Composite Materials: Characterization and Non-Destructive Testing

An Online Continuing Education Course for Engineers

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Composite Materials: Characterization and Non-Destructive Testing

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Introduction

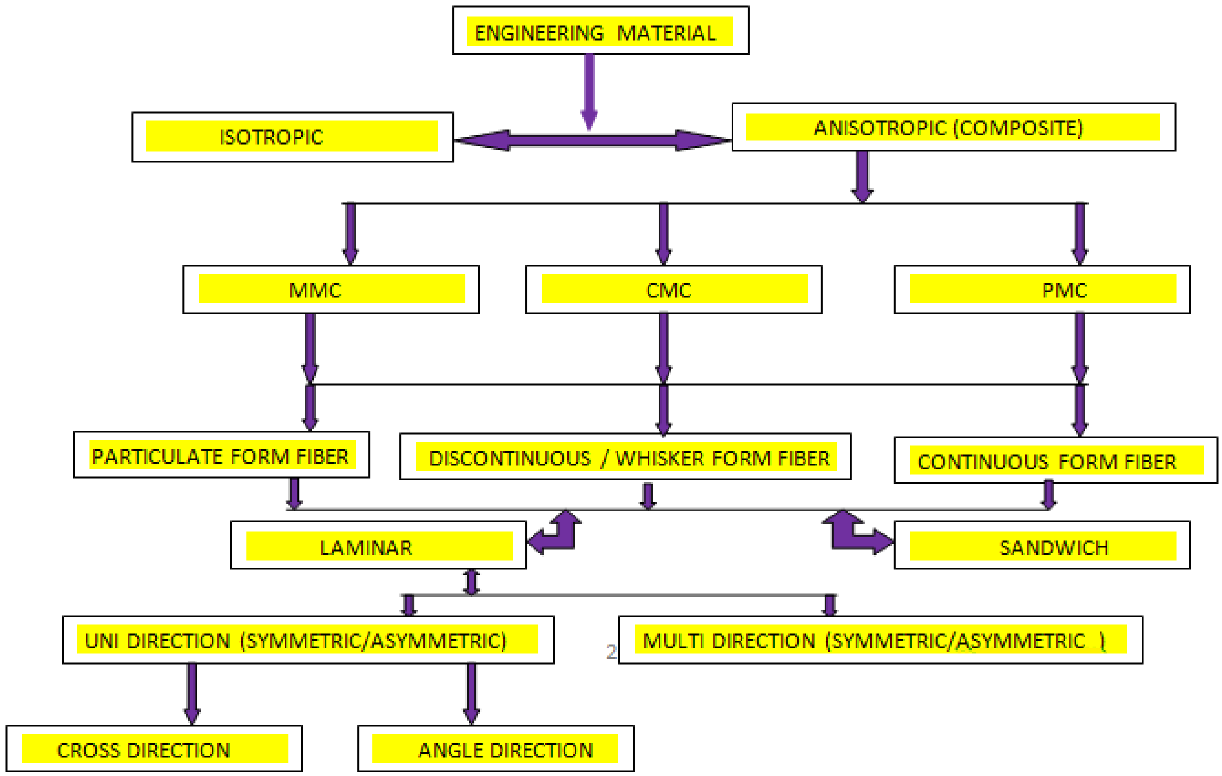
Non-Destructive Testing (NDT) is defined by the American Society for Non-Destructive Testing (ASNT) as: "The determination of the physical condition of an object without affecting that object's ability to fulfill its intended function. Non-destructive testing techniques typically use a probing energy form to determine material properties or to indicate the presence of material discontinuities (surface, internal or concealed)." The application of non-destructive testing methods can be summarized in the following three groups:

1) **Defectology of materials:** Allows for the detection of discontinuities, assessment of corrosion, and deterioration caused by environmental agents, the determination of tensions, and the detection of leaks.

2) **Characterization of materials**: Assessment of the chemical, structural, mechanical and technological features of materials, physical properties (elastic, electrical and electromagnetic), and heat transference and isotherm pathways.

3) **Metrology of materials**: Control of thicknesses; measurements of thicknesses on a single side, measurements of coating thicknesses, and filling levels.

Composite materials are advantageous for manufacturers due to their high performance and low costs. Composite materials fall into the general category of anisotropic materials, for which the material properties exhibit directional characteristics. On the other hand, common engineering materials such as steel are considered isotropic because there is no dependence of material properties on direction. Isotropic materials can be characterized by two independent material constants only. However, for anisotropic materials, the number of constants can be as high as twenty-one (21) depending on the number of planes of material symmetry the material possesses. The classification of composite materials is provided in the figure below.



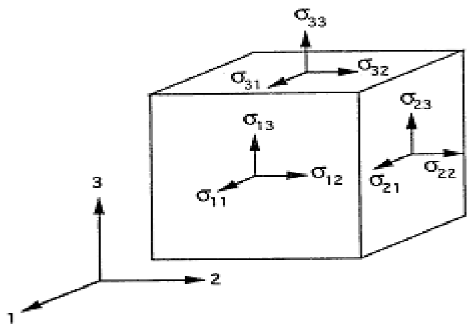
Basics of Composite Materials

Constitutive Relationships:

The constitutive relationship for the anisotropic materials is obtained through generalized Hooke's Law, and is expressed as follows:

$\sigma_{ij} = C_{ijkl}\, \epsilon_{kl}$ (i, j, k, l=1, 2,3)
$\epsilon_{ij} = S_{ijkl}\, \sigma_{kl}$ (i,j,k,l=1,2,3)

Where σ_{ij} and ϵ_{kl} are stress and strain tensors, respectively, C_{ijkl} is the stiffness matrix, and S_{ijkl} is the compliance matrix.



Generalized Hooke's Law can also be expressed in terms of contracted notation:

$\sigma_{ij} = C_{ij}\epsilon_j$ (i,j=1,2,3,…6)
$\epsilon_{ij} = S_{ij}\sigma_j$ (i,j=1,2,3,….6)
$\sigma_{11}=\sigma_1$ $\epsilon_{11}=\epsilon_1$
$\sigma_{22}=\sigma_2$ $\epsilon_{22}=\epsilon_2$
$\sigma_{33}=\sigma_3$ $\epsilon_{33}=\epsilon_3$
$\sigma_{23}=\sigma_4=\tau_4=\tau_{23}$, $2\epsilon_{23}=\gamma_{23}=\epsilon_4$
$\sigma_{31}=\sigma_5=\tau_5=\tau_{31}$, $2\epsilon_{31}=\gamma_{31}=\epsilon_5$
$\sigma_{12}=\sigma_6=\tau_6=\tau_{12}$, $2\epsilon_{12}=\gamma_{12}=\epsilon_6$

and

$C_{1111}=C_{11}$, $C_{1122}=C_{12}$, $C_{1133}=C_{13}$, $C_{1123}=2C_{14}$, $C_{1131}=2C_{15}$, $C_{1112}=2C_{16}$
$C_{2211}=C_{21}$, $C_{2222}=C_{22}$, $C_{2233}=C_{23}$, $C_{2223}=2C_{24}$, $C_{2231}=2C_{25}$, $C_{2212}=2C_{26}$

$C_{3311}=C_{31}$, $C_{3322}=C_{32}$, $C_{3333}=C_{33}$, $C_{3323}=2C_{34}$, $C_{3331}=2C_{35}$, $C_{3312}=2C_{36}$

$C_{2311}=C_{41}$, $C_{2322}=C_{42}$, $C_{2333}=C_{43}$, $C_{2323}=2C_{44}$, $C_{2331}=2C_{45}$, $C_{2312}=2C_{46}$

$C_{3111}=C_{51}$, $C_{3122}=C_{52}$, $C_{3133}=C_{53}$, $C_{3123}=2C_{54}$, $C_{3131}=2C_{55}$, $C_{3112}=2C_{56}$

$C_{1211}=C_{61}$, $C_{1222}=C_{62}$, $C_{1233}=C_{63}$, $C_{1223}=2C_{64}$, $C_{1231}=2C_{65}$, $C_{1212}=2C_{66}$

Both stiffness and compliance matrices are symmetric, and the compliance matrix is the inverse of the stiffness matrix. These matrices contain 81 elastic constants. These reduce to 36 due to the symmetry of stress and strain tensors, and further reduce to 21 due to the symmetry of stiffness and compliance matrices**.** Hence, for a general anisotropic material, a total of 21 elastic constants are needed to fully characterize the material. Materials may exhibit planes of material symmetry, which reduces the number of elastic constants needed to characterize the material. The direction perpendicular to the plane of material symmetry is known as the principal material axes.

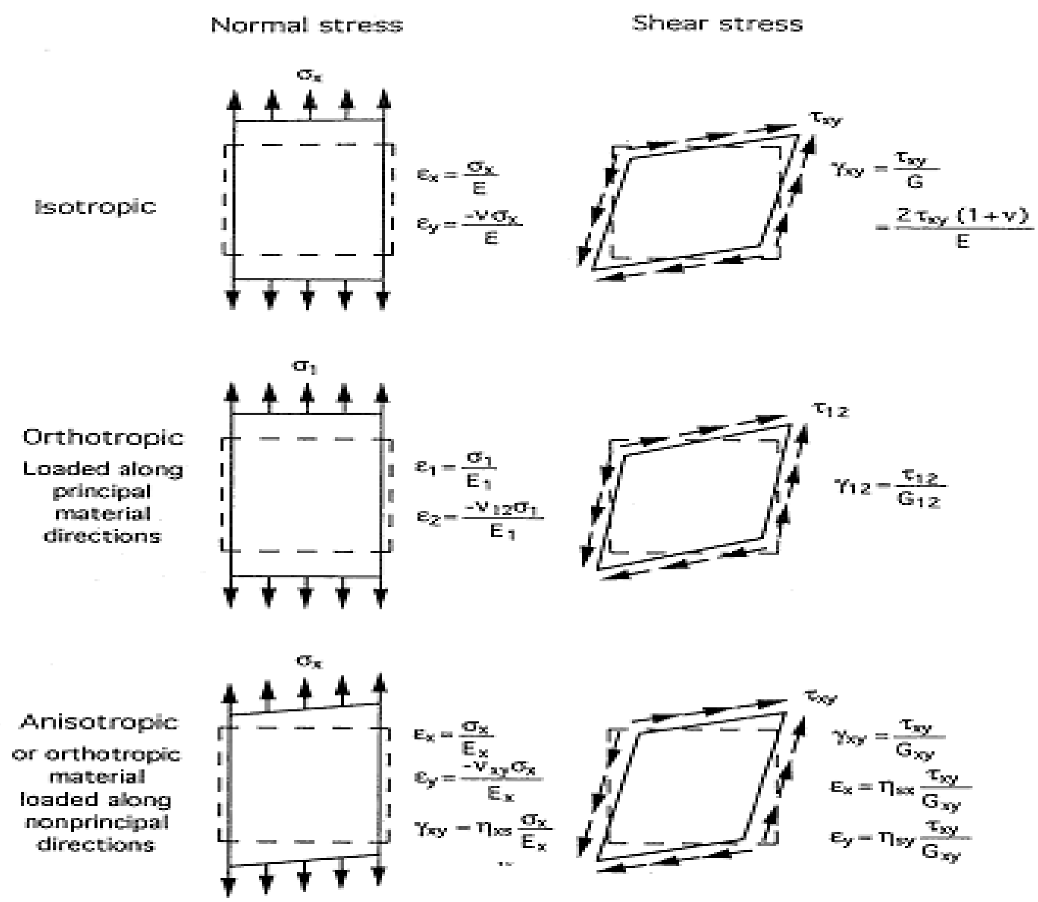
Based on the number of planes of material symmetry that a material possesses, the materials are classified as follows:

Monoclinic materials: These materials contain one plane of material symmetry. The number of elastic constants needed is 13.

Orthotropic materials: Two mutually orthogonal planes of material symmetry exist, and the number of elastic constants needed to characterize the material reduces to nine. Note that if there are two planes of material symmetry, then a third plane of material symmetry exists which is mutually orthogonal to the other two.

Transversely isotropic materials: These materials have one plane of symmetry, and the number of elastic constants reduces to five.

Isotropic materials: Every plane is a plane of material symmetry, and only two elastic constants are needed to characterize the material.



$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_4\\ \tau_5\\ \tau_6\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46}\\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56}\\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}\end{bmatrix} \begin{bmatrix}\epsilon_1\\ \epsilon_2\\ \epsilon_3\\ \gamma_4\\ \gamma_5\\ \gamma_6\end{bmatrix}$$

$$\begin{bmatrix}\epsilon_1\\ \epsilon_2\\ \epsilon_3\\ \gamma_4\\ \gamma_5\\ \gamma_6\end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16}\\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26}\\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36}\\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46}\\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56}\\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66}\end{bmatrix} \begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_4\\ \tau_5\\ \tau_6\end{bmatrix}$$

For an orthotropic … t to its principal material directions is as fol…

$$\cdots \; 0 \quad S_{55} \quad 0 \; \Big| \; \tau_5$$

$$\gamma_6 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad S_{66} \; \Big| \; \tau_6$$

$$S_{11} = \frac{1}{E_1} \quad S_{12} = S_{21} = -\frac{\nu_{21}}{E_2} = -\frac{\nu_{12}}{E_1}$$

$$S_{22} = \frac{1}{E_2} \quad S_{13} = S_{31} = -\frac{\nu_{31}}{E_3} = -\frac{\nu_{13}}{E_1}$$

$$S_{33} = \frac{1}{E_3} \quad S_{23} = S_{32} = -\frac{\nu_{32}}{E_3} = -\frac{\nu_{23}}{E_2}$$

$$S_{44} = \frac{1}{G_{23}} \quad S_{55} = \frac{1}{G_{13}} \quad S_{66} = \frac{1}{G_{12}}$$