Composite Mechanics

Composite materials need to be understood at different scales of measurement. At the most fundamental level, composites are mixtures of fibers(or particles) matrix and an interface material which connects fibres (or particles) to the matrix material.

Micromechanics helps us understand interactions between different constituents of composite on a microscopic scale. Such a field of study helps us understand:

Failure mechanisms in fibers (tensile, buckling, splitting, etc.) Failure mechanism in matrix (tensile, compressive, shear)

Interface failure mechanisms–Fracture toughness, fatigue life, and strength –Basis of macro-level elastic properties. However, micromechanics is an impractical tool to understand behavior of large structures, due to computational limitations.

Scales of Analysis for Composites

- At the constituent level, material under analysis is not homogenous. Hence its behavior changes significantly between different constituent materials.
- The next level of analysis in composites may be conducted for a lamina, i.e

a single layer of composite material. At this level, material is assumed to be homogenous, and material properties of the lamina is assumed to be an averaged (smeared) value of those of constituent materials. Such an analysis is known as macro-mechanics.

Such an approach of study works well for individual composite layers. It helps us predict failure and performance of individual lamina, in terms of smeared properties of the composite. However,
such an approach does not refer to local failure mechanisms. At the next level, principals of macro-mechanical analysis are further
developed to understand stacks of laminae ie laminates. Several theories have been developed towards this
end, the most widely used being Classical Laminate Theory (CLT). Such a
theory predicts properties of laminates as a function of three variables: Properties of individual layers; Thickness of individual layers; Orientation and arrangement of individual layers.
Finally, analysis is performed at the component level. Here, structural
Analysis is deployed to understand overall behavior of the structure in
terms of its: Performance (stresses, deflections, strains); Dynamics; Stability; Failure.

Basic Terminology

- Micromechanics: Study of composite materials by understanding interaction between constituent materials on a microscopic scale. Such an approach helps one theoretically compute material properties, and failure mechanisms of composites. Such an approach is difficult to use for large structures because of computational limitations.
- Macro-mechanics: Study of composite materials presumed to be homogeneous. In such an approach of study, averaged (smeared) properties of composite material are used to account for the effects of constituent materials. Such an approach works well for large structures and prediction of stresses at micro-level is not accurate.

Istoropy, Anisotropy, and Homogeneity:

- Most composite materials are neither homogeneous nor isotropic. A homogeneous material is one where properties are uniform throughout, i.e. they do not depend on position in body.

An isotropic material is one where properties are direction independent.

- Composites are inhomogeneous (or heterogeneous) as well as non-isotropic in nature.

An inhomogeneous(or heterogeneous) material's properties vary from point-to-point.

A non-isotropic material is one where material properties depend on direction. In such materials the modulus may be different in mutually orthogonal directions (x, y, and z) of measurement.

Basic Terminology

- Lamina: A flat (sometimes curved as well) sample of unidirectional/woven fibers held together by a matrix. If a fiber breaks in a lamina it is the matrix, which transfers load from one broken end to other broken end of the fiber through shear forces.

Plural of lamina is laminae. Also known as layer, and ply.

- Laminate: A laminate is a stack of several laminae oriented in different directions which are glued together. There may be significant shear stresses present between two adjacent plies due to the tendency of each layer to deform independently.

These stresses are maximum at edges of a laminate, and may cause delamination at such locations.

Material axes in unidirectional composites

A lamina is the building block of modern composite laminated structures.

Each lamina may have in itself more than one types of fibers. These fibers may be oriented in different directions.

A laminate has several layers, or laminae.

Each lamina may have different: Thickness, Fiber orientation angle, Fiber material and Matrix material.

Understanding the mechanical behavior of a lamina is the first step in understanding mechanics of laminated composite structures.

A lamina is also known as a ply, or a layer.

Each layer in a laminate has in general three planes of material symmetry.

Because of this, they exhibit orthotropic behavior. A lamina cut across these planes of symmetry will exhibit same mechanical properties.

Lines which are normal to these planes of material symmetry are called material axes. These axes are quite often designated as 1, 2and 3axes. Axis-1 runs parallel to the direction of fibers, and its direction is called longitudinal direction. Axis-2 runs normal to axis-1, but in the plane of lamina. Direction associated with axis-2 is called transverse direction. Axis-3 runs normal to axis-1 and axis 2. This is also transverse direction.

1, 2 and 3 are also known as principal material directions.

Given the fact that fibers’ strength and stiffness are significantly larger than that of the matrix, a lamina is stiffest and strongest in longitudinal direction. Further, in 2 and 3 directions its mechanical properties are roughly the same. In fact, a lamina’s mechanical properties in any direction lying in the 2-3 plane are quite similar. For this reason, a unidirectional lamina is considered as transversely isotropic, i.e. it is isotropic in the 2-3 planes.

The thickness of a typical carbon or glass fiber ply is 0.127 mm

This thickness depends on number of filaments in a tow. In such plies, fiber diameter may be approximately 10microns. Each ply may be constructed of yarns or rovings. A yarn is a collection of long continuous and interlocked fibers.

A roving is a narrow and long bundle of several fibers.

Failure in Isotropic v/s Transversely Isotropic Materials.

- In isotropic materials, failure prediction requires calculating principal stresses or strains and comparing them to allowable stress/strain limits prescribed for the material.
- In non-isotropic materials (e.g. transversely isotropic materials), this approach does not work.

The notion of principal stress makes no sense for these materials as material strength changes with direction, and the direction of principal stress may not in most of the cases coincide with direction of maximum strength.

- Thus, for unidirectional materials, we evaluate allowable stress field in context of different strengths of material in principal material directions. These are: – Longitudinal tensile strength, Lateral tensile strength,

Longitudinal compressive strength, Lateral compressive strength and In-plane shear strength.

These five material strength parameters for unidirectional composites are fundamental material properties of a lamina.

- Experimental data shows that these material strength properties of a unidirectional lamina are mutually independent, particularly at macro-scale.
- Hence, if we are able to calculate stress-field in a unidirectional lamina using 1-2-3 axes as reference frame, then we can predict failure in lamina.

Volume and Mass Fraction

The relative proportions of fiber and matrix have a significant influence on the mechanical properties of composite lamina. These proportions can be expressed either as volume fractions or as mass fractions. While mass fractions are easier to obtain during fabrication of composites, volume fractions are handier in theoretical analyses of composites.

If v_c, v_m, and v_f, are volumes of composite, matrix, and fiber, respectively, the volume fraction of matrix (V_m) and fiber (V_f) are defined as: $V_m = v_m/v_c$ and $V_f = v_f/v_c$ where, $v_c = v_m + v_f$.

And if m_c, m_m and m_f, are masses of composite, matrix, and fiber, respectively then mass fraction of matrix (M_m) and fiber (M_f) are defined as, $M_m = m_m/m_c$ and $M_f = m_f/m_c$ where, $m_c = m_m + m_f$

Volume and Mass Fraction

Using volume fractions we can now calculate the overall density of the composite. If ρ_m, ρ_f, and ρ_c are densities of matrix, fiber and composite respectively then density of composite (ρ_c) can be calculated as:

$m_c = m_m + m_{f,}$ and $\rho_c v_c = \rho_m v_m + \rho_f v_f$

Dividing this above relation by volume of composite, we can write, $\rho_c = \rho_m v_m / v_c + \rho_f v_f / v_c$

$\rho_c = \rho_m V_m + \rho_f V_f$ This equation gives the density of the composite if we know the volume fractions and densities of matrix and fibre.

Similarly, we can also develop a relation for composite’s density in terms of weight fractions and densities of fibre and matrix.

High points of the Note are:

Material axes of a lamina, and the notion of transverse isotropy

How to calculate density of a composite, using volume and mass fraction values.

The rationale underlying development of predictive methodologies for estimating composite material properties

Relations to predict longitudinal modulus of a unidirectional lamina.

Relations to predict strength of unidirectional lamina.

Different failure criterion for a unidirectional lamina which undergoes pure uniform tension.