Module 8: Composite Testing
Lecture 37: Tensile and Compressive Testing

Introduction

In the previous lecture we have introduced the method to assess the quality of the composite and methods to measure the physical properties like density, volume fractions, void content and moisture content. In the lecture we will introduce some methods used for mechanical property characterization.

The Lecture Contains

- Mechanical Property Characterization
- Strain Measurement
- Tensile Testing
- Orthotropic Laminae and Laminate
- Off-Axis Laminae
- Measurement of Modulus
- Compression Testing
- Examples
- Homework

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Module 8: Composite Testing

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Mechanical Property Characterization

The characterization of composites for mechanical properties is very important from design and analysis as well as life prediction point of view. The general considerations for mechanical property characterization have already been seen in the earlier lectures. However, we will revise the key considerations in brief in the following.

1. Specimen must provide desired state of stress and strain
2. Cost of material, fabrication, testing
3. Specimens used to generate the data must be of same fiber volume fractions, thickness and fabrication method.
4. Flat laminates and laminated tube type specimens

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Strain Measurement

The strain measurement along with stress measurement is an essential component of the measurements during the testing. The stress-strain variation depicts the behaviour of the composite material under test. It gives the information about the linear and non-linear behaviour. This information is very essential when one is measuring the other properties like moduli, Poisson's ratios and other engineering properties. When one is deriving the engineering properties from these behaviours then the initial linear portion of the behaviour must be used. This is because in this initial linear behaviour it is assumed that there are no damages due to the loading and plasticity effects, if any, introduced.

There are three commonly used methods to measure the strains. The strains can be measured using extensometers, strain gages and optical methods.

1. Extensometers: They provide average strain over a finite length, typically of the order 1 in (25.4 mm).

   These are used primarily for measurement of axial strains. They can also be used to measure transverse strains.

2. Strain gages: The strain gages can be uniaxial, bi-directional and rosettes. They measure strain in one, two and three directions, respectively.

3. Rosettes: They provide a complete description of the average strain over the region of measurement through strain transformation equations.

The strain gages are available in a range of sizes with smallest of the order 1.59 mm bidirection and rosettes can be stacked or adjacent

The length of the gauge may be specified by the relevant standards, but should always be significantly shorter than the gauge length of the specimen. Composites can cause particular difficulties not encountered with metals. The issues that must be addressed are as follows:

1. High gauge resistances are desirable because high voltages (2–4 V) with low current can then be used; this improves hysteresis effects and zero load stability.
2. If possible, use gauges with lead wires attached, or solder wires to the gauge before installation; this should avoid soldering damage to the composite.
3. Ideally the pattern of the autoclave scrim cloth should be removed before gauge installation; this is particularly important if contact adhesives are used.
4. Corrections may be necessary to gauge transverse sensitivity effects; errors of over 100% between actual and measured strains can be obtained.
5. Gauges must be precisely aligned; errors of 15% can result from a 2° misalignment. There is no universally acceptable way of ensuring alignment. The scrim cloth pattern can be misleading. Sometimes C-scan after installation can be useful or checking with failure surfaces after fracture.
6. Dummy gauges are the preferred method for temperature compensation but, again, precise alignment is needed. It is necessary to mount the dummy gauges on an 'identical' piece of laminate, with the same orientation relative to the fibres as used for the active gauges.

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Rosette Principle

The normal strains are measured along any three directions $\theta_1, \theta_2, \theta_3$ and then strain transformation equations are used to determine global strains $\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}$.

$$\varepsilon_1(\theta_1) = m^2(\theta_1)\varepsilon_{xx} + n^2(\theta_1)\varepsilon_{yy} + m(\theta_1)n(\theta_1)\frac{\gamma_{xy}}{2}$$

$$\varepsilon_2(\theta_2) = m^2(\theta_2)\varepsilon_{xx} + n^2(\theta_2)\varepsilon_{yy} + m(\theta_2)n(\theta_2)\frac{\gamma_{xy}}{2} \qquad (8.7)$$

$$\varepsilon_3(\theta_3) = m^2(\theta_3)\varepsilon_{xx} + n^2(\theta_3)\varepsilon_{yy} + m(\theta_3)n(\theta_3)\frac{\gamma_{xy}}{2}$$
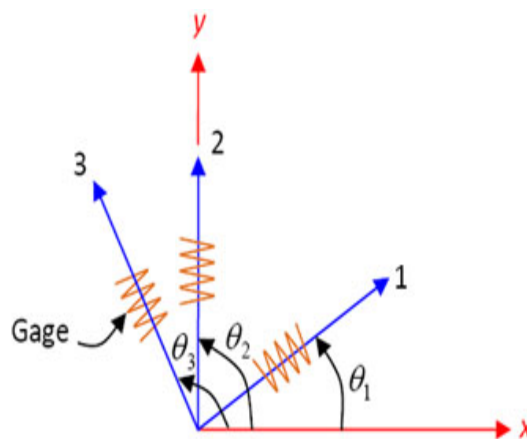

Figure 8.2: Strain gage rosette principle

When the normal strains $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are known then, Eq. (8.7) is a system of three equations with three global strains $\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}$ as the unknowns. It should be noted that when the rosettes are placed on both sides of flat specimen it provides the most complete information as to axial, transverse and shear strains. Further, it provides the information on the development of specimen curvature. The Figure 8.2 shows the arrangement of strain gages in a rosette.

One should pay attention while using the rosettes that the measurements are sensitive to temperature. Hence, appropriate gage should be used for the test. Further, the measurements are sensitive to fiber orientation of the composite and gage alignment. Therefore, it is very important to measure the fibre orientation and gage alignment accurately and must be used appropriately in the analysis of experimental results.

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Tensile Testing

The well known purpose of the tensile testing is to measure the ultimate tensile strength and modulus of the composite. However, one can measure the axial Poison's ratio with additional instrumentations. The standard specimen used for tensile testing of continuous fiber composites is a flat, straight-sided coupon. A flat coupons in ASTM standard D 3039/D 3039M-93 for 0° and 90° have been shown in Figure 8.3(a) and (b), respectively.

The specimen, as mentioned above is flat rectangular coupon. The tabs are recommended for gripping the specimen. It protects the specimen from load being directly applied to the specimen causing the damage. Thus, the load is applied to the specimen through the grips. Further, it protects the outer fibres of the materials. The tabs can be fabricated from a variety of materials, including fiberglass, copper, aluminum or the material and laminate being tested. When the tabs of composite material are used then according to ASTM specifications the inner plies of the tabs should match with the outer plies of the composite. This avoids the unwanted shear stresses at the interface of the specimen and tabs. However, the recent versions of the ASTM standards allow the use of tabs with reinforcement at $\pm 45^{\circ}$. Further, end-tabs can also facilitate accurate alignment of the specimen in the test machine, provided that they are symmetrical and properly positioned on the specimen. The tabs are pasted to the specimen firmly with adhesive.

This specimen can provide data on:

1. The axial modulus E_x,
2. In-plane and through thickness Poisson's ratio γ_{xy}, γ_{xz}
3. Tensile ultimate stress σ_x^{ult},
4. Tensile ultimate strain ε_x^{ult},
5. Any nonlinear, inelastic response

In general, the tensile tests are done on coupons with 0° laminae/laminate for corresponding axial properties and coupons with 90° laminae/laminate for corresponding transverse properties. The off axis laminae specimen also provides data on coefficient of mutual influence and the in-plane shear response.
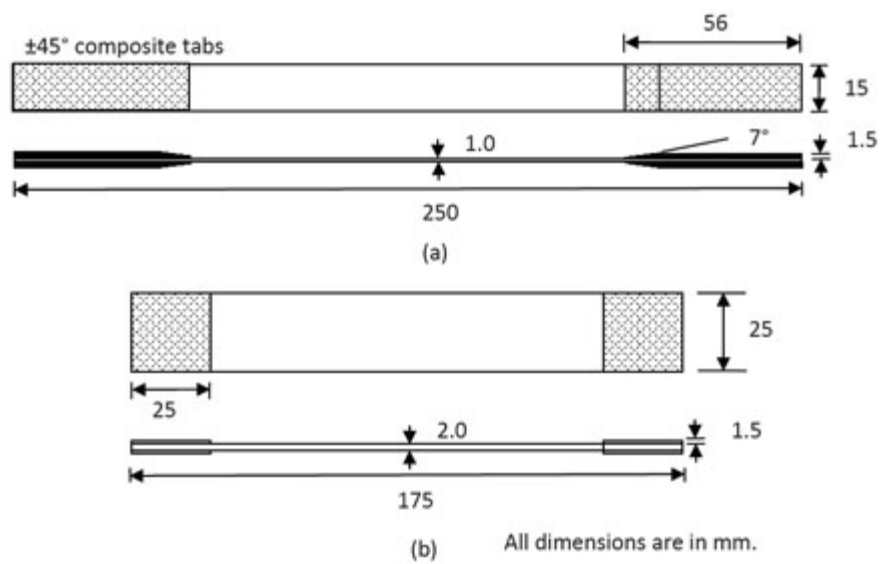
Figure 8.3:Composite tensile test specimens
(a) ASTM D 3039 for 0° and
(b) ASTM D 3039 for 90°.

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Orthotropic Laminae and Laminate:

For orthotropic, symmetric laminates with $0°$ and $90°$ laminae, the effective axial modulus and Poisson's ratio is given as

$$E_x = \frac{1}{a_{11}^*}, v_{xv} = \frac{-a_{12}^*}{a_{11}^*}$$

(8.8)

where, the quantities with asterisk are for laminate as mentioned in Chapter on Laminate Theory. These properties can be measured directly from a tensile test on a specimen of thickness t under axial force per unit length N_x as follows:

$$E_x = \frac{\sigma_{xx}}{\varepsilon_{xx}} = \frac{N_{xx}}{t\varepsilon_{xx}}, v_{xy} = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}}$$

(8.9)

The tensile strength is defined as the average stress at failure. Thus, the tensile strength can be given using the maximum applied force per unit length N_x and thickness t as

$$\bar{\sigma}_x^{ult} = \frac{N_x^{max}}{t}$$

(8.10)

It should be noted that the failure of laminates is often influenced by inter laminar stresses along the free edge effects of the coupon. These factors will be explained in brief in one of the lecture.

The measurement of tensile strength by experiments can also provide information on the comparison of laminate theory with experiments.

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Off-Axis Laminae

One can measure the tensile properties by conducting experiments on off-axis laminae. However, there are certain issues associated with this kind of experiments. For example, the presence of axial-shear coupling is associated with the nonzero a_{16}^* . Alternately, one can say that this term is associated with coefficient of mutual influence $\eta_{xy,x}$. Hence, these tests are not straight forward as in case of symmetric laminates with $0°$ and $90°$ laminae. Therefore, sometimes these tests are called as specialized tests.

When the experiments are conducted to measure the properties like E_x, v_{xy} and v_{xz} one can get the other properties along with these tests. For example, the coefficient of mutual influence $\eta_{xy,x}$, the nonlinear response and strength of an off-axis lamina for given fibre orientation can also be obtained.

There is an important issue associated with these tests is that what boundary conditions one should impose on the specimen? If a pure, uniform state of axial stress $\sigma_{xx} \neq 0, \sigma_{yy} = \tau_{xy} = 0$ can be applied to the ends and sides of a specimen and the specimen is free to assume any desired deformation pattern, the state of stress will be uniform and constant through-out the specimen. The deformation pattern is shown in Figure 8.4(a).

For uniform, far-field axial stress loading, that is $\sigma_{xx} \neq 0$, the stresses in principal material directions can be given as

$$\sigma_{11} = m^2 \sigma_{xx}, \sigma_{22} = n^2 \sigma_{xx}, \tau_{12} = -mn\sigma_{xx} \qquad (8.11)$$

Further, the global elastic constants associated with axial stress loading are measured as

$$E_x = \frac{\sigma_{xx}}{\varepsilon_{xx}}, v_{xy} = -\frac{\varepsilon_{yy}}{\varepsilon_{xx}}, \eta_{xy,x} = \frac{\gamma_{xy}}{\varepsilon_{xx}} \qquad (8.12)$$

Combining above two equations, we get

$$\varepsilon_{11} = \frac{\sigma_{11}}{E_1} - \frac{v_{21}\sigma_{22}}{E_2} = (m^2 - n^2 v_{12})\frac{\sigma_{xx}}{E_1}$$

$$\varepsilon_{22} = -\frac{v_{12}}{E_1}\sigma_{11} + \frac{\sigma_{22}}{E_2} = \left(-\frac{v_{12}m^2}{E_1} + \frac{n^2}{E_2}\right)\sigma_{xx} \qquad (8.13)$$

$$\gamma_{12} = \frac{\tau_{12}}{G_{12}} = \frac{-mn\,\sigma_{xx}}{G_{12}}$$

From the above equation all three strain components can be obtained for non zero value of axial stress. Thus, from the third of the above equation we can find the shear modulus.
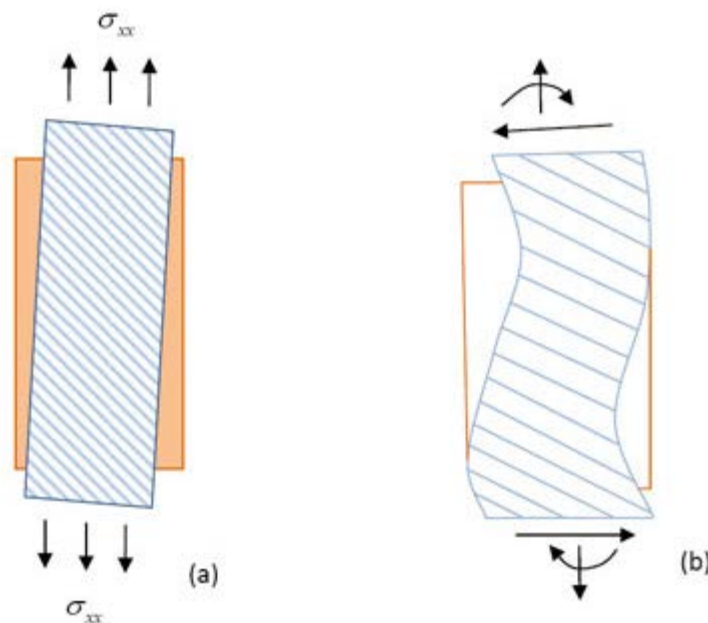
Figure 8.4: Axial load on off-axis laminae with effect of end constraint
(a) unconstrained displacement and
(b) constrained displacement

It is not easy to apply pure, uniform tensile stress to an off-axis coupon. The specimens are gripped in such a manner that the ends of the specimen are constrained and boundary condition is actually a specification of the axial end displacement. Further, there are more issues with these tests like the constrained displacement induces a doubly curved displacement field in the specimen. The deformed shape of the coupon with restrictions on the ends is depicted in Figure 8.4(b). We will not deal the complete analysis for the measurements of the properties with tests on off-axis laminae.

The bone shaped specimens for chopper-fiber, metal matrix composite tensile tests. More details can be seen in ASTM D3552-77(1989). Further, for the tensile testing for transverse properties of hoop-wound polymer matrix composite cylinders are used. The details of this testing can be seen in ASTM D5450/D5450M-93.

Measurement of Modulus

It should be noted that due to progressive damage the stiffness of the lamina or laminae/laminate changes causing the stress strain curve to be non-linear. The measurement of modulus in a tensile testing from a non-linear loading curve can be done by three methods.

In the first method the modulus is taken as a tangent to the initial part of the curve. In the second method a tangent is constructed at a specified strain level. For example, in the Figure 8.5 the modulus is measured at 0.25% strain or 0.0025 strain (Point B). In the third method, a secant is constructed between two points. For example in Figure 8.5 a secant is constructed between points A and B. Typically, the strain values at these points are 0.0005 and 0.0025. In ASTM standards the secant is called as *chord*. The modulus measured by these methods is known as '*initial tangent modulus*', '*B% modulus*' and '*A%-B% secant (chord) modulus*', respectively.
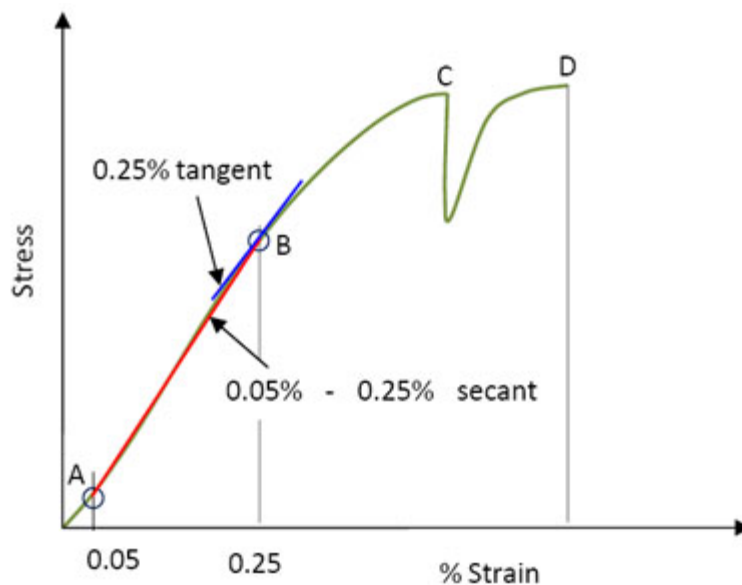

Figure 8.5: Typical tensile stress-strain curve with details

Compression Testing

Most of the structural members include the compression members. Such members can be loaded directly in compression or under a combination of flexural and compression loading. The axial stiffness of such members depends upon the cross-sectional area. Thus, it is proportional to the weight of the structure. One can alter the stiffness by changing the geometry of the cross section within limits. However, some of the composites have low compressive strength and this fact limits the full potential application of these composites.

The compression testing of the composites is very challenging due to various reasons. The application of compressive load on the cross section can be done in three ways: directly apply the compressive load on the ends of a specimen, loading the edges in shear and mixed shear and direct loading. These three ways of imposing the loads for compression testing are shown in Figure 8.6.

During compression loading the buckling of the specimen should be avoided. This demands a special requirement on the holding of the specimen for loading purpose. Further, it demands for special geometry of the specimen. These specimens are smaller in size as compared to the tensile testing specimens. A compression test specimen according to ASTM D695 (modified) standard is shown in Figure 8.7.

The compression testing of composites is a vast topic. Additional reading on this topic from other literature is suggested to readers.
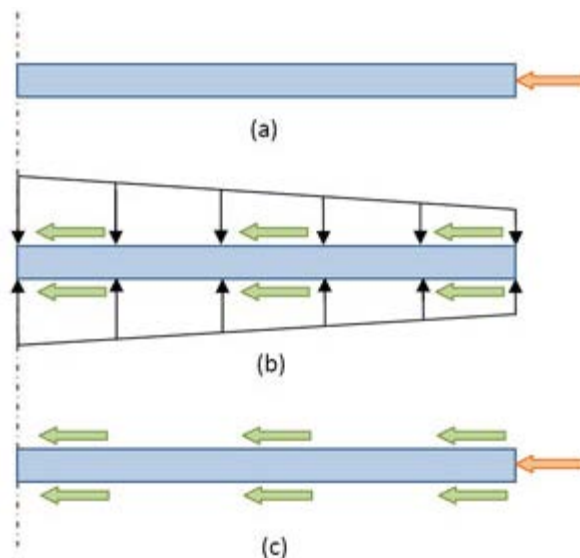

Figure 8.6: Load imposition methods for compression testing. (a) Direct end loading (b) Shear loading and (c) Mixed shear and direct loading
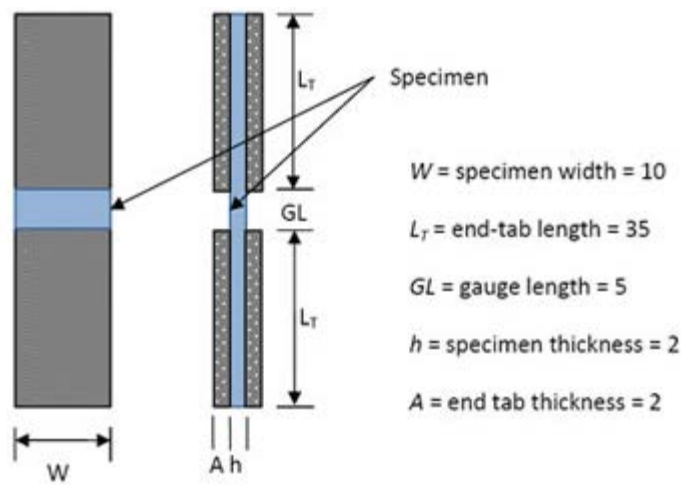
W = specimen width = 10

L_T = end-tab length = 35

GL = gauge length = 5

h = specimen thickness = 2

A = end tab thickness = 2

Figure 8.7: Composite compression test specimen according to ASTM D695 (modified) standard.

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Examples:

Example 8.1

The $45°$ strain rosette is mounted on a structure as shown in Figure below. The readings in each strain gage are $\varepsilon_a = 600 \times 10^{-6}, \varepsilon_b = -400 \times 10^{-6}$, and $\varepsilon_c = 500 \times 10^{-6}$. Determine the strains in global directions.
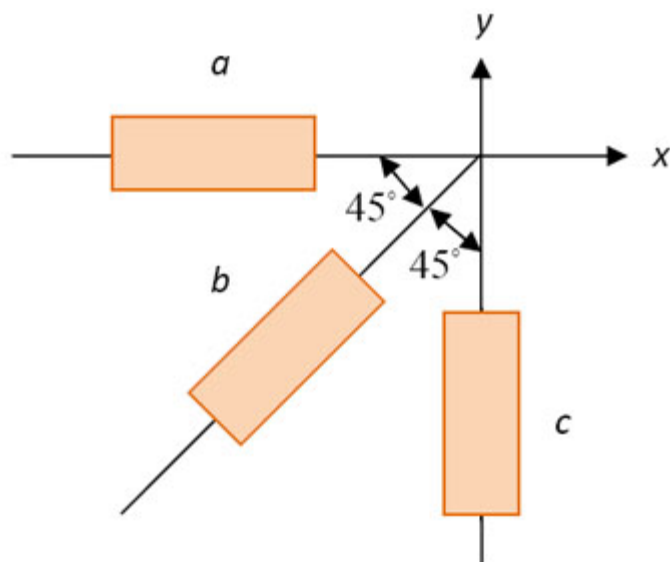

Figure: Rosette on a structure (Example 8.1)

Solution:

From the figure, we have the following data:

$$\theta_a = 180°, \theta_b = 225°, \theta_c = 270° \text{ and}$$
$$\varepsilon_a = 600 \times 10^{-6}, \varepsilon_b = -400 \times 10^{-6}, \varepsilon_c = 500 \times 10^{-6}$$

Applying Equation (8.7), we get

$$\varepsilon_a = 600 \times 10^{-6} = \varepsilon_{xx} \cos^2(180°) + \varepsilon_{yy} \sin^2(180°) + \gamma_{xy} \sin(180°)\cos(180°)$$
$$\varepsilon_b = 400 \times 10^{-6} = \varepsilon_{xx} \cos^2(225°) + \varepsilon_{yy} \sin^2(225°) + \gamma_{xy} \sin(225°)\cos(225°)$$
$$\varepsilon_c = 500 \times 10^{-6} = \varepsilon_{xx} \cos^2(170°) + \varepsilon_{yy} \sin^2(170°) + \gamma_{xy} \sin(170°)\cos(170°)$$

Solving, we get

$$\varepsilon_{xx} = 600 \times 10^{-6}$$
$$\varepsilon_{yy} = 500 \times 10^{-6}$$
$$\gamma_{xy} = -1900 \times 10^{-6}$$

Example 8.2

The $45°$ strain rosette is mounted on a wing as shown in Figure below. The readings in each strain gage obtained are $\varepsilon_a = 300 \times 10^{-6}, \varepsilon_b = -200 \times 10^{-6}$, and $\varepsilon_c = -500 \times 10^{-6}$. Determine the strains in global directions.
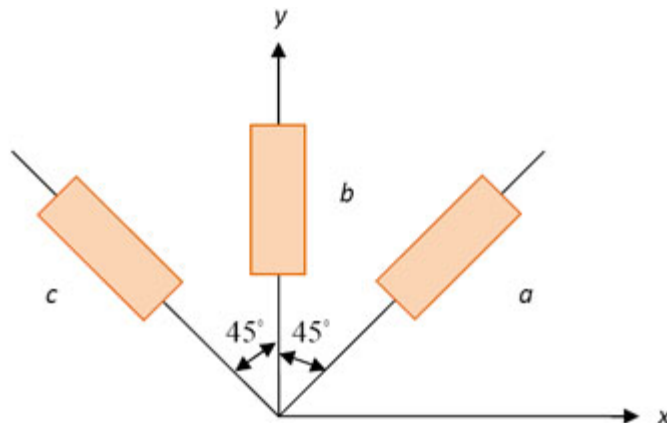

Figure: Rosette on a wing (Example 8.2)

Solution:

From the figure, we have the following data:

$$\theta_a = -45°, \theta_b = 90°, \theta_c = 135° \text{ and}$$
$$\varepsilon_a = 300 \times 10^{-6}, \varepsilon_b = -200 \times 10^{-6}, \varepsilon_c = -500 \times 10^{-6}$$

Applying Equation (8.7), we get

$$\varepsilon_a = 300 \times 10^{-6} = \varepsilon_{xx}\cos^2(45°) + \varepsilon_{yy} \sin^2(45°) + \gamma_{xy} \sin(45°)\cos(45°)$$
$$\varepsilon_b = -200 \times 10^{-6} = \varepsilon_{xx} \cos^2(90°) + \varepsilon_{yy} \sin^2(90°) + \gamma_{xy} \sin(90°)\cos(90°)$$
$$\varepsilon_c = -500 \times 10^{-6} = \varepsilon_{xx} \cos^2(135°) + \varepsilon_{yy} \sin^2(135°) + \gamma_{xy} \sin(135°)\cos(135°)$$

Solving, we get the following set of equations

$$\varepsilon_{xx} + \varepsilon_{yy} + \gamma_{xy} = 600 \times 10^{-6}$$
$$\varepsilon_{yy} = -200 \times 10^{-6}$$
$$\varepsilon_{xx} + \varepsilon_{yy} - \gamma_{xy} = -1000 \times 10^{-6}$$

Putting the value of $\varepsilon_{yy} = -200 \times 10^{-6}$ in the first and third of above relation and upon solving them, we get

$$\varepsilon_{xx} = 0$$
$$\gamma_{xy} = 800 \times 10^{-6}$$

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Home Work:

1. What are the methods for strain measuring? Explain in detail the rosette principle.

2. What are the key points in tensile testing?

3. Explain the method of measuring the tensile modulus using symmetric laminates with $0°$ and $90°$ laminae.

4. Explain the method of measuring the tensile modulus using off-axis laminae.

5. Explain the method to measure the modulus from stress-strain curve.

6. Write a short note on compression testing.

7. What are the ways of imposing a compression load on a specimen for compression testing?

8. The $60°$ strain rosette is mounted on a shaft as shown in Figure below. The following readings are obtained for each gage: $\varepsilon_a = 200 \times 10^{-6}$, $\varepsilon_b = -450 \times 10^{-6}$, and $\varepsilon_c = 250 \times 10^{-6}$. Determine the strains in global directions.
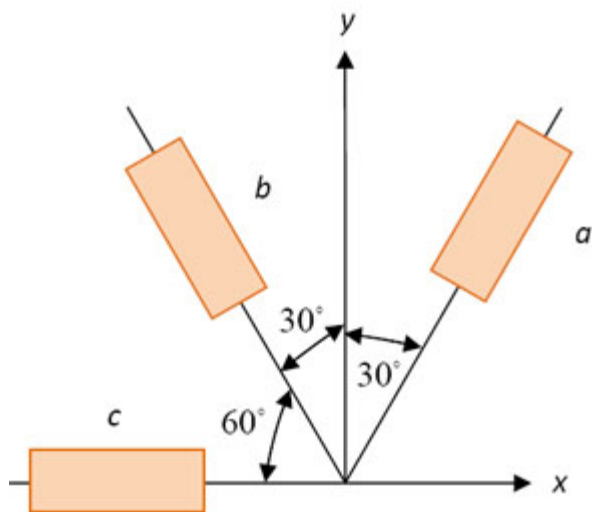

Figure: Rosette on a shaft

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