is more ductile than the fibers, then the ultimate tensile strength of the lamina in equation (2) will be transformed to:

$$\sigma_l^{\,u} = \sigma_f^{\,u} V_f + \sigma_m^{\,f}\left(1 - V_f\right) \tag{4}$$

Where the superscript u denotes an ultimate value, and $\sigma_m^{\,f}$ is the matrix stress when the fibers fracture as shown in fig. (2) Below:
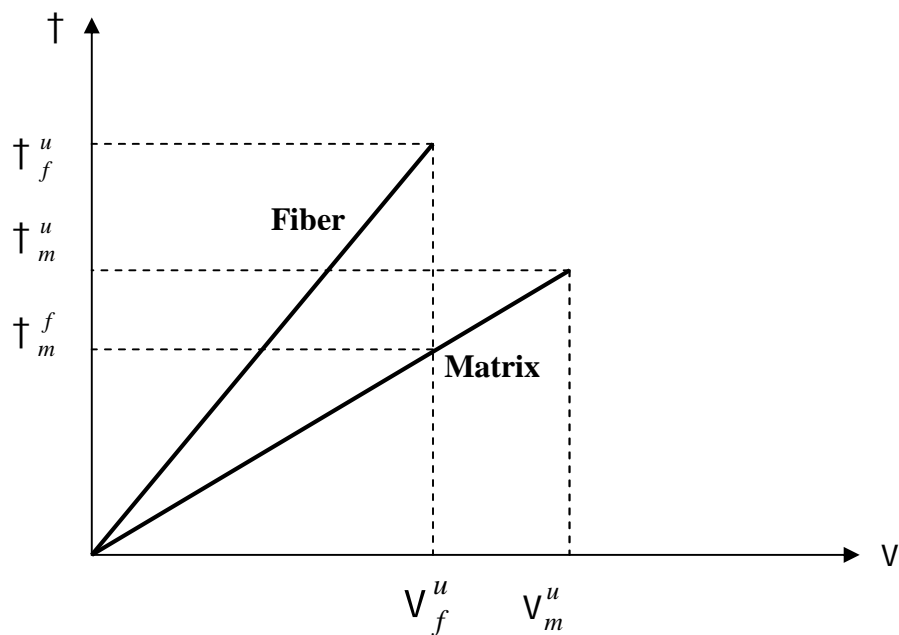

Fig. (2) Stress-strain relationships for fiber and matrix

It is clear that if the fiber volume fraction is very small, the behaviour of the lamina is controlled by the matrix.

This can be expressed mathematically as follows:

$$\sigma_l^{\,u} = \sigma_m^{\,u}\left(1 - V_f\right) \tag{5}$$

If the lamina isassumed tobe useful in practical applications, then there is a minimum fiber volume fraction that must be added to the matrix. This value is obtained by equating equations (4) and (5) i.e.

$$V_{min} = \frac{\sigma_m^{\,u} - \sigma_m^{\,f}}{\sigma_f^{\,u} + \sigma_m^{\,u} - \sigma_m^{\,f}} \tag{6}$$

The variation of the strength of the lamina with thefiber volume fraction is illustrated in fig.(3) It is obvious that $0 < V_f < V_{min}$ when the strength of the lamina is dominated by the matrix deformation which is less than the matrix strength. But when the fiber volume fraction exceeds a critical value (i.e. $V_f > V_{Critical}$), Then the lamina gains some strength due to thefiber reinforcement.
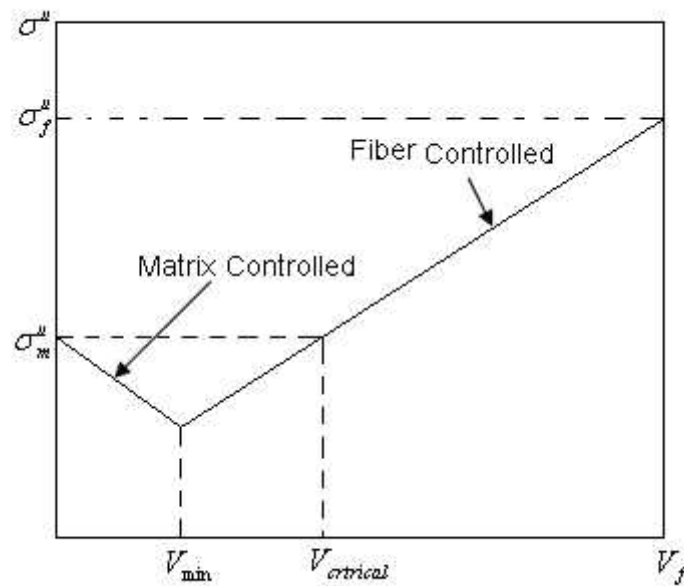

Fig. (3) Variation of unidirectional lamina strength withthe fiber volume fraction

The micromechanical approach is not responsible forthe 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 ofthe fibers in the matrix, voids in fibers and matrix, delaminated regions, and initial stresses in the lamina as a result of it's 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 tendto 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 fiberdirection can be

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determined experimentally by loading the lamina longitudinally. When the test results are plotted as in fig. (4)Below, the required properties may be evaluated as follows: -

$$E_1 = \dagger_1 / \vee_1 \quad ; \quad \dagger^u = P^u / A \quad ; \quad \in_{12} = -\vee_2 / \vee_1$$
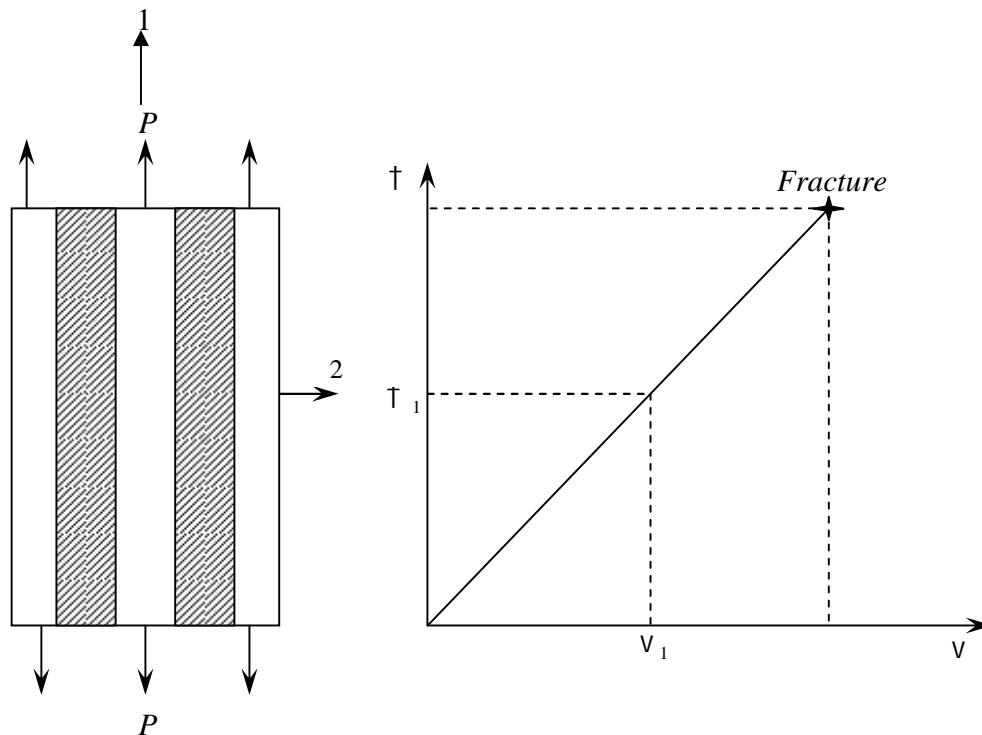

Fig. (4) Unidirectional lamina loaded in the fiber-direction

Similarly, the properties of the lamina in a direction perpendicular to the fiber direction can be evaluated in the same procedure.

2.1.2. Analytical modeling of composite laminates

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

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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. Yet, they can explain many of the effects of the constituents. (Refer to Ref. [3]).

3. CONCLUSION

This paper is designed to shed light on the elastic mechanical properties of the main constituents of composite laminated plates (i. e. fibers and matrix).

From the present review, it has been observed that the concept of representative volume element is very important in the discussion of micromechanics. The composite stress and strain are defined as volume fractions of the stress and strain fields. In addition, it has been shown that, the results of advanced methods could be put in a form similar to the rule of mixtures equations.

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