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Lamina Thermoelastic Response

Most materials change their dimensions as the temperature is changed. Thermal expansion is defined as the change of dimensions of a body or material as a result of a temperature change. Such a property is very important in the application of composite materials in structures that undergo temperature changes, such as engine parts and space structures. The material property constant describing this phenomenon is the coefficient of thermal expansion (CTE), indicated by the symbol α , and defined as

$$\alpha = \frac{\Delta\varepsilon}{\Delta T} \quad (10.1)$$

where $\Delta\varepsilon$ is the increment of strain measured for an unconstrained material subject to a temperature change, ΔT . For an orthotropic composite lamina under plane deformation, Equation (10.1) becomes

$$\alpha_1 = \frac{\Delta\varepsilon_1}{\Delta T} \quad (10.2a)$$

$$\alpha_2 = \frac{\Delta\varepsilon_2}{\Delta T} \quad (10.2b)$$

where $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ are the thermally induced strains in the principal material directions.

Several methods have been devised for measuring thermal expansion coefficients of composite materials [1]. Basically, this determination requires a controlled temperature chamber and a deformation measuring device. ASTM Standards E228 [2], D696 [3], and E831 [4] propose using a vitreous silica dilatometer or thermomechanical analysis (TMA) apparatus for materials with CTE values as small as $5 \times 10^{-6}/^\circ\text{C}$. ASTM Standard E289 [5] describes a method based on interferometry, which permits determination of CTE of materials with extremely small thermal expansion coefficients, as low as $10^{-8}/^\circ\text{C}$, over a large temperature range. For composites, strain gages have been successfully used for measuring thermal expansion coefficients as low as about $10^{-5}/^\circ\text{C}$ [6–8]. Strain gages are readily available and require

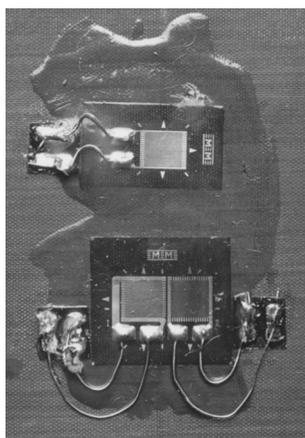


FIGURE 10.1

Typical carbon/epoxy specimen fitted with strain gages (bottom) and temperature sensor (top).

no special apparatus except for the strain-reading instrument. Strain gages may be bonded to the surface of a specimen or embedded between the plies in a laminate. Here, we will restrict attention to surface-bonded strain gages.

The test specimen used for determining the CTEs of a unidirectional lamina or woven fabric ply using strain gages should be a flat panel. Although the in-plane dimensions are not critical, a commonly used specimen size is 50×50 (mm) (Figure 10.1). The thickness of the panel is commonly about 1 mm. Panels that are too thin are easily cracked if they are unidirectional, and panels that are too thick require a long soaking time to achieve thermal equilibrium (uniform temperature). The temperature can be monitored with a temperature sensor or a thermocouple. The temperature range should be selected with regard to the type of strain gages and sensors used and the temperature capability of the resin in the composite. For a typical 175°C -cure epoxy–matrix composite, a suitable temperature range is 20 to 150°C . Because moisture induces dimensional changes in many resin systems, it is important to dry the specimens in an oven at 70°C until the weight stabilizes before measuring the thermal strains. As discussed in Reference [1], an important limitation of strain gages is their upper use temperature. Maximum-accuracy gages can only be used up to 65°C [9]. Other types of strain gages may be used to extend this range. Another important limitation of the use of strain gages is undesirable local reinforcement of the test material by the metal foil strain gage [1]. At elevated temperatures the transverse stiffness of unidirectional polymer–matrix composites will decrease as a result of softening of the matrix resin. Local reinforcement of the tested material by the gage would lead to apparent CTE values that are too small.

The adhesive bond between the strain gage and specimen is also an important factor when measuring CTE with strain gages. Because it is typically a polymer resin, the adhesive may soften at elevated temperatures and exhibit viscoelastic creep or stress relaxation effects that would

influence the strain readings. Selection of strain gage adhesive to match the anticipated temperature range is thus important.

10.1 Temperature Gage Sensing System

To monitor temperature, it is convenient to use a resistance gage circuit, which allows the experimenter to monitor the temperature of a test specimen while simultaneously taking strain readings. The temperature gage (such as a Micro Measurements Type ETG-50B or equivalent [9]) consists of a sensing grid of high-purity nickel foil that is bonded to the specimen by standard strain gage techniques using a high-temperature adhesive (M-Bond 600 or equivalent [9]) (Figure 10.1). This temperature sensor exhibits a linear change in resistance with temperature.

After the gage has been properly mounted and wired, it is connected to the gage scanning equipment along with the other strain gages being used. A special resistance network (Micro Measurements Type LST-10F-350D, or equivalent [9]) may be incorporated in the circuit, which modifies the gage signal, producing a direct readout of the temperature in degrees celsius or fahrenheit. The temperature readout is set to room temperature before testing, and then the proper gage factor is set. Lead wires exposed to temperatures greater than about 75°C should be protected with a high-temperature plastic wrap. Many laboratories use thermocouples as an alternative to temperature gages. One or several thermocouples may be attached to the specimen.

10.2 Temperature Compensation

In nonisothermal applications of strain gages, techniques must be employed to compensate for changes in the performance characteristics of the gages resulting from a change in temperature [10]. The change in performance of the gage relates to the following:

- The gage dimensions change with temperature.
- The resistance of the gage changes with temperature.
- Transverse strain sensitivity of the gage (Chapter 4) will induce an error in the measurements.
- The gage factor may change with temperature.

To account for the influence of some of these factors, consider a strain gage bonded to a composite specimen. For a given temperature change $\Delta T = T - T_0$,

where T_0 is the initial temperature, the relative change in gage resistance, $\Delta R/R$, may be expressed as

$$(\Delta R/R) = (\alpha_c - \alpha_g)S_g\Delta T + \gamma\Delta T \quad (10.3)$$

where α_c and α_g are the CTEs of the composite and the gage, respectively; γ is the temperature coefficient of resistivity of the gage material; and S_g is the gage factor, here assumed to be constant. For a large temperature change, it is also necessary to take into account the temperature dependence of the gage factor. Thus, the gage will be subjected to a strain mismatch of $(\alpha_c - \alpha_g)\Delta T$. If the coefficient γ is not zero, the strain measuring system will record an apparent strain that physically does not exist. To correct the apparent strain reading, a common temperature compensation method includes a reference gage, identical to the one bonded to the composite, mounted on a substrate with known CTE. For the gage bonded to the composite, Equation (10.3) gives

$$(\Delta R_1/R) = (\alpha_c - \alpha_g)S_g\Delta T + \gamma\Delta T \quad (10.4a)$$

and for the gage bonded to the reference substrate,

$$(\Delta R_2/R) = (\alpha_r - \alpha_g)S_g\Delta T + \gamma\Delta T \quad (10.4b)$$

where α_r is the CTE of the reference substrate. Combining of Equations (10.4) yields

$$\alpha_c = \alpha_r + \frac{\Delta R_1 - \Delta R_2}{RS_g\Delta T} \quad (10.5)$$

or equivalently,

$$\alpha_c = \alpha_r + (\epsilon_c - \epsilon_r)/\Delta T \quad (10.6)$$

where ϵ_c and ϵ_r are the strain readings for the composite and the reference substrate, respectively.

If the gages are connected in a Wheatstone half-bridge, the changes in resistance of the two gages, ΔR_1 and ΔR_2 , are subtracted (Figure 10.2). Thus, the output voltage of the bridge is directly proportional to the difference $(\epsilon_c - \epsilon_r)$.

The choice of reference material should be determined by the anticipated magnitude of α_c . If the values of α_c and α_r are very close, the apparent strain measured, $\epsilon_c - \epsilon_r$, will be very small and the sensitivity of the measurement will suffer. A common reference material is quartz (with $\alpha_r \approx 0.56 \times 10^{-6}/^\circ\text{C}$). Consequently, measurements of CTEs less than $0.56 \times 10^{-6}/^\circ\text{C}$ may exhibit poor resolution. In addition, the accuracy of the gage and strain measuring

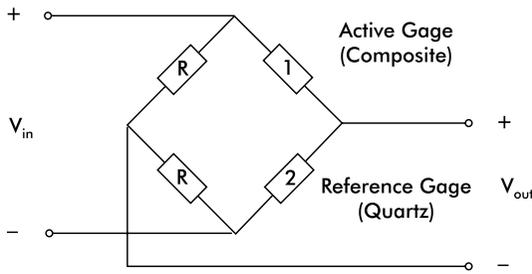


FIGURE 10.2
Wheatstone half bridge circuit.

system, typically $\pm 2 \times 10^{-6}$, may limit the accuracy of the measurement of small CTEs.

To measure the generally very small CTEs in the fiber direction of unidirectional composites (see Table 1.2) with sufficient accuracy, it may be necessary to use the dilatometric or interferometry techniques mentioned early in this chapter.

10.3 Measurement of Thermal Expansion

1. Bond two strain gages (Micro Measurements Type WK-06-125AC or equivalent [9]) and one temperature sensor (or thermocouple) to the composite specimen. Align the strain gages (Figure 10.1) parallel to the principal material directions. Use a high temperature strain gage adhesive cured according to adhesive specifications. Locate the strain gages and temperature sensor near the specimen center and on the same side to minimize the possible influence of thermal gradients.
2. Place the composite specimen and the reference material inside a laboratory oven (near the center). The gage lead wires inside the oven should be protected by a temperature-resistant coating such as Teflon.
3. Connect the strain gages and the temperature sensor (or thermocouple, or both) to the recording system.
4. Raise the oven temperature slowly to 150°C. Monitor the oven thermometer, making strain and temperature measurements at regular temperature intervals. After a temperature of 150°C is reached, reduce the oven temperature slowly to room temperature. Take strain and temperature measurements also during this cool down period. Occasionally some composites display hysteresis during the first cycle, but stabilize during subsequent cycles. Multiple temperature cycles are therefore desirable.

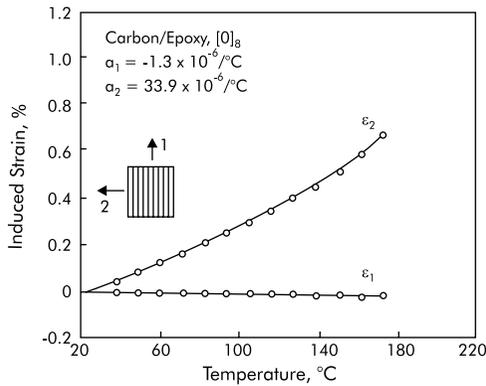


FIGURE 10.3

Thermal expansion strains for a carbon/epoxy composite. (From Whitney, J.M., Daniel, I.M., and Pipes, R.B., *Experimental Mechanics of Fiber Reinforced Composite Materials*, rev. ed., Prentice-Hall, Englewood Cliffs, NJ, 1984. With permission.)

10.4 Data Reduction

From the apparent strain measured via the half bridge, $\epsilon_A = \epsilon_c - \epsilon_r$, the actual strain, ϵ_c , is determined from Equation (10.6),

$$\epsilon_c = \alpha_t \Delta T + \epsilon_A \quad (10.7)$$

Plot ϵ_c vs. the temperature, T , or the change in temperature, $\Delta T = T - T_0$, where T_0 is the initial temperature of the specimen. Figure 10.3 shows typical thermal strain data for a carbon/epoxy specimen upon heating [6]. To determine the CTE in the actual temperature range, evaluate the slope of the strain vs. temperature plot. Figure 10.4 shows examples of plots of thermal strains vs. temperature for Kevlar (E.I. du Pont de Nemours and Company)/epoxy and S-glass/epoxy composites. The determination of CTE discussed here inherently assumes linear expansion over the temperature range considered. For polymers at temperatures above their glass transition temperature, T_g , the CTE is larger than at temperatures below T_g . Such phenomena and other factors make the expansion vs. temperature curve more complex, and sometimes nonlinear. For such cases it is common to specify a temperature range of interest and calculate CTE for this range using a linear least-squares fit.

Hysteresis is often observed upon cooling (Figure 10.5). Hysteresis is generally thought to be a result of viscoelastic creep and stress relaxation effects in the adhesive that bonds the gage to the specimen that are magnified by the increased temperature. It is also possible that residual thermal stresses in the composite will relax at elevated temperatures, which may change the dimensions. Higher rates of temperature change appear to

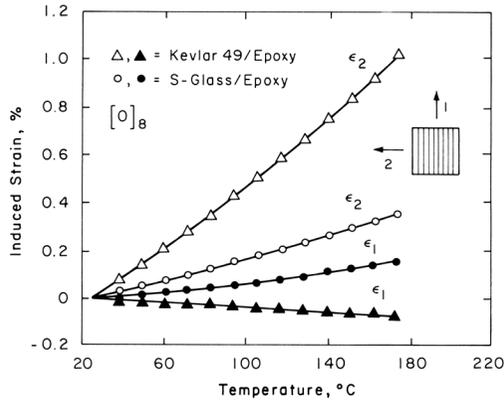


FIGURE 10.4

Thermal expansion strains for Kevlar/epoxy and S-glass/epoxy composites. Kevlar/epoxy: $\alpha_1 = -4.0 \times 10^{-6}/^\circ\text{C}$, $\alpha_2 = 57.6 \times 10^{-6}/^\circ\text{C}$. S-glass/epoxy: $\alpha_1 = 6.6 \times 10^{-6}/^\circ\text{C}$, $\alpha_2 = 19.7 \times 10^{-6}/^\circ\text{C}$. (From Whitney, J.M., Daniel, I.M., and Pipes, R.B., *Experimental Mechanics of Fiber Reinforced Composite Materials*, rev. ed., Prentice-Hall, Englewood Cliffs, NJ, 1984. With permission.)

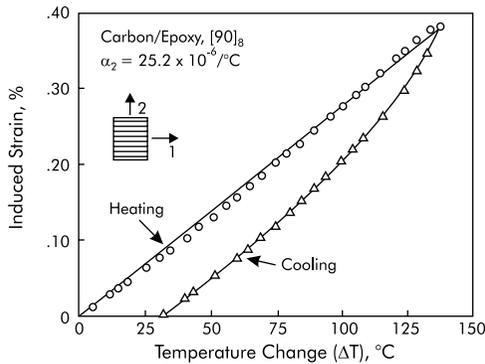


FIGURE 10.5

Thermal expansion response in the transverse direction for a carbon/epoxy composite showing hysteresis upon cooling.

produce more hysteresis, indicating that the material is not in thermal equilibrium. However, at lower temperatures the slopes of the heating and the cooling curves are consistent.

References

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