Resistance-foil Strain-gage Technology as Applied to Composite Materials

by M.E. Tuttle and H.F. Brinson

ABSTRACT—A general review of existing strain-gage technologies as applied to orthotropic-composite materials is given. The specific topics addressed are gage-bonding procedures, transverse-sensitivity effects, errors due to gage misalignment, and temperature-compensation methods. The discussion is supplemented by numerical examples where appropriate.

It is shown that the orthotropic behavior of composites can result in experimental error which would not be expected based on practical experience with isotropic materials. In certain cases, the transverse sensitivity of strain gages and/or slight gage misalignment can result in strain-measurement errors exceeding 50 percent.

Introduction

In recent years the use of advanced composite materials has expanded into a wide variety of market places. Products that have been fabricated, at least in part, from composite materials include aircraft structures, space vehicles, rocket-motor cases, turbine blades, automobile components, pressure vessels, and a variety of sporting goods. All indications are that composites will become an increasingly important structural-material system, primarily due to their very high strength-to-weight ratios.

During these developments the stress analyst has been called upon to experimentally determine the mechanical properties of these new material systems. Many of the same experimental methods and techniques used to study conventional isotropic materials have been used to study composite materials which are both orthotropic and heterogeneous. Because most practical experience is based upon the familiar behavior of isotropic materials, composites can exhibit surprising and unusual behavior which may lead to erroneous interpretation of experimental results.

This paper consists of a review of existing strain-gage technologies as applied to orthotropic-composite materials. Although the discussion centers around epoxy-matrix composites, many of the comments made also apply to metal-matrix composites or, for that matter, to any orthotropic material.

It should be noted that isolated aspects of this subject have been alluded to by several researchers. For example, Whitney, Daniel, and Pipes[1] have briefly described temperature-compensation techniques and the importance of correcting for transverse-sensitivity effects. Chamis and Sinclair[2] have mentioned that gage alignment is of critical importance when testing a 10-deg off-axis tensile specimen. However, to the authors' knowledge this is the first time in which many of the important aspects of this subject have been fully documented with analysis and graphs for easy interpretation. In particular, the errors due to misalignment of gages on orthotropic materials have not been fully documented previously, although these effects have been mentioned. Also included is a section on specimen-preparation procedures which should prove to be especially useful to the experimentalist.

The specific topics addressed are: strain-gage-selection criteria, gage-bonding procedures, transverse-sensitivity effects, gage-misalignment errors, and temperature-compensation methods. Each of these topics is discussed in a separate section below, followed by a discussion and conclusion section. The effects of orthotropic-material behavior is emphasized throughout. The discussion is supplemented by numerical examples where appropriate.

Strain-gage-selection Criteria

One of the first steps in any experimental program involving the use of strain gages is selection of the appropriate gage type. In general, the conditions under which the gages will be used must be considered when selecting the strain gage. For general-purpose strain gaging, some of the parameters involved in this selection are:

—surface contour of the test specimen,
—degree of heterogeneity of test material,
—thermal-expansion characteristics of test material,
—thermal-conduction characteristics of test material,
—test-environmental conditions
—maximum expected strain levels,
—maximum expected strain-field gradients,
—test duration,
—stress-field characteristics (i.e., unknown biaxial-stress, field vs. known biaxial-stress field), and
—desired level of measurement accuracy and stability.

Generally speaking, epoxy-matrix composites do not place requirements on strain-gage capabilities which are more demanding than those posed by other materials. As examples, the heterogeneity of composites is related to the characteristic fiber dimension (about 1 mil in diameter or less) and is not of major concern. Composites are generally not used in environments which would be damaging to most strain-gage types, and maximum-strain levels usually do not exceed two to three percent.

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Once the various testing parameters affecting strain-gage performance have been identified, a specific gage type may be selected from the multitude of strain-gage designs commercially available. This selection will involve specifying (at minimum) the following gage parameters[3]:

—a strain-sensitive gage alloy,
—a backing (carrier) material,
—a gage length,
—a gage pattern,
—a self-temperature-compensation number, and
—a gage (grid) resistance.

Due to the wide diversity of possible applications, further discussion describing the general process of gage selection is beyond the scope of this paper. The interested reader is referred to the literature on gage selection (see for example Refs. 3 and 4). However, there are a few initial considerations common to all strain-gage installations involving epoxy-matrix composite materials. These are (at least) gage-excitation levels, self-temperature compensation, and the attachment of leadwires to the gage.

Strain-gage-excitation Levels

It is well known that when strain gages are mounted to polymeric materials, the gage-excitation level must be kept to a relatively low level. This is because polymeric materials are poor thermal conductors; hence the flow of heat away from the gage site is retarded, as compared to most metallic materials. If gage-excitation levels are excessive, gage performance is adversely affected in a variety of ways. These include a loss of self-temperature compensation, an increase in hysteresis and creep effects, and a decrease in zero (no-load) gage stability.[5]

The first effect listed is not particularly important when strain gaging composites, since self-temperature compensation is not normally used, as will be seen. The second and third factors are important, however, and are directly related to the thermal conductivity of the composite.

The thermal conductivity of the epoxy matrix alone (referred to as the 'neat resin') is quite low, as would be expected. The effective thermal conductivity of most epoxy-matrix composites is higher than the neat resin, however, due to the relatively high thermal conductivity of the fibers. Nevertheless, gage excitation remains an important consideration.

A detailed discussion of strain-gage excitation levels can be found in Ref. 5. As a general rule, high-grid resistances are desired; they allow relatively high bridge-excitation levels while still maintaining low gage-current levels. This provides for good gage stability while still allowing reasonable gage sensitivity. As a 'ball park' estimate of acceptable excitation levels, the authors have found that a power density in the range of about 0.31 kW/m^2 (0.2 W/in.^{2}) to 1.20 kW/m^2 (0.77 W/in.^{2}) is appropriate for use with graphite-epoxy composites. Having selected an appropriate power density, the bridge-excitation level (and gage current) is determined by the specific grid geometry and resistance selected. Using the Micro-Measurements gage EA-06-125AC-350 as an example, the above power densities correspond to excitation levels ranging from about 2 to 4 v.

Self-temperature Compensation Number

A strain gage is said to be self-temperature compensated when the strain-gage alloy is processed so as to minimize apparent strain due to temperature effects. The gage manufacturer provides an apparent strain curve with each strain gage which represents the nominal gage response with temperature when mounted to the appropriate material. This technique normally lowers apparent strains to levels less than about 100 μin./in. over a temperature range of about −20 to 205 °C (0 to 400 °F).

This compensation technique is not well suited for use with composite materials. The major difficulty is that the thermal expansion of composites is in general a highly orthotropic material property, making the selection of an appropriate S-T-C number difficult if not impossible. Since S-T-C is not normally used with composites, the selection of the gage S-T-C number becomes somewhat arbitrary; usually a relatively low S-T-C number is selected, e.g., an S-T-C number of 00 or 06.

Attachment of Gage Leadwires

A common concern when attaching leadwires is the possibility of damaging the composite specimen during soldering. This is probably not a problem if a low-temperature solder is used and installation is performed by an experienced technician. However, this may be of concern if a high-temperature solder is used, where the soldering-tip temperature may exceed 305 °C (580 °F), or if inexperienced personnel are used to install the gage. In either case excessive amounts of heat may be introduced into the composite substrate, possibly causing local damage in the form of broken fibers, damaged epoxy matrix, or both. In these instances it is advisable to either purchase strain gages with preattached leadwires, or to solder the leadwires to the strain gage prior to gage installation.[6]

Strain-gage-bonding Procedures

The procedures used to adhesively bond strain gages to composite materials are very similar to those used with more conventional structural materials such as steel or aluminum. Composites do require some additional considerations, however, as discussed below.

Selection of Adhesive

To the authors' knowledge, all commercially available strain-gage adhesives are compatible with epoxy-matrix composite materials. However, a concern arises when adhesives requiring an elevated-temperature-cure cycle are used. Possible problems in these cases include the following.

(1) The glass-transition temperature (T_g) of polymer-matrix composites is typically in the range of 135-232 °C (275-450 °F), whereas many of the elevated-temperature adhesives are normally cured at or above these temperatures. If the temperature of an unconstrained composite specimen is near (for a long time) or above (for a short time) the T_g during curing, specimen warping often occurs.

(2) Many of the mechanical properties of polymeric materials, especially the viscoelastic properties, are dramatically affected by previous thermal excursions at or near the T_g.[7] To assure representative and repeatable material response, composite specimens are often subjected to a carefully controlled postcure thermal cycle.[8-10] This careful thermal conditioning can be destroyed if a gage assembly is subsequently cured at temperatures near the T_g.

These potential difficulties can often be avoided by using the lowest curing temperatures possible with the

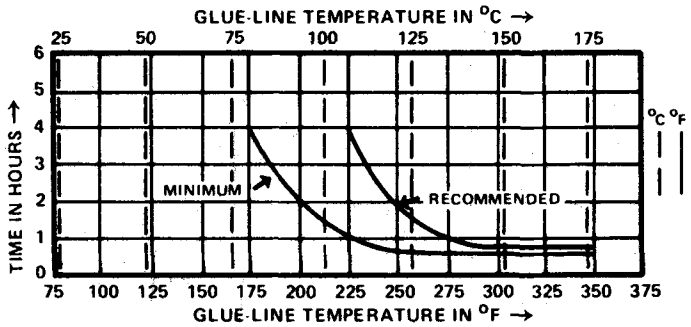


Fig. 1—Recommended curing times and temperatures for the M-Bond 600 strain-gage adhesive system[11]

adhesive system being used, which usually necessitates long curing times. As an example, appropriate curing times vs. curing temperatures published by Micro-Measurements for the M-Bond 600 adhesive system are shown in Fig. 1.[11] Both a 'recommended' cure cycle and a 'minimum' cure cycle are indicated. The authors have found that for gages bonded to T300/5208 graphite-epoxy, with a T_g of about 163 °C (325 °F), M-Bond 600 cured at 85 °C (185 °F) for a period of eight hours or greater will provide a very satisfactory adhesive bond, while still avoiding any perturbation of the careful thermal conditioning these specimens are subjected to during preparation. Thus, the lower cure temperature avoids the potential problems described above. This approach must be used with caution however, because if the cure temperature is too low, the epoxy adhesive will not form a properly gelled glass during cure but rather a weak and brittle ungelled glass.[12] Therefore in some cases it may be necessary to incorporate the adhesive-cure cycle with the post-cure cycle.

Surface Preparation

In conventional strain-gage practice, the specimen surface is usually abraded so as to provide a surface appropriate for adhesive bonding. The amount of abrasion required depends of course on the original condition of the surface. For general-purpose strain gaging, a surface finish in the range of 1.6-3.2 μm rms (63-125 μin. rms) is normally recommended.[13]

Many composites are routinely produced with a very smooth surface finish, and require very little (if any) surface abrasion. In other cases a cloth-like pattern is imprinted on the surface of the composite during fabrication by the scrim cloth. This relatively rough surface usually requires some preparation prior to strain-gage bonding, although strain gages have been successfully bonded directly to this surface for tests conducted at room temperature.[14] For tests conducted at even moderately elevated temperatures the cloth-like surface pattern can result in bond failure, however.

Two methods to provide a surface suitable for adhesive bonding have been investigated by Yeow,[15] and further refined and reported by Griffith, *et al.*[14] The first method is to apply an epoxy precoat (Epoxylite 5403) to fill the surface irregularities. It was thought that this procedure was advantageous in that it avoids any possible damage to the composite due to more conventional surface abrasion. While this procedure does eliminate bond failure, the resulting bond line is relatively thick, resulting in high levels of adhesive creep, particularly at elevated temperatures. Therefore, a second method of surface preparation was investigated, which involves very light surface abrasion, using 320-400 grit paper. With this technique one to two mils of material is removed from the specimen surface, resulting in an acceptably smooth surface. The thin surface layer removed is a resin-rich area. A slight change in mechanical properties due to this abrasion was anticipated. No changes could be detected, however. This method proved to be the superior procedure. It should be emphasized that abrasion must be kept to a minimum, however, to avoid possible damage to fibers in the outer ply of the composite laminate.

The general procedures followed during surface preparation are as follows.

—initial cleaning of the specimen using propanol or freon,
—light surface abrasion using 320-400 grit paper (if required), and
—thorough cleaning of the specimen using propanol or freon, M-Prep Conditioner A, and M-Prep Neutralizer 5.

Following surface preparation the gage is mounted to the specimen using the procedures recommended for the adhesive being used. At times there is a concern that water-based cleaning agents may increase specimen moisture content, particularly if an adhesive which is cured at room temperature (rather than at an elevated temperature) is used. In these cases it is advisable to heat the specimen to a moderately high temperature for a few hours prior to gage bonding.

Note that it is not possible to use burnished alignment marks to aid in strain-gage alignment, as is common practice with conventional structural materials such as steel or aluminum. Subsequently, strain gages are often mounted 'by eye.' It will be shown later in this paper that misalignment errors of only a few degrees can produce large errors in strain measurement under certain conditions. Hence, the practical difficulties associated with gage alignment will be seen to be of some importance.

Transverse-sensitivity Effects

The term 'transverse sensitivity' refers to the fact that a strain gage will, in general, respond to a strain field acting perpendicular to the major axis of the gage. This effect is due to a variety of factors, including grid geometry, gage alloy, gage-backing and encapsulation materials, and several manufacturing variables. Transverse sensitivity is an undesirable effect since it results in a strain reading which is a combination of the gage response to both axial and transverse strains. As several authors have noted,[1,2] strain measurements obtained using strain gages mounted to composite materials are especially susceptible to transverse-sensitivity errors. This propensity

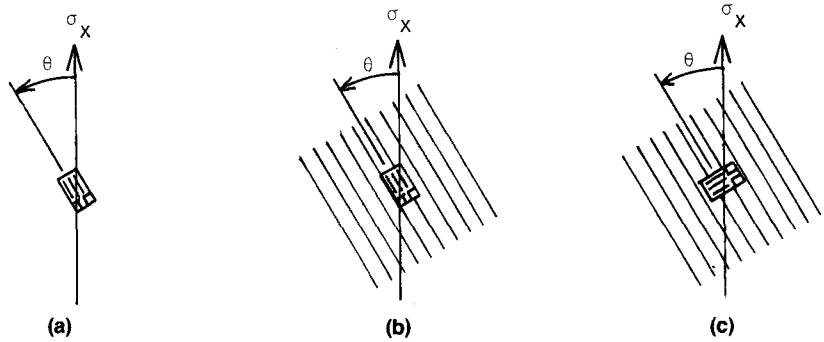


Fig. 2—Assumed loading configurations illustrating transverse-sensitivity effects, (a) gage on isotropic material, (b) gage mounted parallel to fibers (Orientation I), (c) gage mounted transverse to fibers (Orientation II)

towards error is directly due to the highly orthotropic behavior of composite materials, as will be shown below.

An excellent review of the data reduction procedures used to correct for transverse sensitivity was recently presented in Ref. 16. Therefore, a limited review of the concepts involved in correcting for transverse sensitivity will be given here; the reader is referred to Ref. 16 if greater detail is desired.

When a strain gage is exposed to a strain field, a small change in grid resistance occurs which is given by

$$\frac{\Delta R}{R} = F_a\epsilon_a + F_t\epsilon_t \tag{1}$$

where

ΔR = change in gage resistance
R = original gage resistance
ϵ_a = strain parallel to major axis of gage
ϵ_t = strain perpendicular to major axis of gage
F_a = axial-gage factor
F_t = transverse-gage factor

The transverse-sensitivity coefficient of the strain gage is defined as

$$K = \frac{F_t}{F_a} \tag{2}$$

This coefficient is one of the calibration parameters supplied by strain-gage manufacturers with each strain gage. The value of K is normally within a range of about -0.05 to 0.05. (Note that gage manufacturers customarily report K as a percentage value, so the range of K as reported by gage manufacturers is from -5 to 5 percent.)

Equation (1) can now be written in terms of K:

$$\frac{\Delta R}{R} = F_a(\epsilon_a + K\epsilon_t) \tag{3}$$

During calibration of the strain gage by the manufacturer, the strain gage is mounted to a standard calibration material and subjected to a uniaxial-stress field. The major axis of the strain gage is parallel to the stress field. Under these conditions, the transverse strain applied to the gage is due to the Poisson effect, and is equal to

$$\epsilon_t = -\nu_0\epsilon_a$$

Equation (3) can be written for this case as

$$\frac{\Delta R}{R} = F_a(1 - \nu_0 K)\epsilon_a \tag{4}$$

where

ν_0 = Poisson's ratio of the calibration material used by the gage manufacturer (normally $\nu_0 = 0.285$)

Finally, the 'gage factor' supplied by the manufacturer is defined as

$$F_g = F_a(1 - \nu_0 K) \tag{5}$$

Under strain conditions in which transverse-sensitivity effects are negligible, the strain measured by a strain gage is given by the familiar equation,

$$\epsilon_m = \frac{\frac{\Delta R}{R}}{F_g} \tag{6}$$

However, if the strain field is such that transverse effects are not negligible, then eq (6) is not applicable. At least two orthogonal strain measurements are required to correct for transverse-sensitivity errors. Denoting the two measured strains as ϵ_{mx} and ϵ_{my}, the true strains in the x and y directions are given by:

$$\epsilon_x = \frac{(1 - \nu_0 K)(\epsilon_{mx} - K\epsilon_{my})}{1 - K^2}$$

$$\epsilon_y = \frac{(1 - \nu_0 K)(\epsilon_{my} - K\epsilon_{mx})}{1 - K^2}$$

These are the standard correction equations used with two-element rectangular rosettes. Note that it has been tacitly assumed that K has the same value for each gage element. See Ref. 16 for the correction equations allowing independent K values, and also for the correction equations used with rectangular or delta three-element rosettes.

The effects of orthotropic-material behavior on transverse-sensitivity effects can be investigated most easily by considering the error that would occur if transverse sensitivity were not taken into account. The error in the measured strain introduced by transverse sensitivity can be expressed as

$$\text{error} = \frac{K\left(\frac{\epsilon_t}{\epsilon_a} + \nu_0\right)}{(1 - \nu_0 K)} \times 100 \text{ percent} \tag{7}$$

Consider a simple uniaxial-tensile test of an isotropic material. Suppose a strain gage is mounted to the test specimen transverse to the load direction. For this case,

the ratio (ϵ_t/ϵ_a) in eq (7) is equal to $(-1/\nu)$, where ν is Poisson's ratio for the isotropic material. Since ν ranges from about 0.20 to 0.40 for most structural materials, the error due to transverse sensitivity ranges from about -4.7 to -2.2 percent, where values for K and ν_0 of 0.01 and 0.285, respectively, were used. Now consider a uniaxial-tensile test of a 90-deg unidirectional composite specimen, again with a gage mounted transverse to the load direction. The ratio (ϵ_t/ϵ_a) in eq (7) now becomes $(-1/\nu_{21})$. While ν_{21} can vary over a wide range, it is commonly on the order of 0.01 to 0.05. Hence, the error due to transverse sensitivity (using the same values for K and ν_0 as before) ranges from -100.0 to -19.8 percent. The increase in error is directly attributable to the very low values of ν_{21}.

To further illustrate these effects, the three loading conditions shown in Fig. 2 were considered. In Fig. 2(a), a strain gage is shown mounted to an isotropic material, subjected to a uniaxial-stress field. The major axis of the gage is oriented an angle θ from the loading direction. In Fig. 2(b) a similar loading condition is defined for a unidirectional-composite lamina, where both the lamina fibers and the major axis of the strain gage are oriented an angle θ from the load direction. This orientation will be referred to as Orientation I. Finally, Fig. 2(c) defines a load case in which the fibers of a unidirectional-composite lamina are oriented an angle θ from the load direction and a strain gage is mounted perpendicular to the fibers. This load case will be referred to as Orientation II. For each condition, the strain measured by the gage without transverse-sensitivity corrections is compared to the actual strain in the direction of the strain gage. The materials considered are steel for the isotropic case and graphite epoxy for the orthotropic case. Assumed material properties are given in Table 1. The mechanical properties assumed for graphite epoxy should only be considered typical values, since they may vary significantly from lot to lot. The values listed were taken from Ref. 17. A uniaxial-stress level of $\sigma_x = 68.95$ MPa (10,000 psi) and a transverse sensitivity coefficient of $K = 0.03$ are used. Note that this stress level is probably somewhat higher than the ultimate strength of a 90-deg specimen of Gr/Ep, although it is much less than the ultimate strength of a 0-deg specimen. Since this numerical example is intended

TABLE 1—TYPICAL MATERIAL PROPERTIES FOR STEEL AND GRAPHITE EPOXY

Material	E_1 psi × 10^6	E_2 psi × 10^6	ν_{12}	G_{12} psi × 10^6	α_1 μin./in./°F	α_2 μin./in./°F
Steel	30.0	—	0.285	11.67	6.0	—
Grapnite Epoxy	30.0	0.75	.250	0.375	0.1	15.0

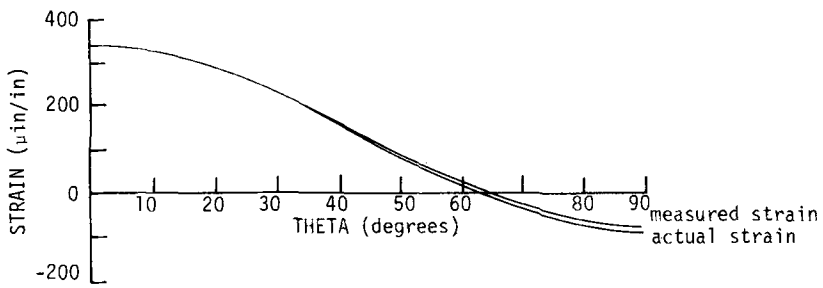


Fig. 3—Error due to transverse-sensitivity effects for steel; $K = 0.03$

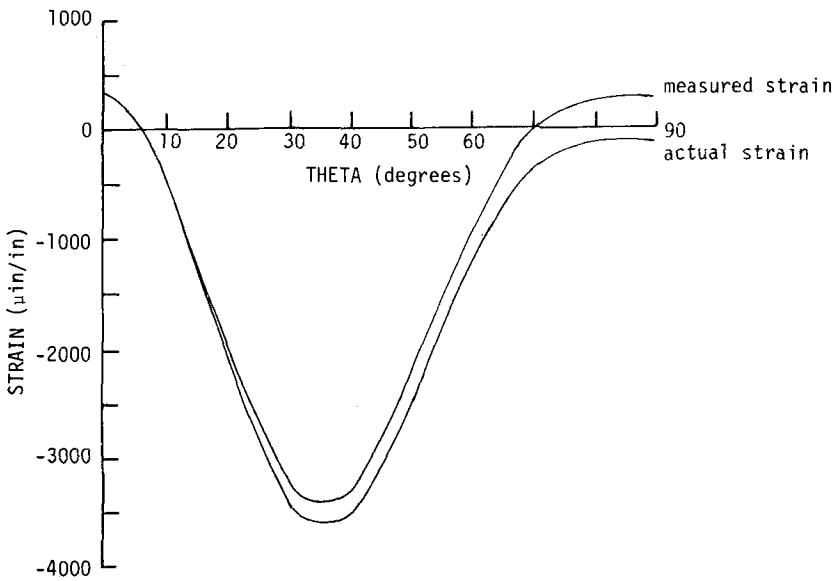


Fig. 4—Error due to transverse-sensitivity effects for graphite epoxy; Orientation I; $K = 0.03$

to illustrate the effects of transverse sensitivity only, the specific level of stress is unimportant and the level chosen is merely for convenience.

The actual axial and transverse strains in the direction of the strain gage (denoted ϵ_a and ϵ_t) can be easily determined for any angle θ using standard mechanics of materials calculations (see for example Ref. 17). For an isotropic material, the axial and transverse strains are given by:

$$\epsilon_a = \frac{\sigma_x}{2E}[1 - \nu + (1 + \nu)\cos 2\theta]$$

$$\epsilon_t = \frac{\sigma_x}{2E}[1 - \nu - (1 + \nu)\cos 2\theta]$$

For an orthotropic-composite material, the axial and transverse strains for Orientation I are given by:

$$\epsilon_a = \sigma_x[\bar{S}_{11}\cos^2\theta + \bar{S}_{12}\sin^2\theta + 2\bar{S}_{16}\cos\theta\sin\theta]$$

$$\epsilon_t = \sigma_x[\bar{S}_{11}\sin^2\theta + \bar{S}_{12}\cos^2\theta - 2\bar{S}_{16}\cos\theta\sin\theta]$$

where

$\bar{S}_{ij}$ = 'transformed-reduced-compliance matrix'

$\bar{S}_{11} = S_{11}\cos^4\theta + (2S_{12} + S_{66})\sin^2\theta\cos^2\theta + S_{22}\sin^4\theta$

$\bar{S}_{12} = S_{12}(\sin^4\theta + \cos^4\theta) + (S_{11} + S_{22} - S_{66})\sin^2\theta\cos^2\theta$

$\bar{S}_{16} = (2S_{11} - 2S_{12} - S_{66})\sin\theta\cos^3\theta - (2S_{22} - 2S_{12} - S_{66})\sin^3\theta\cos\theta$

$$S_{11} = \frac{1}{E_1} \quad S_{12} = -\frac{\nu_{12}}{E_1} \quad S_{22} = \frac{1}{E_2} \quad S_{66} = \frac{1}{G_{12}}$$

Note that for Orientation II the axial and transverse strains are reversed. That is, ϵ_a and ϵ_t for Orientation II correspond to ϵ_t and ϵ_a, respectively, for Orientation I.

Given that ϵ_a and ϵ_t are known, an expression for the measured strain ϵ_m can be obtained substituting eqs (3) and (5) into eq (7), which results in

$$\epsilon_m = \frac{(\epsilon_a + K\epsilon_t)}{(1 - \nu_0 K)}$$

The results for the case of steel are presented in Fig. 3. As would be expected, the difference between the measured and actual strain is a maximum at an angle of θ = 90 deg. The error is seen to increase uniformly with θ, and unless a very high degree of accuracy is required, the transverse-sensitivity effects in this case would probably be neglected.

The results for the graphite-epoxy specimens are presented in Figs. 4 and 5. It is seen in Fig. 4 that for the case of Orientation I significant errors are introduced at fiber/gage angles ranging from about 30 deg to 90 deg. Although one might have anticipated significant error at θ = 90 deg, the errors for angles as low as θ = 30 deg are somewhat surprising. On the other hand, results presented in Fig. 4 for Orientation II indicate transverse-sensitivity errors as low as those encountered in the isotropic case. It is interesting to note that, as a general rule, transverse-sensitivity errors are most severe for unidirectional-composite lamina when the strain gage is mounted parallel or nearly parallel to the fibers.

As previously mentioned, K values range from about −0.05 to 0.05. In Fig. 6 a comparison is made between the actual strain and measured strain for K values of −0.05 and 0.05 for graphite epoxy in Orientation I. This result serves to emphasize that when applying strain gages to composite materials, transverse-sensitivity effects must always be considered, and that under certain conditions transverse-sensitivity effects can completely dominate the actual strain to be measured.

Errors Due to Gage Misalignment

A common method of gage alignment when mounting strain gages to conventional structural materials is to first burnish alignment marks on the specimen surface during initial specimen preparation. These alignment marks are usually applied using a relatively blunt-tipped instrument, such as a 4-H drafting pencil or a ball-point pen. The strain gage is then aligned using these marks, often with the aid of a short length of transparent tape. While this procedure is quite satisfactory for general-purpose strain-gage applications, gage alignment cannot be guaranteed to tolerances better than about ±1 to 2 deg from the intended gage direction. Under most conditions, gage misalignments of 1 to 2 deg produce negligible measure-

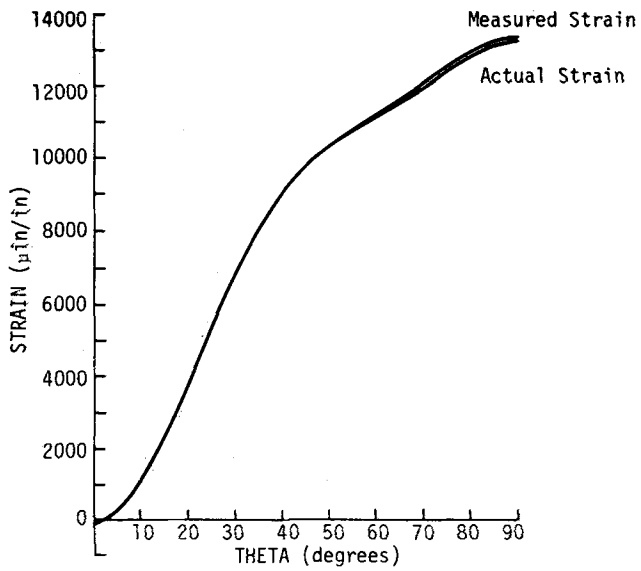


Fig. 5—Error due to transverse-sensitivity effects for graphite epoxy; Orientation II; K = 0.03

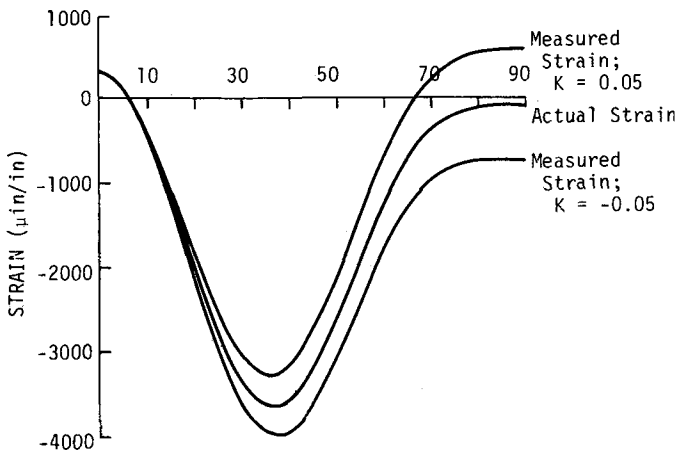


Fig. 6—Errors due to transverse sensitivity for graphite epoxy

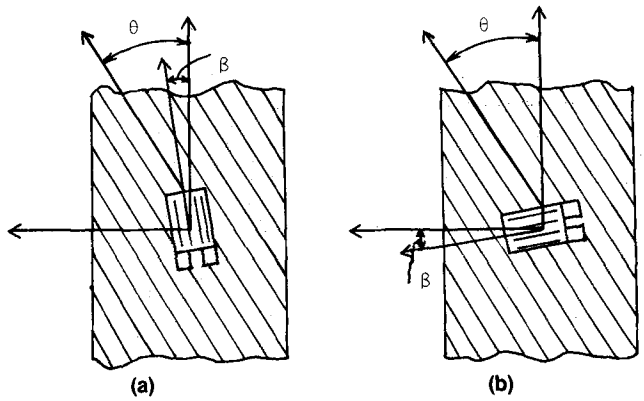


Fig. 7—Assumed loading configurations illustrating gage-misalignment effects, (a) axial gage misaligned by an angle β, (b) transverse gage misaligned by an angle β

ment errors when mounted to an isotropic material. For a single strain gage mounted to an isotropic material and subjected to a uniform-biaxial strain field, the magnitude of the error due to misalignment depends upon three factors (ignoring transverse-sensitivity effects):[18]

—the ratio of the algebraic maximum- to the algebraic minimum-principal strains,
—the angle ϕ between the maximum-principal-strain axis and the intended axis of strain measurement, and
—the angular-mounting error, β, between the gage axis after bonding and the intended axis of strain measurement.

These three general conclusions for isotropic materials also hold for composite materials. However, as in the case of transverse-sensitivity effects, the orthotropic nature of composites serves to produce results quite different from those for isotropic materials. For example, consider a uniaxial-tensile specimen of an isotropic material. Suppose it is intended to mount a gage along the major axis of the specimen but the gage is misaligned by some small amount, say an angle β_0. Since the specimen material is isotropic, the principal-strain directions coincide with the principal-stress directions. Hence the gage is aligned very closely with the principal-strain directions, since β_0 is small. The error due to misalignment is therefore small. Now consider a uniaxial-tensile specimen of an off-axis composite lamina, i.e., a tensile specimen consisting of a unidirectional-composite material whose fibers are at an angle θ away from the major axis of the specimen. Again let an axial gage be misaligned by a small angle β_0. Since the off-axis composite specimen is orthotropic, the principal-strain directions do not in general coincide with the principal-stress directions. Hence, the angle ϕ between the maximum-principal-strain axis and the intended axis of strain measurement is much larger in the orthotropic case than in the isotropic case. The same small misalignment error therefore produces a much larger error in strain measurement for the composite case than for the isotropic case.

As previously mentioned, the use of burnish marks to aid in gage alignment is not possible with epoxy-matrix composites; hence gages are often mounted to tensile specimens 'by eye.' The cloth-like pattern left by the scrim cloth on many composites can also be misleading, as one is tempted to align the gage using this pattern as a guide—yet this pattern does not necessarily reflect the true fiber direction. These considerations indicate that unless further precautions are taken, gage alignments on composites cannot be held to tolerances better than about ±2 to 4 deg from the intended gage direction.

Unfortunately, there are presently no established mounting procedures available which can assure more precise gage alignment. At VPI & SU, unidirectional specimens are normally fabricated from small square plates. In these cases the 0-deg fiber direction is easily established by fracturing a thin strip of material along an edge parallel to the fibers. Fiber orientation for off-axis specimens is then determined relative to this fracture plane. Gage alignment is maintained during mounting by using a low-power magnifying glass. If the specimen is subsequently loaded to failure, and if the fracture surface is smooth and uniform, a postmortem inspection is performed as a check of gage alignment. These techniques are not suitable for more general laminates however, because general laminates do not normally fracture along easily defined planes. In some cases it may be possible to check gage alignment after mounting by employing a nondestructive-inspection technique such as the C-scan method.

Given that misalignment errors of these magnitudes can easily occur when using conventional gage-mounting techniques, the error in strain measurement due to possible misalignment may be easily calculated. Consider the two uniaxial-load cases shown in Fig. 7. In Fig. 7(a), an axial-strain gage has been mounted to a θ-deg off-axis tensile specimen. The gage is assumed to be misaligned by the angle β. A similar condition is shown for a transverse-strain gage in Fig. 7(b). These two cases will be used to assess the error in strain measurement due to the gage misalignment β. In practice, the strains measured by the gages would have to be corrected for transverse-sensitivity effects, as previously shown. To avoid undue complication of this example, transverse-sensitivity effects will be ignored; i.e., K will be set equal to zero.

The actual axial and transverse strains, ϵ_x and ϵ_y, acting in the x and y directions may be determined through Hooke's law for an orthotropic-composite material:[17]

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \overline{S}_{11} & \overline{S}_{12} & \overline{S}_{16} \\ \overline{S}_{12} & \overline{S}_{22} & \overline{S}_{26} \\ \overline{S}_{16} & \overline{S}_{26} & \overline{S}_{66} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ 0 \\ 0 \end{Bmatrix}$$

or, for this case:

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \sigma_x \begin{Bmatrix} \overline{S}_{11} \\ \overline{S}_{12} \\ \overline{S}_{16} \end{Bmatrix}$$

Since the strain gages have been misaligned by the small angle β, the strains measured by the gages are not the actual axial and transverse strains ϵ_x and ϵ_y, but rather the strains ϵ_x' and ϵ_y', found by rotating the strain vector through an angle β:

$$\begin{Bmatrix} \epsilon_x' \\ \epsilon_y' \\ \gamma_{xy}'/2 \end{Bmatrix} = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & m^2-n^2 \end{bmatrix} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy}/2 \end{Bmatrix}$$

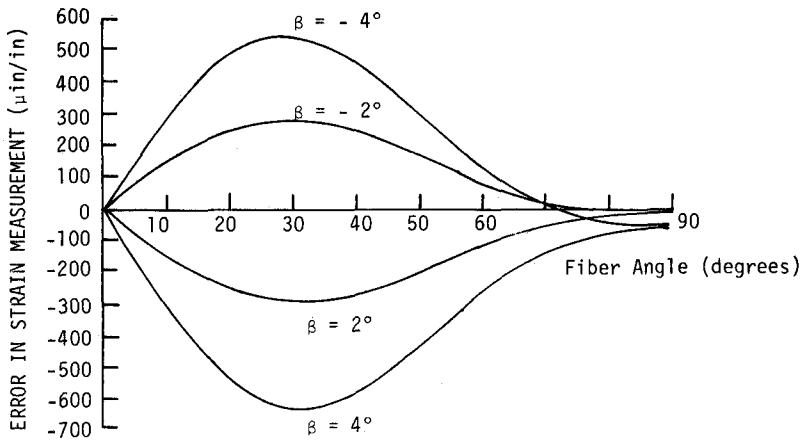


Fig. 8—Error induced by misalignment of axial-strain gage; graphite epoxy

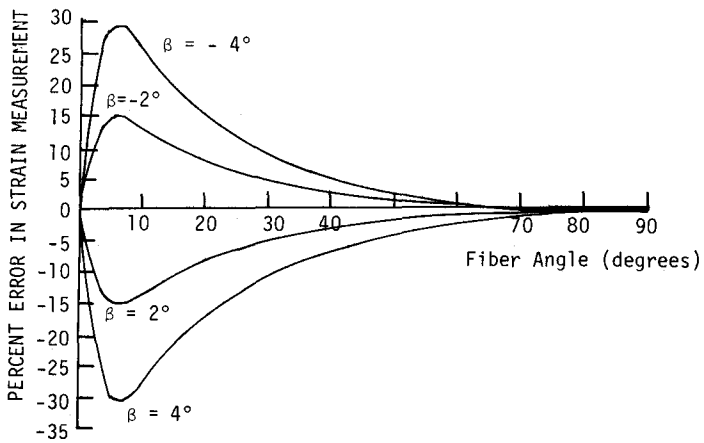


Fig. 9—Percent error induced by misalignment of axial-strain gage; graphite epoxy

where

$$m = \cos\beta$$
$$n = \sin\beta$$

Using this approach the errors due to gage misalignment were evaluated for graphite epoxy, using a stress level of σ_x = 68.95 MPa (10,000 psi) and the material properties previously given in Table 1. The results for the axial gage are given in Figs. 8 and 9. In Fig. 8 the numerical error in μin./in. between the actual axial strain ϵ_x and the measured axial strain ϵ_x' is presented as a function of fiber angle θ, for misalignment errors of -4, -2, 2 and 4 deg. In Fig. 9 this error is expressed as a percentage of the actual axial strain. Note that at fiber angles of 0 and 90 deg the error due to misalignment is very small, which would be expected since at these fiber angles the principal-strain directions coincide with the principal-stress directions. The percentage of error due to misalignment is appreciable for fiber angles ranging from about 3 to 40 deg; the error is a maximum for a fiber angle of about 8 deg.

The results for the transverse-strain gage for the same assumed misalignment errors are presented in Figs. 10 and 11. Comparing these results with those for the axial gage, it is seen that while the numerical error for the transverse gage is much less than for the axial gage, the percentage error is much higher. Obviously, this is because the magnitude of the transverse strains is lower than that of the axial strains. Note that the sharp 'tail' in percentage error near θ = 90 deg in Fig. 11 is misleading, since this percentage error corresponds to a numerical error of only a few μin./in. The curves are of the same general shape for both axial and transverse cases. The percentage error for the transverse case is again appreciable over a fiber angle ranging from about 3 to 40 deg, and reaches a maximum at a fiber angle of about 8 deg.

These results are for a graphite-epoxy lamina possessing the mechanical properties listed in Table 1. Similar results would be obtained for other composite materials, or for any orthotropic material. Note that while these errors are produced by misalignment of the strain gages, similar errors would result if the fibers were slightly misaligned. Also note that the percentage error is quite high for a 10-deg off-axis specimen. This particular specimen is often used to characterize the behavior of composites in shear.[2] Thus, both fiber and gage alignment must be kept within close tolerances when using the 10-deg off-axis specimen, as pointed out by Chamis and Sinclair.[2]

Thermal-compensation Techniques

Of all the potential sources of error associated with the use of strain gages, the most commonly encountered and potentially most serious are those errors due to thermal effects. A change in temperature can affect strain mea-

surement in two ways. The first is that the sensitivity of the gage to strain changes, i.e., the gage factor, changes with changing temperature. Often, the gage factor decreases with increasing temperature, although the opposite can also be true depending on the particular gage alloy being used. The percentage change in gage factor with temperature is quite small, and is normally on the order of 0.5 percent per 55 °C (100 °F).[19] Since this change is so small, gage-factor changes with temperature are often neglected. Gage-factor variation with temperature is not affected by orthotropic-material behavior and will not be further discussed in this paper.

The second effect due to temperature, and by far the most serious effect, is commonly referred to as 'apparent strain' due to temperature. Apparent strain is the result of several different factors, principally:

—a change with temperature of the electrical resistance of the strain gage,
—a mismatch between the thermal-expansion coefficients of the strain gage and the test specimen, and
—a change with temperature of the electrical resistance of the strain-gage leadwires.

Apparent-strain effects can be very large and, if not properly accounted for, can completely obliterate the gage response to mechanical loading.

For purely dynamic-strain measurement, the need for thermal compensation is often avoided by separating the relatively low-frequency apparent-strain effects from the relatively high-frequency dynamic response. This is usually accomplished by passing the gage signal through a high-pass electrical filter. The only exception is when high-frequency temperature changes occur, such as those encountered when using strain gages to measure explosively generated shock waves, for example. For the purposes of the present discussion, it will be assumed that the temperature fluctuations being considered are of low frequency, so that the temperature at any point in time can be considered quasisteady state.

When static or combined static/dynamic strain measurements are made, thermal compensation is almost always required. In modern strain-gage practice two methods of temperature compensation are most often used: self-temperature-compensation (S-T-C) used in conjunction with a three-leadwire system, or temperature compensation using a 'compensating' or 'dummy' strain gage. These two thermal-compensation techniques as applied to composites will be discussed in the following two paragraphs. It should be noted that, at least in theory, thermal compensation is only required when the specimen temperature varies during the course of a strain measurement. However, the level of thermal stability

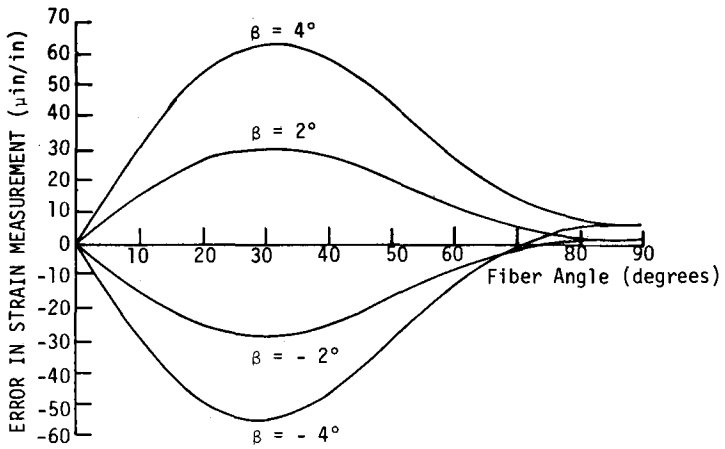


Fig. 10—Error induced by misalignment of transverse strain gage; graphite epoxy

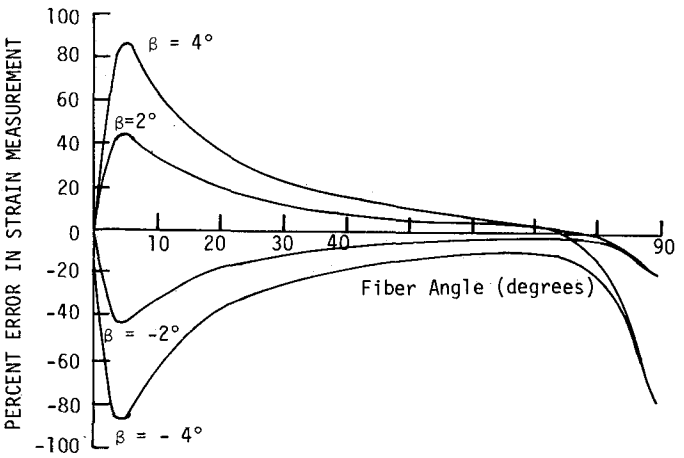


Fig. 11—Percent error induced by misalignment of transverse-strain gage; graphite epoxy

required in order to avoid thermal effects is very difficult to obtain except under closely controlled laboratory conditions. In practice, some form of thermal compensation is usually provided.

Self-temperature Compensation

A strain gage is said to be self-temperature compensated when the strain-gage alloy is processed so as to minimize apparent-strain effects due to temperature when the gage is mounted to the material for which the gage was compensated. This calibration is normally applicable over a range of about −20 to 205 °C (0 to 400 °F). In practice, one selects the gage S-T-C number which most closely matches the thermal coefficient of expansion of the test material. For example, gages with S-T-C numbers of 06 and 13 are compensated for use with steel and aluminum, respectively.

The S-T-C method of compensation is normally used in conjunction with the three-leadwire system and the conventional Wheatstone-bridge circuit.[4,19] The three-leadwire system provides compensation for changes in leadwire resistance due to temperature changes by placing equal lengths of leadwire in adjacent arms of the Wheatstone bridge. Due to the characteristics of this circuit, the leadwire effects cancel and thermal compensation for leadwire effects is achieved.

The S-T-C method is not as well suited for use with composites as with more conventional isotropic materials. Some of the difficulties encountered are:

—The thermal expansion of composites is in general a highly orthotropic material property. This implies that the appropriate gage S-T-C number would depend on both material type and desired gage orientation with respect to the principal material axis.
—The thermal properties of epoxy-matrix composites often vary from lot to lot and even more so from manufacturer to manufacturer.
—The thermal properties of epoxy-matrix composites depend to a certain extent on the previous thermal history of the composite.
—The effective thermal-expansion coefficient(s) of a composite laminate depends upon laminate layup, and may be varied over a wide range of values.

These factors severely restrict the S-T-C method of compensation when applied to composites. It is interesting to note that even if these difficulties were overcome, thermal compensation may still not be satisfactory, due to transverse-sensitivity effects. That is, the gage has been calibrated for an assumed isotropic expansion or contraction, whereas the composite expands or contracts orthotropically. This results in a transverse strain being applied to the gage, which would have to be accounted for due to transverse-sensitivity effects.

Thermal Compensation Using a Dummy Gage

By far the most widely used method of thermal compensation as applied to composite materials is the use of a compensating or dummy gage, in conjunction with the standard Wheatstone-bridge circuit. A typical configuration is presented in Fig. 12. The 'active' gage is mounted to the composite specimen and is subjected to all the mechanical loads (including thermally induced mechanical loads) and temperature changes which occur during the course of the test. The dummy gage is mounted to a sample of the composite material, and is placed as physically close to the active gage as possible. Ideally, the dummy gage experiences the same temperature changes as does the active gage, but none of the mechanical loads. Due to the characteristics of the Wheatstone-bridge circuit, the apparent-strain effects due to the temperature changes cancel; the output from the active gage is due to mechanical loading only, as desired.

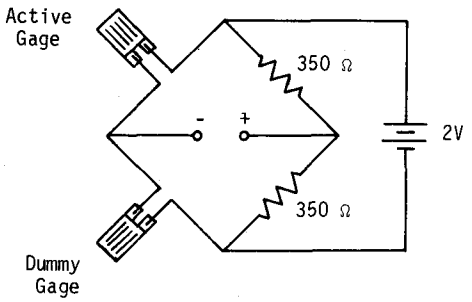


Fig. 12—Typical Wheatstone-bridge circuit using a dummy gage for thermal compensation

The orthotropic behavior of composites impacts this form of compensation by again requiring precise gage alignment. That is, if the dummy gage is not aligned in exactly the same orientation as is the active gage, then the dummy gage does not experience the same axial or transverse strains as the active gage. Hence, temperature compensation is not achieved.

The following numerical example will illustrate this effect. Figure 13(a) depicts strain gages mounted in axial directions on two off-axis tensile specimens. The active gage is assumed to be perfectly aligned along the specimen axis, whereas the dummy gage has been misaligned by an angle β. A similar situation for transversely mounted gages is shown in Fig. 13(b).

Assuming a uniform temperature rise, ΔT, the perfectly aligned active gage experiences a strain field given by:

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \Delta T \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix}$$

where

$$\alpha_x = (\alpha_1 - \alpha_g)\cos^2\theta + (\alpha_2 - \alpha_g)\sin^2\theta$$

$$\alpha_y = (\alpha_1 - \alpha_g)\sin^2\theta + (\alpha_2 - \alpha_g)\cos^2\theta$$

$$\alpha_{xy} = 2(\alpha_1 - \alpha_2)\sin\theta\cos\theta$$

α_1, α_2 = coefficients of thermal expansion of composite
α_g = effective coefficient of thermal expansion of strain gage

Since the dummy gage has been misaligned, it experiences a strain field given by:

$$\begin{Bmatrix} \epsilon_x' \\ \epsilon_y' \\ \gamma_{xy}' \end{Bmatrix} = \Delta T \begin{Bmatrix} \alpha_x' \\ \alpha_y' \\ \alpha_{xy}' \end{Bmatrix}$$

where

$$\alpha_x' = (\alpha_1 - \alpha_g)\cos^2(\theta - \beta) + (\alpha_2 - \alpha_g)\sin^2(\theta - \beta)$$

$$\alpha_y' = (\alpha_1 - \alpha_g)\sin^2(\theta - \beta) + (\alpha_2 - \alpha_g)\cos^2(\theta - \beta)$$

$$\alpha_{xy}' = 2(\alpha_1 - \alpha_2)\sin(\theta - \beta)\cos(\theta - \beta)$$

To avoid undue complication, the S-T-C number of the strain gage (effectively α_g) is assumed to be zero; transverse sensitivity effects are ignored. Using this approach, the results presented in Figs. 14 and 15 for graphite epoxy were obtained. Thermal properties required are given in Table 1. A temperature rise of 28 °C (50 °F) was assumed. Misalignment errors of −4, −2, 2, and 4 deg were considered, as before.

The results for the axial and transverse cases are seen to be very similar and are in fact mirror images of each other. A maximum apparent strain of about 50 μin./in. occurs in both cases for a misalignment error of 4 deg, and at a fiber angle of about 45 deg. This may or may not be a significant error, depending on the strain levels and accuracy requirements involved in a given test. The point is that even under these idealized conditions temperature compensation is not achieved due to a relatively small alignment error.

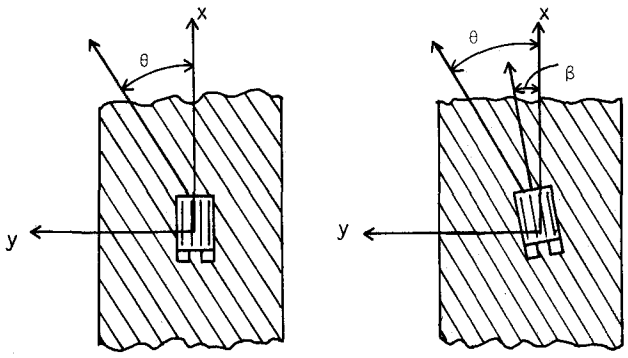
Discussion and Conclusions

This paper presents a review of strain-gage technologies as applied to orthotropic-composite materials. Given the wide range of possible applications and test environments under which composites might be used, a completely general discussion including all possible aspects of this topic is beyond the scope of a single paper. Instead, an attempt has been made to include the fundamental variables which must be considered when selecting a strain-gage system for use with epoxy-matrix composites. Some of the unusual problems which may be encountered due to the orthotropic behavior of composites are also discussed. Unidirectional graphite epoxy is used to illustrate these effects, although any composite material would exhibit a similar response. In general, the more pronounced the orthotropic behavior, the more pronounced these effects become.

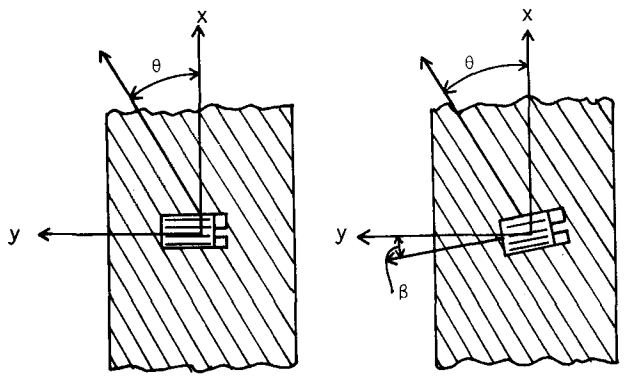
With regard to strain-data acquisition and reduction, this paper emphasizes two points. (1) Transverse-sensitivity effects should always be considered when dealing with strain data obtained for composite materials. (2) Precise knowledge of the principal-material directions, and precise strain-gage alignment with respect to these directions is required.

The first point is important because most practical experience is based upon the behavior of isotropic materials. As has been shown, the orthotropic nature of composites results in a propensity towards transverse-sensitivity errors which would not be expected based upon experience with isotropic materials. This enhancement of transverse-sensitivity effects also implies a greater need for accurate measurement of the transverse-sensitivity coefficient than is the case for isotropic materials.

The second point is shown in this paper to be important both from the standpoint of error due to the misalignment itself, and from the standpoint of reduced or impaired thermal-compensation capability. Gage alignment is relatively easy to assure under controlled laboratory conditions, particularly when small unidirectional specimens are being used. Alignment is less easy to assure, however, when tests are being conducted in the field, when general laminates are being used, or when specimen



(a) Assumed strain-gage orientation for axial-gage case



(b) Assumed strain-gage orientation for transverse-gage case

Fig. 13—Strain-gage alignments for thermal compensation

size becomes quite large. In these cases considerable care must be given to both identification of the principal-material directions and to strain-gage alignment.

Perhaps a final note regarding the measurement of strain near a free edge is appropriate. As conventionally applied, a strain gage measures surface strains. Classical lamination theory is based upon the assumptions of plane stress and the Kirchhoff hypothesis, i.e., a line which was initially straight and perpendicular to the middle surface of the laminate is assumed to remain straight and perpendicular to the middle surface after deformation.[17] These assumptions are well satisfied at regions away from a free edge. It can be shown[20] that surface-strain measurements can be used to infer subsurface-lamina strains in these regions. However, near a free edge neither the plane-stress assumption nor the Kirchhoff hypothesis is valid. Surface strains may not be related to subsurface-lamina strains. Therefore caution must be exercised when applying strain gages near a free edge—when attempting to measure stress concentrations near a cutout in a laminate, for example.

Acknowledgments

The authors are indebted to the contributions of many individuals who have helped make this work possible.

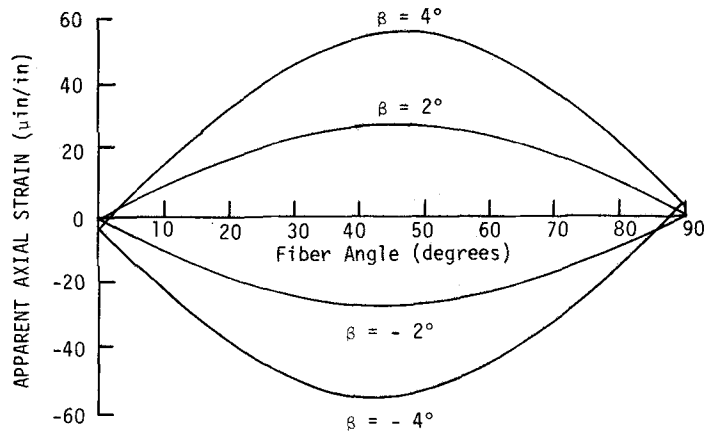


Fig. 14—Apparent axial strain due to a temperature increase of 50°F; transverse sensitivity coefficient = 0.0; graphite epoxy

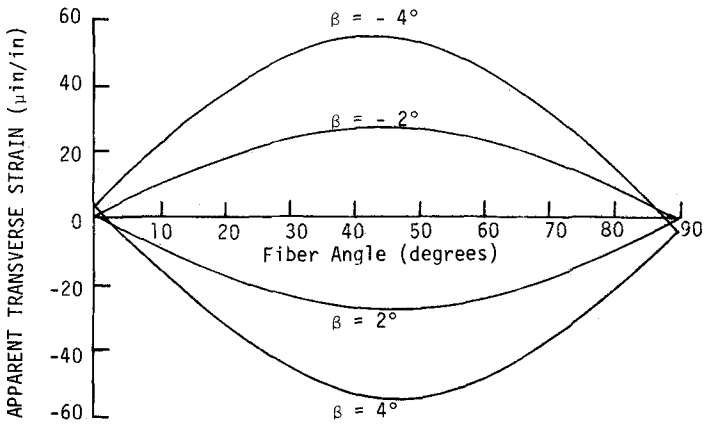


Fig. 15—Apparent transverse strain due to a temperature increase of 50°F; transverse-sensitivity coefficient = 0.0; graphite epoxy

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