Elastic Properties of Fibrous Composite Materials

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Abstract:

The study evaluates various mechanical properties of composite materials, such as modulus of elasticity, tensile strength, and elongation at break, using tensile, compression, and bending tests. It also investigates vibration damping capacity and water absorption/loss. Composite laminates comprise multiple layers engineered to achieve specific mechanical characteristics, including in-plane stiffness and thermal expansion coefficients. Understanding these properties is essential for assessing a material's suitability for different applications.

The paper identifies two main failure mechanisms during low-velocity impact (LVI): intralaminar damage, which occurs within the composite layers (e.g., fiber and matrix failures), and interlaminar damage, notably delamination. The properties of composites are influenced by several factors, including the characteristics of constituent materials (including additives), fiber length, orientation, cross-sectional shape, fiber distribution, and the volume fractions of the fiber and matrix materials.

Keywords: Strength; Stiffness; Lamina; Matrix; Delamination; Elastic Properties.

1. Introduction:

Composite materials have been acknowledged as structural components for over seventy-five years, during which they've garnered increasing attention across diverse fields including materials science, manufacturing technology, and theoretical research. The term "composite," when broadly interpreted, can refer to nearly any material, as all materials can be analyzed as composites made up of various constituents. However, in modern materials engineering, it specifically refers to a matrix reinforced with fibers. For instance, the term "FRP," or fiber-reinforced plastic, primarily describes a thermosetting polyester matrix enhanced with glass fibers, which represents a significant segment of the commercial market today.

Many of the composites in use today are at the forefront of materials technology, particularly noted for their performance and cost-effectiveness in demanding applications such as aerospace. Remarkably, nature has employed heterogeneous materials that combine the optimal properties of various components for millions of years. Ancient civilizations mirrored these designs; for example, the Book of Exodus mentions the use of straw mixed with clay to strengthen bricks. In Sudan, as observed by local scholars, a combination of dung and clay has served as a robust building material since the Meroitic civilization.

As illustrated in Table 1 below, referenced by David Roylance, Stephen et al., and Turvy et al., the fibers in modern composites exhibit significantly greater strength and rigidity than those found in traditional structural materials. The remarkable strength of glass fibers is largely due to processing techniques that minimize defects from internal or external fractures typically associated with glass, while the strength and rigidity of aramid polymer fibers are a result of the nearly perfect alignment of their molecular chains along the fiber axis [1] – [12].

Table 1 Properties of Composite Reinforcement Fibers

Material	E (GN/m^2)	σ_b (GN/m^2)	ε_b (%)	ρ (Mg/m^3)	E/ρ (MN.m/kg)	σ_b/ρ (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

In this context, (E) represents Young's modulus, (σ_b) denotes the breaking stress, (ε_b) indicates the breaking strain, and (ρ) refers to mass density. Typically, these materials are not effective as standalone fibers; they are often paired with a matrix material that aids in transferring loads to the fibers while also protecting them from wear and environmental damage. Although incorporating a matrix may slightly diminish certain properties, the improved characteristics (adjusted for weight) of these materials still result in a greater reliance on polymers. Unsaturated polyester resins containing styrene are frequently used in low- to medium-performance applications, whereas epoxy and more complex thermosetting materials are reserved for higher-performance situations. While there is an increasing interest in thermoplastic matrix composites, their main drawback lies in the challenges associated with processing.

Recently, composite materials have become increasingly popular across multiple disciplines, including mechanical, civil, and aerospace engineering, primarily due to two significant features: high specific stiffness (stiffness relative to density) and high specific strength (strength relative to density). Furthermore, the ability to tailor their properties by adjusting fiber orientations and stacking sequences grants designers' substantial flexibility. It is well documented that combining high-strength, high-modulus fibers with low-density composite matrix materials results in structural composites with an exceptional strength-to-weight ratio. This advantage has led to extensive research into the theoretical behavior of these materials for potential applications in aerospace, underwater, and automotive structures.

One common application of composite structures is the construction of multilayered panels that form high-strength laminated composites. Each layer includes fiber reinforcement in a single direction, while adjacent layers generally have varying fiber orientations. These characteristics contribute to the ongoing substitution of traditional materials with composites in structural applications. Indeed, as the cost of composites continues to decrease due to advancements in manufacturing techniques and rising market demand, they are increasingly recognized as the structural materials of the future. [1], [7] – [12].

2. Structure of Composites:

In engineering, there are many situations where a single material fails to meet particular design specifications. Instead, two materials can be combined to collectively exhibit the desired characteristics, offering a viable solution to material selection issues. A composite is defined as a material made up of two or more distinct phases, usually consisting of a reinforcing material embedded within a compatible matrix, meticulously combined in specific proportions to achieve targeted physical and chemical properties.

To categorize and differentiate composite materials, a commonly accepted distinction is made between two types; please refer to the works of Vernon, Jan Stegman, Eric Lund, David Roylance, and Osama Mohammed Elmardi Suleiman, as cited at the conclusion of this paper [2] – [7].

2.1 Fibrous Composite Materials:

Fibrous composite materials are made up of strong fibers that are embedded in a matrix. This matrix plays essential roles, including binding the fibers together, protecting them from damage, and allowing the transfer of loads between the fibers. {See Figure 1 below for an illustration of different types of fiber-reinforced composite sheets}.

Where:

(a) unidirectional fibers,
(b) bidirectional fibers,
(c) discontinuous fibers, and
(d) woven fibers.

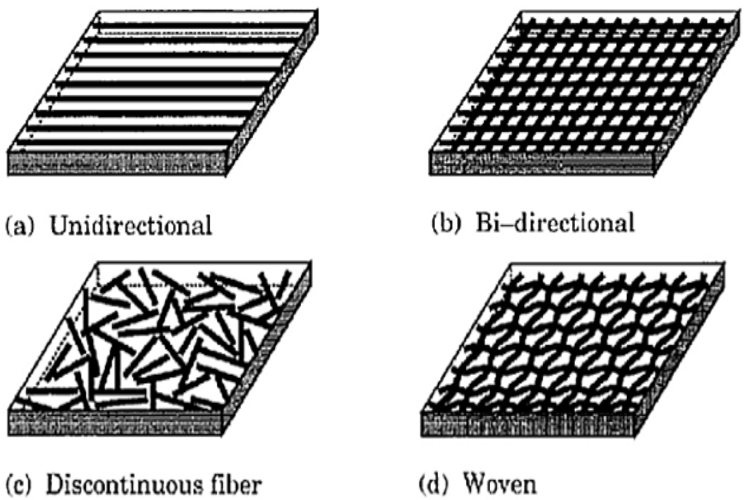

Figure 1 Various Types of Fiber-Reinforced Composite Sheets

2.2 Particulate Composite Materials:

These are made up of particles enclosed within a solid matrix, like powders or particles embedded in materials such as ceramics. {See Figure 2 below}.

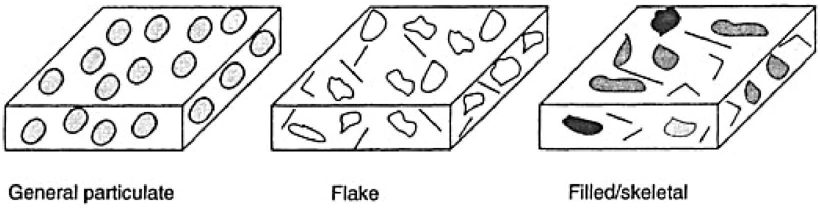

Figure 2 Various Types of Composite Plates Reinforced with Particles

This research paper focuses on fiber-reinforced composite materials, which are essential components in the construction of rectangular laminated plates. These materials usually comprise stacks of interlayered sheets (or plies) made from fiber-reinforced substances. The layers are often positioned at different angles to achieve targeted strength and stiffness in the laminates. As a result, the strength and rigidity of fiber-reinforced composite materials can be customized to fulfill the specific design needs of the structural elements being developed [1], [7] – [12].

3. Mechanical Properties of a Fiber Reinforced Lamina:

Composite materials exhibit a range of mechanical properties that set them apart from traditional engineering materials like metals. Typically heterogeneous, composites demonstrate varied characteristics. This variation allows for analysis from two distinct mechanical perspectives: micromechanical and macro mechanical.

In micromechanics, the behavior of the heterogeneous lamina is closely linked to the properties of its individual components. Conversely, macro mechanics treats the material as homogeneous, considering the effects of its constituents as averaged, macroscopic properties. This macro mechanical approach is commonly employed to model the overall response of composite structures.

However, micromechanics is often more advantageous for analyzing composite materials as it focuses on the volume fractions of the constituent materials to determine the lamina's stiffness and strength. The primary objective of micromechanics is to establish the flexibility and strength properties of the lamina in relation to the elastic moduli and the volume fractions of both fibers and matrix. It is assumed for this analysis that both the fibers and the matrix are homogeneous, analogous, and exhibit linear elastic behavior.

3.1 Stiffness and Strength of a Lamina:

Fibers within the material can be oriented in a random manner, or they may be aligned purposefully in the direction expected to endure the maximum stresses. This results in the material displaying anisotropic properties, indicating that it has different characteristics depending on the direction of measurement. Managing anisotropy is vital for optimizing materials for particular uses. At the microscopic level, the attributes of these composites are influenced by the orientation and distribution of the fibers, along with the properties of both the fibers and the matrix material.

Consider a typical region of the material with unit dimensions, which contains a volume fraction, V_f, of fibers all oriented in a single direction. Thus, the volume fraction of the matrix is given as $V_m = 1 - V_f$. This region can be idealized by aggregating all the fibers together, allowing the matrix to occupy the remaining volume. When a stress is applied along the direction of the fibers, both the fiber and matrix phases work in parallel to bear the load. In this parallel arrangement, the strains in each phase must be identical; hence, the strain in the direction of the fibers ε_l can be expressed as follows:

$$\varepsilon_l = \varepsilon_f = \varepsilon_m \qquad (1)$$

Where the subscripts L, f, and m denote the lamina, fiber, and matrix, respectively. In each stage, the forces must be added to balance the total load on the material. Since the forces at each stage are the phase stresses multiplied by the area (which here corresponds to the volume fraction), we have:

$$\sigma_l = \sigma_f V_f + \sigma_m V_m = E_f \varepsilon_l V_f + E_m \varepsilon_l V_m \qquad (2)$$

The stiffness is determined in the direction of the fibers by dividing stress by strain.

$$E_l = \frac{\sigma_l}{\varepsilon_l} = E_f V_f + E_m V_m \qquad (3)$$

(Where E is the longitudinal Young's modulus)

This relationship is characterized by the mixing rule for the overall moduli, which reflects the properties of the individual phases and their corresponding volume fractions. Strength estimates obtained from the mixing rule follow similar principles to those used for stiffness. For example, take a unidirectional reinforced composite that is pulled in tension until the fibers start to break. If the matrix is more flexible than the fibers, the maximum tensile strength of the laminate in equation (2) will be modified to:

$$\sigma_l^u = \sigma_f^u V_f + \sigma_m^f (1 - V_f) \qquad (4)$$

Where the upper letter "u" denotes the ultimate value, which represents the matrix stress at the point of fiber fracture, as illustrated in Figure 3 below:

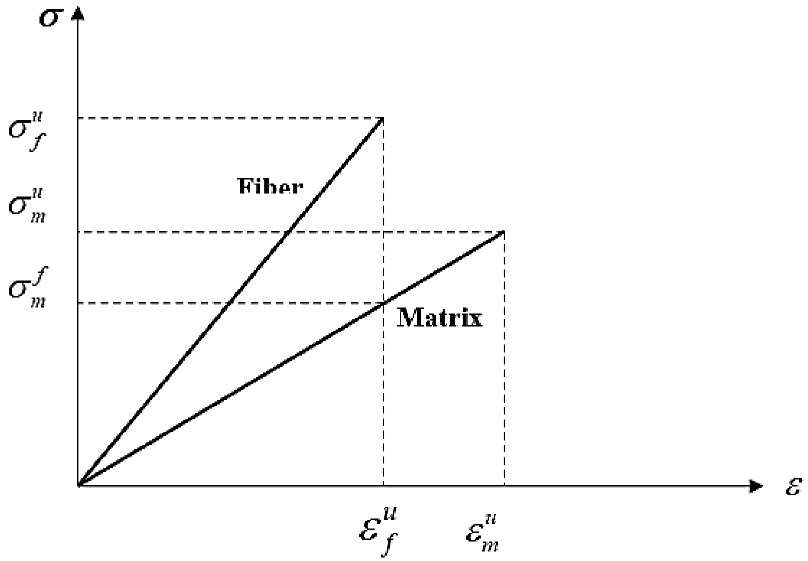

Figure 3 The Relationships between Stress and Strain for Both the Fibers and the Matrix

It is evident that if the fractional part of the fiber volume is exceedingly diminutive, the behavior of the laminate is governed by the matrix. This can be mathematically expressed as follows:

$$\sigma_l^u = \sigma_m^u\left(1 - V_f\right) \qquad (5)$$

If the plate is intended to be beneficial in practical applications, there is a minimum fiber size that must be incorporated into the matrix. This value is derived by equating equations (4) and (5).

$$V_{min} = \frac{\sigma_m^u - \sigma_m^f}{\sigma_f^u + \sigma_m^u - \sigma_m^f} \qquad (6)$$

Figure 4 illustrates the variation in plate strength relative to the volume fraction of the fibers. It is evident that when the volume fraction of the fibers $(V_f)(V_f)$ is greater than zero but less than the minimum volume fraction $(V_{min})(V_{min})$, the strength of the plate is primarily influenced by matrix deformation, which is inferior to the strength of the matrix itself. However, once the fiber volume fraction surpasses a critical threshold $(i.e., V_f > V_{criical})(i.e., V_f > V_{criical})$, the plate begins to gain strength owing to the reinforcement provided by the fibers.

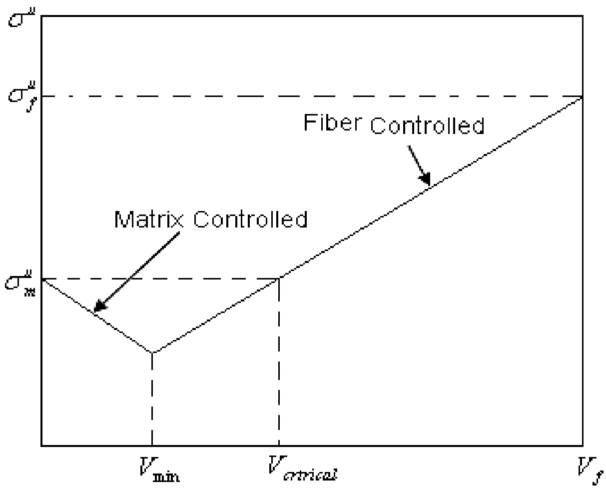

Figure 4 The Variation of Unidirectional Plate Strength with the Volumetric Fraction of the Fibers

The micromechanical approach bears no responsibility for the various defects that may arise in the fibers, matrix, or laminate as a result of their manufacturing. These defects, when present, may include misalignment of fibers, cracks within the matrix, irregular fiber distribution in the matrix, voids in both fibers and matrix, delaminated regions, and residual stresses within the laminate due to its fabrication and subsequent treatment. The aforementioned defects tend to propagate when the laminate is subjected to loading, thereby accelerating the failure rate. In such cases, both experimental and theoretical results typically exhibit discrepancies. Consequently, due to the necessary constraints in idealizing the laminate components, the estimated properties must be experimentally validated based on micromechanics. This validation involves a remarkably simple physical test in which the laminate is considered homogeneous with perpendicular fibers. In this experiment, the ultimate strength and the modulus of elasticity in the fiber-aligned direction can be empirically determined by longitudinally loading the laminate. When the test results are graphed as depicted in figure 5 below, the desired characteristics can be evaluated accordingly.

$$E_1 = \sigma_1/\varepsilon_1 \quad ; \quad \sigma^u = P^u/A \quad ; \quad \nu_{12} = -\varepsilon_2/\varepsilon_1$$

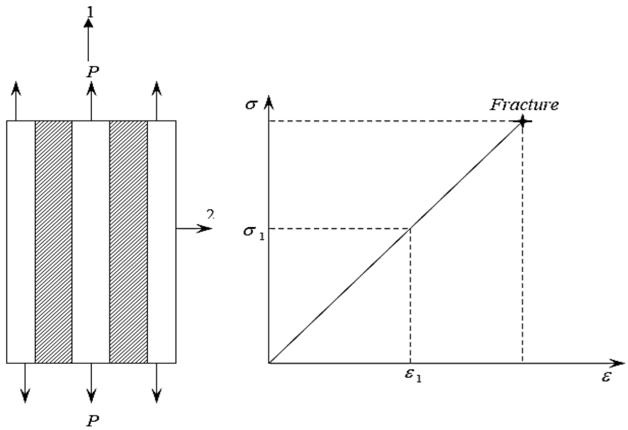

Figure 5 A Unidirectional Plate Subjected to Loading in the Direction of the Fibers

Similarly, the properties of the laminate can be evaluated in the vertical direction relative to the fiber orientation using the same methodology.

3.2 Analytical Modeling of Composite Laminates

The behavior of composite laminates hinges on their geometric configurations and the properties of the individual materials used. An in-depth analysis of the connection between these structural elements and their characteristics can be quite complex due to the multitude of variables involved. To simplify the process, several assumptions have been made regarding the structural details and the stress conditions present in the composite. The concept of the representative volume element, along with the appropriate selection of boundary conditions, plays a crucial role in micromechanical discussions. In this context, the composite stress and strain are defined as volume averages of the stress and strain fields within the representative volume element. By establishing a relationship between the composite stresses and strains in relation to the properties of its constituents, one can derive equations that describe the composite behavior. Additionally, research has shown that the outcomes of advanced modeling techniques can be formulated similarly to the rule of mixtures.

The prediction of composite strengths poses a considerable challenge due to the numerous unknown factors involved, especially since failure is heavily influenced by the presence of defects. Nonetheless, the impact of the constituent materials, including the interface between fibers and the matrix, can be broadly understood in relation to composite strength. It is clear that failure modes can differ significantly based on the specific material combinations used. As such, one cannot expect an analytical model designed for a specific set of materials to yield the same results when applied to a different set. Ideally, a universally applicable analytical model would exist for various material combinations; however, no such model is currently available. Therefore, it is preferred to offer models that apply specifically to known failure modes while also highlighting the diverse effects of the constituent materials [7] – [12].

4. Conclusion:

This research study focuses on the elastic mechanical properties of the main components of laminated panels (i.e. fibers and matrices). It highlights the importance of the representative volume element in micromechanics discussions, treating stress and strain as volumetric fractions. Additionally, it demonstrates that advanced methodologies can yield results comparable to the basic equations of mixtures.

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