

Strain Gage Measurements on Plastics and Composites

Introduction

The bonded resistance strain gage, which is central to the topics treated here, was invented in the late 1930's and is now at about the mid-century mark in its career. During the first fifty years of its existence, the strain gage has been applied to virtually every known load-bearing material – ranging from asphalt to zirconium, and missing few, if any, of the letters in between. Whether the material be natural or man-made, metallic or nonmetallic, organic or inorganic, elastic or inelastic, someone has likely perceived the need to measure the surface strains resulting from applied loads. By far the most common way of doing so has been, and still is, the resistance strain gage.

Despite the broad range of materials to which the strain gage has been applied (with sometimes questionable credibility), it should be recognized that the majority of practical industrial applications have been on the common structural metals, particularly steel and aluminum alloys. As a result, contemporary expertise in strain gage technology lies primarily in this segment of the materials spectrum. Currently, however, it is evident that we are entering a new era of strain gage utilization in which a significant fraction of all strain measurements will be made on plastics and composites (where the latter term, as used here, refers specifically to reinforced plastics).

The preceding statement cannot readily be dismissed as simply a futuristic claim which may or may not prove true, since the evidence is rapidly accumulating around us. In the U.S., for instance, plastic production is currently in the order 45×10^9 lbs per year, and rising steadily (by about 5% from 1985 to 1986).^{*} The bulk of the poundage continues to flow, of course, into the myriad plastic products not generally requiring experimental stress analysis – e.g., packaging, unit containers, sheet, film, extruded shapes, etc. But examination of almost any hardgoods manufacturing industry will quickly verify the trend for replacing metals by plastics (reinforced and otherwise) in numerous structural and load-bearing components. Examples include aerospace and defence, commercial and general aviation, automotive, marine, pipelines, machinery and equipment, construction, and appliances and other consumer products.

^{*} According to the Society of the Plastics Industry, 1986 U.S. shipments of reinforced plastics amounted to about 2.3×10^9 lbs.

The motivation for changing to plastics/composites may differ somewhat from industry to industry, and from application to application, but economic factors generally predominate, directly or indirectly. Even though the "advanced" composites are usually very expensive, their use in commercial aircraft, for instance, can often be justified by the payback from lower-weight components in terms of carrying capacity and fuel consumption. In automobiles, refrigerators, and other large, high-volume consumer products, weight reduction is a common benefit, but the primary economic gains derive in many cases from the potential for greatly reduced manufacturing costs. Major savings can be realized, for example, by "component integration". This refers to replacing a complex assembly, formerly made by joining a number of individually produced metal components, with a monolithic structure, fabricated from a reinforced plastic in a single molding cycle. Moreover, when surface finish is important, as in an automotive body panel, the desired finish can often be achieved in the same molding operation. There is a further potential advantage in production tooling costs, which are often much lower for the plastic and composite materials.

With the increasing number of plastic/composite structural components, it can be expected that the need to measure service strains on these materials will increase correspondingly. If such strain measurements are to yield the necessary data for the design and development of reliable plastic-based products, then strain gage application technology must be advanced accordingly. This situation may call for more of a reformation in the technology than merely the extension of past practices.

The need for upgraded expertise on the part of the strain gage user arises because plastics and composites, while qualitatively similar to the structural metals, have radically different mechanical, thermal, and chemical properties. As a result, some of the extraneous effects which are ordinarily negligible in strain measurement on metals can become significant error sources with plastic-based materials. The properties of the materials must therefore be recognized and accounted for in each stage of the strain measurement process if dependably accurate data are to be obtained. In addition, determination of working stresses from measured strains may require the application of much more sophisticated theoretical mechanics (due to creep, anisotropy, etc.) than typically employed in the past.

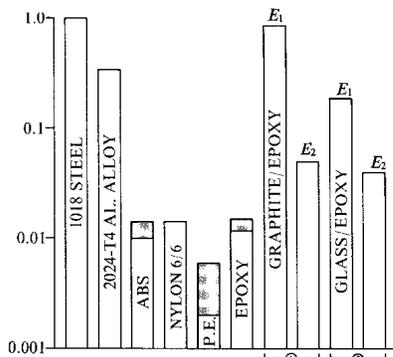
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Although the format of this paper does not permit a comprehensive treatment of the foregoing topics, an attempt has been made to draw attention to some of the more prominent factors which should be considered when performing experimental stress analysis on plastic and composite test objects.

Plastics and Composites as Mechanical Test Materials

In terms of experimental stress analysis, one of the more significant differences between plastics and metals is certainly in the basic mechanical properties such as the modulus of elasticity. As illustrated in the following graph, elastic moduli for plastics are often two or more orders of magnitude lower than those for metals. A practical consequence of this difference is that measured strains on plastic test objects tend to be considerably larger than on metals, and can readily exceed 1 percent. The relatively high-elongation strain measurements in such cases can place special demands on strain gage bonding and wiring procedures.

(a) Elastic Modulus



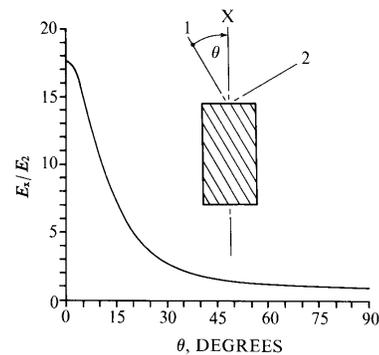
Order-of-magnitude comparison of room-temperature and elastic modulus – selected materials versus 1018 steel. [(1) T300/5208 graphite/epoxy; (2) Scotchply1002 glass/epoxy; (Subscripts 1, 2 denote fiber and transverse directions, respectively). (Ref. 3)].

APPLICATION NOTE

Another potentially significant effect of the lower elastic modulus – and one that is less amenable to user alleviation – is that the presence of the installed strain gage may, at least locally, reinforce the test material. Perhaps indicative of the state of the art in strain measurement on plastics is the dearth of published data on reinforcement effects. There are indications, nevertheless, that reinforcement by the gage can lead to very large measurement errors, particularly for the lower-modulus plastics. (Ref. 1 and 2).

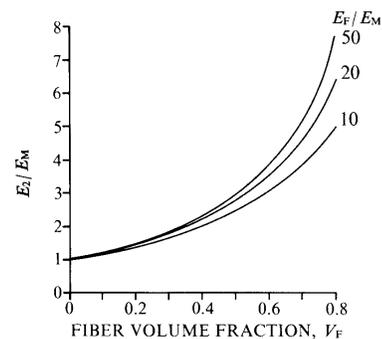
Although the foregoing remarks were implicitly confined to unreinforced plastics, the same considerations may sometimes apply to composites as well. In composites with randomly oriented short-fiber reinforcement, for instance, the elastic modulus is often less than 1×10^6 psi (~7 GPa),

depending on the matrix and fiber materials, the volume fraction of reinforcement, and the aspect ratio of the fibers. A similar condition can be found in unidirectionally reinforced composites when directions other than the fiber direction are examined. The elastic modulus is normally lowest in the transverse directions but, as illustrated in the next figure, it tends to be low, and not much greater than the transverse modulus, in all directions except for 30 degrees or so either side of the fiber direction. Moreover, the transverse modulus itself may not be far above that of the matrix resin.



Variation of uniaxial elastic modulus with direction in a unidirectionally reinforced graphite/epoxy (T300/5208).

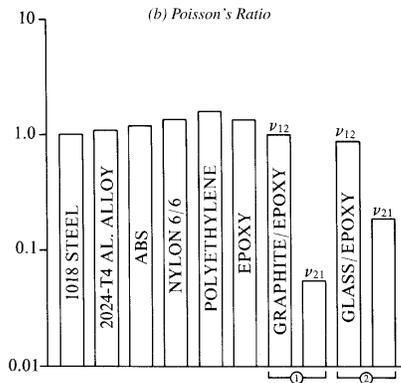
The ratio of the transverse modulus (E_2) to the matrix modulus (E_M) is plotted against fiber volume fraction (V_F) in the illustration below, based on micro mechanics considerations (Ref. 3). It can be seen that when V_F is less than about 0.5, the modulus ratio E_2/E_M lies in the range from 1 to 2.5, largely independent of the fiber modulus (E_F).



Effect of fiber volume fraction (V_F) on the transverse elastic modulus (E_2) of a unidirectionally reinforced plastic (E_F , E_M denote elastic moduli of fiber and matrix materials, respectively). (Ref. 3)

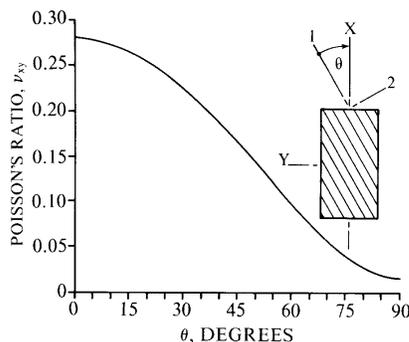
Poisson's ratio (ν) for plastics and composites is also usually different from that for metals (see below). In the case of plastics, ν typically falls in the range from 0.35 to 0.45; and values for random-fiber-reinforced plastics do not differ greatly.

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Order-of-magnitude comparison of room-temperature and Poisson's ratio – selected materials versus 1018 steel. [(1)T300/5208 graphite/epoxy; (2) Scotchply1002 glass/epoxy; (Subscripts 1, 2 denote fiber and transverse directions, respectively). (Ref. 3)].

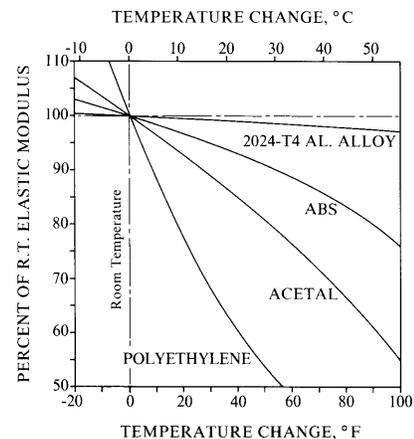
With orthotropic materials such as unidirectionally reinforced composites, however, n can vary widely, depending on the properties of the constituents, V_F , and the direction of the measurement (shown below). While the theoretical upper limit for n in an isotropic material is 0.5, this limit does not apply to orthotropic materials, where the value of P can be much greater (Ref. 4). At the other extreme, for certain combinations of material properties, and certain orientations relative to the reinforcement direction, negative Poisson's ratios can occur (as, in theory, they can for isotropic materials*). When the Poisson's ratio differs significantly from 0.29, correction for the transverse sensitivity of strain gages is generally necessary.



Variation of Poisson's ratio with direction in a unidirectionally reinforced graphite/epoxy (T300/5208).

* Poisson's ratio for an isotropic material can theoretically vary from -1.0 to +0.5, and negative values of ν have been reported for specially treated foam materials (Ref. 5).

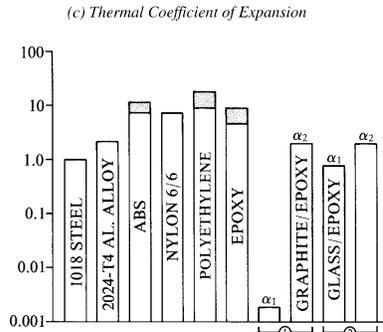
The mechanical properties of plastics and composites also differ noticeably from those of metals in other important respects. An example is the variation of elastic modulus with temperature, as indicated below. Generalization of this effect is very difficult, since it depends on the basic molecular structure of the plastic, the degree of cross-linking, the presence of copolymers, etc.; but mechanical properties can change drastically as the temperature approaches the glass-transition region. In addition, some of the plastics/composites are non linear in their stress/strain behaviour (particularly in shear). One of the most significant differences is in the time-dependence of the properties, as manifested in creep, stress relaxation, and sensitivity to loading rate. Obviously, these characteristics must be taken into account during the strain-measurement process, and in subsequent reduction of the data for determining stress magnitudes.



Comparative effect of temperature change on elastic modulus -- aluminum alloy versus selected thermoplastics.

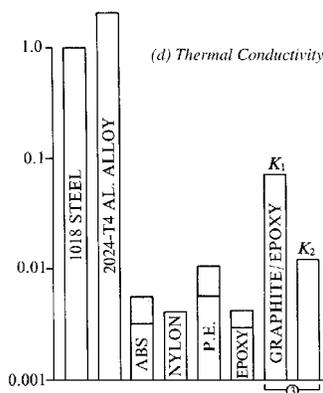
In addition to the mechanical properties of plastics and composites, their thermal properties generally require special consideration. The thermal coefficients of expansion of unreinforced plastics, for instance, are characteristically from 5 to 10 times greater than for the structural metals (see below). Although this need not be a factor in isothermal testing, correction or compensation for the thermal output of the strain gage can become a serious problem if measurements must be made in a variable thermal environment. The practical difficulty in achieving correction or compensation is particularly severe with unidirectionally reinforced composites, since the expansion coefficient can differ greatly between the fiber and transverse directions. With a strain gage rosette installed on this type of material, the difference in thermal output between a gage aligned with the fibers and another in the perpendicular direction can exceed 20 microstrain per deg F (35 microstrain per deg C) with temperature change – irrespective of self-temperature compensation.

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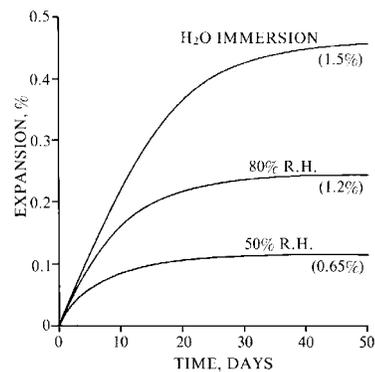
Order-of-magnitude comparison of room-temperature and temperature coefficient of expansion – selected materials versus 1018 steel. [(1) T300/5208 graphite/epoxy; (2) Scotchply1002 glass/epoxy; (Subscripts 1, 2 denote fiber and transverse directions, respectively). (Ref. 3)].

Another important difference in thermal properties between plastic-based materials and the metals is in thermal conductivity. For many plastics and fiberglass-reinforced composites, the thermal conductivity is from 1 to 2 orders of magnitude lower than for structural metals (see below). This property obviously affects selection of the gage size and resistance, as well as the excitation voltage (i.e., the power dissipation per unit of grid area), if stable gage operation is to be achieved. Gage installation technique may also be affected, since preattached lead wires are generally preferable with these materials. Additionally, the low thermal conductivity tends to compound the usual difficulty in maintaining an active and dummy strain gage continually at the same temperature in a variable thermal environment.



Order-of-magnitude comparison of room-temperature and thermal conductivity – selected materials versus 1018 steel. [(1) T300/5208 graphite/epoxy; (2) Scotchply1002 glass/epoxy; (Subscripts 1, 2 denote fiber and transverse directions, respectively). (Ref. 3)].

Since plastics tend to absorb moisture from the environment, this factor must also be considered. The absorption of moisture (or any change in moisture content) produces two principal types of effects. One of these is dimensional; that is, the material expands or contracts with a change in moisture content as it does with a temperature change. When this occurs, a strain gage mounted on the material will falsely register a "hygro" output which is indistinguishable from thermal output. As indicated below for an acrylic plastic, the false gage output due to hygroscopic expansion is not especially trivial. For this material, a change in relative humidity from 50% to 80% produces (at equilibrium) an expansion in excess of 1000 microstrain. The tendency for moisture absorption and expansion varies greatly with the type of plastic. Polyethylene, for example, absorbs almost no moisture. In nylon 6/6, on the other hand, both moisture absorption and expansion are much greater than that shown below. The second important effect is on the properties of the material. Since the mechanical properties are usually altered, and sometimes degraded, by increasing moisture content, tests of the material in a moisture-conditioned state may be required. Whether strain gages are to be installed before moisture conditioning or after, this situation calls for special attention in the selection of the gage type, adhesive, and protective coating.



Linear expansion of acrylic plastic with moisture absorption.

With metals, except for the more exotic alloys, the chemical properties of the test material do not enter significantly into the process of strain measurement. For plastics and composites, on the other hand, the situation is often greatly different. To begin with, care must always be taken to avoid reaction between the test material and the various chemicals contained in the usual cleaning solvents, adhesives, and protective coatings. Although abrasive treatment of the material surface is the normal practice with metals, this may not be permitted for some of the high-performance composites, in which case different procedures for surface preparation will be required.

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Aside from the foregoing, there can sometimes be rather severe problems in achieving or maintaining an adequate bond between the strain gage and the plastic or composite. Examples include the "waxy" plastics such as polyethylene and polypropylene. Similar problems can also arise with molded composite products, particularly when silicone-based mold-release compounds are involved, or the plastic is formulated with a lubricant additive

Properties Data for Plastics/Composites

In its usual mode of application, experimental stress analysis begins with the measurement of presumed significant strains in the test part under some set of actual or simulated service loads. The resulting data are subsequently converted to stresses, using the appropriate system of constitutive relationships. Finally, the stresses thus inferred are compared to pre-established norms, or allowable values, consistent with the expected service life and environment for the product.

The stress/strain relationships employed in this process generally require, as a minimum, the elastic modulus and Poisson's ratio of the material in the test part; and, for anisotropic materials, the directional characteristics and shear properties are needed as well. Additional parameters may be involved if the material is non linear in its elastic properties, or if the properties vary measurably with time, temperature, or moisture content.

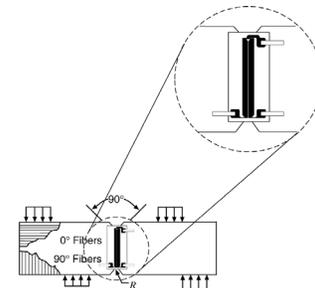
Stress analysts working with metals are accustomed to quite readily accessible and reasonably accurate data on the mechanical properties of a wide range of closely specified standard alloys. When the need arises, well-established technology is available for measuring the properties, in the case of a nonstandard alloy or other special circumstances. The situation with plastics and composites is much less orderly, however. There are, for instance, few, if any, plastic materials which could be considered "standard", with accurately known, repeatable mechanical properties. Even for the same nominal material, the properties may vary significantly from one source to another, due to differences in formulation and processing. It must be kept in mind, also, that plastics designations such as epoxy, ABS, polyester, etc. do not refer to specific materials (in an engineering sense), but to families of materials, distinguished principally by their respective chemistries. In addition to the wide range of properties that can be found within a family, further variation is introduced by the common practice of "doctoring" the plastics with special-purpose additives, plasticizers, colorants, antioxidants, fire retardants, and the like. This situation can be expected to grow still more complex with time, due to the continual development of new plastics and plastics "alloys".

Composites, in general, are still less subject to standardization in their properties. Frequently, the material is formulated on-site, by combining the reinforcing fibers with the matrix resin directly in the process of fabricating the end product. The composite material is thus essentially

custom-made, and specific to the product. Moreover, the properties of the composite can be strongly affected by the fabricating process itself. Processes such as injection molding and bulk-compound molding, for example, can lead to fiber breakage, and to regional inhomogeneities in fiber distribution and orientation, depending primarily on the shape of the mold cavity and (for injection molding) on the gating design. Resin-transfer molding, filament winding, pultrusion, and the other common fabricating methods offer their own sources of variability in the mechanical properties of the material in the finished product.

It should not be forgotten that polymeric materials are subject, in varying degrees, to aging; that is, to bulk chemical changes caused by environmental exposure (ultraviolet light, oxidation, chemical vapors, etc.). Although this is not ordinarily a factor in strain measurement as such, the effects of the chemical changes on the mechanical properties must be considered for applications involving long-term exposure to deleterious environments.

The foregoing suggests that it will be increasingly necessary for the stress analyst to obtain the required mechanical and thermal properties by actually measuring them on the as-produced material, or on similarly fabricated specimens. Basic tensile tests for elastic modulus and Poisson's ratio will not, in many cases, be sufficient, since data may also be needed on creep, impact, fatigue, or other properties. Furthermore, with materials such as anisotropic (or even "quasi-isotropic") composites, the mechanics of the material response must be well understood to obtain meaningful data from even basic mechanical tests. If the material is orthotropic, for example, it is usually necessary to determine four independent properties: the elastic modulus in two directions, Poisson's ratio for uniaxial stress applied along the stiffer of the material axes, and the shear modulus. Measurement of the shear modulus involves its own complications, but these can be largely overcome by using the Iosipescu shear test in conjunction with special-purpose shear-modulus strain gages. As shown below, the dual-element shear gages span the depth of the Iosipescu specimen from notch to notch, averaging the non uniform shear strain which exists on the vertical centerline (Ref. 6).



V-notch (Iosipescu) test specimen with shear-modulus strain gages installed. Strain gages are Micro-Measurements type N2A-XX-C032A-500/SP61.

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The average shear stress is simply the load divided by the cross-sectional area between the notches. Dividing the average shear stress by the average shear strain yields an accurate measure of the shear modulus of the specimen material. Shear-modulus strain gages should always be used on both sides of the Iosipescu specimen (and connected to form a full-bridge circuit) to eliminate the effects of specimen twisting and out-of-plane bending.

For purposes of design evaluation, some form of material failure criterion is ordinarily required as a standard or level against which to compare the working stresses (or strains) in the test part. However, the failure modes of plastics and composites may be quite unlike those commonly observed in metals. Moreover, failure mechanisms differ noticeably with the type of plastic and with the nature and extent of reinforcement, if present. Since failure data on plastic-based materials are not generally well documented, experimental measurement will often be necessary.

The situation described here seems to hold rather significant implications for the field of experimental stress analysis and its practitioners. If the latter are to play an important role in the functional validation of plastic-based products, much of their experimental activity may consist of measuring material properties. This represents not only an opportunity, but also a challenge, since mastery of the mechanics of such materials is a prerequisite to obtaining reliable properties data. In most cases, that same mastery is equally necessary for the proper planning and implementation of stress analysis tests on the product design.

Some Practical Considerations

Obviously, specific procedures and techniques appropriate to a particular strain-measurement problem must be dictated by the nature of the problem itself -- that is, by the test object and its material; the purpose, duration, and environment of the test; the required accuracy; and other constraints typical of this activity. When planning to make strain gage measurements on plastics or composites, the stress analyst should turn first, of course, to the recommendations of the gage manufacturer -- not only for gage type and adhesive, but also for preferred installation procedures such as surface preparation, bonding, wiring, and environmental protection. Because of the unusual problems sometimes involved in testing plastic-based materials, it is good practice to experimentally verify the adequacy of a procedure (and the achievable accuracy) before proceeding with actual strain measurement. Given in the following are brief guidelines for dealing with a few of the more prominent special requirements apt to be encountered in static strain measurement on plastics and composites. Many others (e.g., for interlaminar gage installations) are too detailed or application-specific for inclusion in the present treatment.

Strain Gage Selection

Beyond the usual criteria for gage selection suitable to the strain-measurement task (i.e., single-element gage versus rosette, gage length, strain range, operating temperature, etc.), the gage resistance can be an important factor because of the characteristically low thermal conductivities of the test materials. High-resistance gages (350 ohms or greater) are generally preferable to minimize heat dissipation; but, in any case, the combination of gage resistance, grid area, and excitation voltage (grid power density) should be low enough to avoid the instability caused by a sensible temperature rise in the gage (Ref. 7). For any given gage installation, the threshold of instability can be established quite easily by starting with a very low excitation voltage and observing the (zero-strain) gage output while gradually increasing the voltage. When using strain gage rosettes, the single-plane rosette is preferred over the stacked variety because of better heat dissipation characteristics and less tendency for reinforcement. These recommendations for dealing with the self-generated heat in a strain gage assume continuous gage excitation since this mode of operation is employed in most contemporary instruments. Heat generation in the gage can also be minimized with pulsed gage excitation, if suitable instrumentation is available.

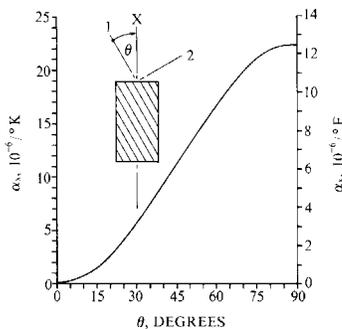
Although the gage length is normally selected for compatibility with the test-specimen geometry and the expected strain distribution, other considerations are also involved when making strain measurements on plastics and composites. One of these, of course, is grid power density, since the grid area commonly increases with gage length. Another is that gages of 1/8 in (3 m/n) length or greater usually offer better performance in terms of stability and strain range. Additionally, with reinforced plastics, it is imperative that the gage length be large with respect to the dimensions of the underlying inhomogeneities in order to obtain any meaningful strain measurements.

Selection of an appropriate self-temperature-compensation (S-T-C) number for use with quarter-bridge circuits can sometimes pose problems if measurements are to be made in a variable thermal environment. To begin with, it is necessary to know the thermal expansion coefficient of the test material, or, if unknown, to measure it (which can be done with strain gages) (Ref. 8 and 9). Even if the expansion coefficient is known for the working temperature range, it may be found that gages with a matching S-T-C number are unavailable. In this case, one option is to select a gage type with the nearest S-T-C number and then calibrate the gage/test-material combination for its thermal output over the specified temperature range. Subsequently, if gage temperature is measured along with the strain, the indicated strain data can be corrected for the thermal output. The same temperature data may be necessary anyway to adjust thermally sensitive mechanical properties when converting strains to stresses.

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An alternative is to employ the half-bridge circuit, with a temperature-compensating dummy gage mounted on an unstressed specimen of the test material and maintained always at the same temperature as the active gage on the test object. The dummy and active gages should have the same S-T-C number, and should be taken from the same manufacturing lot to minimize differences in thermal output characteristics. While, in theory, any S-T-C number should suffice, a selection closest to the expansion coefficient of the test material can be expected to provide the best compensation.

Temperature compensation can be particularly difficult to achieve with an orthotropic material, such as a unidirectionally reinforced composite. Since the expansion coefficient varies directionally in this case, the preceding measures must always be referred to a specific direction with respect to the fiber orientation (see below). The severity of the problem is compounded when a strain gage rosette is involved, since the thermal output is obviously different for each differently oriented grid. In every case, whether calibrating for thermal output or employing a dummy gage, precise matching of gage orientation relative to the principal material directions is a critical requirement. It is worth noting that thermal-output errors may occur even with some of the laminated composites commonly labelled as "quasi-isotropic". Depending on the stacking sequence and lamina orientations, both thermal and mechanical properties may still exhibit appreciable variation with direction.



Variation of thermal expansion coefficient with direction in a unidirectionally reinforced graphite/epoxy (T300-5208).

Although not directly relevant to strain gage selection, it should be observed that the preceding considerations also apply to false gage outputs caused by moisture absorption in the test material. In an orthotropic composite, for instance, the hygroscopic expansion coefficient varies directionally in the same manner as the thermal expansion coefficient, illustrated above. The only means of compensation for hygroscopically induced output, when present, is through the use of a matching dummy gage on an unstressed specimen of the same material. The same dummy can thus

serve for both temperature and moisture compensation when the specimen and test object are maintained in equilibrium with the same environment. Since the diffusion of moisture through the material occurs at a rather low rate, an extended stabilizing period at the specified temperature and humidity is required to assure uniform distribution of moisture (Ref. 10). A gradient in moisture content produces "hygroscopic" stress, analogous to the thermal stress caused by a temperature gradient.

Other selectable strain gage attributes such as backing and foil materials can also have a bearing on gage performance when installed on a plastic or composite. Generally, a conformable, low-modulus backing material such as polyimide is advantageous in several respects -- greater elongation capability, lower gage stiffness, and (in the case of high-performance composites) greater resistance to premature failure from local fiber breakage or matrix cracking. More rigid, creep-resistant backing materials may be required, however, for elevated-temperature applications.

Considering the expected strain range, some practitioners tend to select high-elongation or post-yield strain gages, made with annealed constantan foil. In many cases, this selection is not necessary, since conventional strain gages are typically rated for maximum strains in the 1% to 3% range. When annealed constantan is employed, it should be realized that such gages will characteristically undergo a zero shift with each strain cycle, and the zero may float back and forth if the sign of the strain changes. Repeated cyclic straining produces a continually increasing zero offset as the foil alloy work-hardens. Although normally processed (S-T-C) constantan foil is satisfactory for most routine applications, the Karma-type nickel-chromium alloy offers advantages in some circumstances. This alloy is serviceable over a much wider temperature range than constantan, it is usually available in higher gage resistances, and it offers considerably better corrosion resistance. The latter property may prove beneficial when gage installations must be made prior to moisture conditioning of the test object. The principal disadvantages of Karma are the greater difficulty in making soldered connections, and its higher modulus of elasticity (when reinforcement of the test material by the strain gage is a factor).

As a result of the low thermal conductivities which characterize plastics and many composites, it is preferable to select gages with pre installed leadwires, or to plan on attaching the leadwires before gage bonding. Pre wiring of gages is ordinarily considered good practice with nonmetallic test objects, which are low in thermal conductivity, since it avoids the risk of damaging the image or test material during soldering operations.

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Surface Preparation

The cleaning compounds and procedures appropriate for surface preparation of plastics and composites tend to be highly material-specific, and do not lend themselves to broad generalizations. The usual first step in this process, however, is to cleanse the surface with a mild solvent to remove adhering films of oil and grease. Depending on the type of plastic, this may consist of chlorine/fluorine-based solutions, isopropyl alcohol, or even household cleanser or detergent. It is necessary, of course, to ascertain that the chemicals do not react unintentionally with the plastic. Recommendations for suitable solvents can usually be obtained from the supplier of the plastic or from the strain gage manufacturer.* If any doubt exists, the proposed solvent should be tested for cleansing effectiveness and compatibility with the plastic.

Surface abrasion (with abrasive paper, grit blasting, or otherwise) is a common procedure in preparing metals for strain gage bonding. It is also effective for many plastics and composites, but should always be preceded by degreasing to prevent embedment of contaminants in the surface. For some high-performance composites, however, abrasion may not be permitted because of the risk of damage to near-surface fibers. Moreover, abrasion is not always adequate with certain types of plastics (e.g., fluorocarbons, polyolefins) for achieving optimum bond strength.

The bondability of plastic adherents can often be improved by chemically altering the surface. A commonly used technique, for instance, is to oxidize the surface by flame burnishing. The more adhesion-resistant plastics can also be treated with etchants such as TetraEtch for the fluorocarbons, and a sodium dichromate/sulfuric acid solution for polyethylene and polypropylene. Significant improvements in bond strength have been reported for "plasma" treatment of these plastics – that is, exposure of the surface to microwave-activated inert gases such as neon or helium.** A more practical adaptation of this technique for strain gage bonding is to locally treat the surface (in air) with the corona discharge from a hand-held 50 000V Tesla coil.

The usual practice, following any of these treatments, is to neutralize the surface with a mild ammonia solution, leaving it with a slightly alkaline pH. In any case, the bonding operation should normally be performed within a few minutes after completing the surface conditioning.

* See, for example, Refs. 11 and 12, which list recommended solvents and surface-preparation procedures for wide varieties of test materials.

** Data in Ref. 13 show significant increases in bond strength due to plasma treatment of polyethylene, polyvinyl fluoride, Teflon, Nylon, and other plastics (room-temperature-curing epoxy adhesive).

Adhesive Selection

Strain gage manufacturers typically supply adhesives which have been developed and validated for use in gage bonding, and can recommend the most suitable adhesive for any particular circumstances. For relatively short-term applications in a benign environment, cyanoacrylate adhesive (where compatible with the plastic) is often a convenient choice because of the simple, quick curing procedure. Epoxy adhesives that cure at room temperature or somewhat above are eminently suitable for bonding strain gages to most types of plastics and composites. These adhesives are available in a wide range of formulations with different characteristics and properties – time/temperature/clamping pressure for curing, elongation capability, expected glue-line thickness, etc. – and should be selected accordingly. When necessary for elevated-temperature testing, epoxies which cure or post-cure at higher temperatures can be employed; assuming, of course, that such temperatures are suitable for the plastic or composite.

An unfilled adhesive is the normal choice for gage bonding, in order to produce a thin, creep-free glue-line. However, a filled epoxy is sometimes used to level an irregular or textured surface prior to gage installation. In a composite which is reinforced with continuous fibers, for example, the fiber pattern may be replicated in the surface texture.

For such cases, a layer of partially filled adhesive (or matrix resin) can first be applied, smoothed, and cured to form a level surface. After curing, the levelled area is cleaned and abraded in the usual manner, preparatory to bonding the gage with an unfilled adhesive. Although this technique solves the problem of the rough surface, the resulting gage installation may exhibit greater than usual creep, particularly if the intermediate layer of resin is thicker than necessary.

Gage Installation

Basically, the procedure for installing the strain gage on a plastic or composite is the same as that for a pre-wired gage (and the selected adhesive) on any other material, as recommended by the manufacturer. The procedure is sometimes modified, however, for continuously reinforced composites if premature gage failure is likely, due to local fiber breakage or to cracking of a brittle matrix. Gage life can usually be extended in such cases by interposing a thin layer of resilient material between the gage and test surface during installation. Following the usual surface preparation, a small piece of 0.001 in (0.025 mm) thick polyimide film that has been surface treated is first bonded to the test piece at the gage site. Then after cleaning and abrading the exposed surface of the polyimide, the strain gage is installed on top of the film. The presence of the film tends to filter out local peaks in the underlying strain distribution. It can also affect, of course, the heat-dissipation, reinforcement, and creep characteristics of the strain gage installation.

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Gage alignment at installation sometimes requires special consideration. If the test material is at least nominally isotropic, the requirements for gage alignment are no more severe than for typical strain measurements on metals. With an orthotropic composite, in contrast, gage orientation is usually much more critical (Ref. 14). In the case of a single-element gage (the use of which is particularly questionable on such a material), precise gage alignment relative to the material axes is necessary to obtain any meaningful strain data. A three-element rosette, on the other hand, can (in theory) be installed with any orientation, but the angle between one of the gage axes and a material axis must be known accurately for data-reduction purposes. When a matching dummy rosette is employed for temperature/humidity compensation, the two rosettes must, of course, be aligned identically with respect to the material axes.

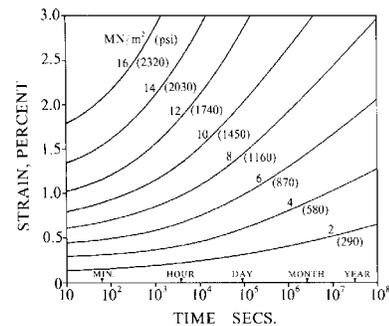
It is always good practice, whether the test is performed on a component for stress analysis purposes, or on a standard specimen for measuring material properties, to complete the installation with some form of protective coating over the gage. The coating compound is selected for compatibility with the test material and with the environment in which strain measurements will be made. To be effective, however, the coating must adhere firmly to the surface of the test object, and form a seal over and completely around the gage. Thus, during surface preparation for gage bonding, the conditioning procedure should be applied to an area large enough to accommodate both the strain gage and the protective coating. After gage bonding, the area must be clean and dry prior to applying the coating. Care is required during the coating application to keep the compound within the prepared area, and to work the material completely around the leadwires so that these penetrations are properly sealed.

Treatment of Strain Data

When strain measurements are completed, it is often necessary to adjust the data for known and correctable errors, if present, prior to data reduction for principal strains and stresses. Typical corrections, irrespective of the test material, may include those for transverse sensitivity, thermal output, gage factor variation with temperature, and, for large strains, Wheatstone bridge non linearity and gage factor variation with strain. Of these, correction for thermal output is potentially the most important since the other errors are normally small compared to the intrinsic uncertainties involved in strain measurement on plastics and composites.

If the test material is a plastic with a low elastic modulus, there can also be a sizable error due to reinforcement by the strain gage. But post-correction for this error obviously requires previous calibration of the reinforcement effect for the subject combination of test material and type of strain gage.

An alternate approximate method is to measure the mechanical properties of the material with the same type of strain gage, and employ the resulting "apparent" properties in the data reduction process (Ref. 15). Problems with a low-modulus thermoplastic can become particularly severe if the material creeps perceptibly during strain measurement. This condition can sometimes be alleviated by simply scaling down the system of applied loads until the creep rate is negligible. In other cases when long-term static loading is involved, it is usually necessary to obtain creep data over the full ranges of stress, time, and temperature relevant to the product application. An example, shown below, illustrates the creep properties of a low-modulus thermoplastic at a single temperature (Ref. 16). This type of information, repeated at other temperatures as appropriate, is obviously required before any rational interpretation can be made of the strains (or strain rates) observed on real test objects. It should also be noted that creep measurements on low-modulus plastics can be significantly affected by strain gage reinforcement effects (Ref. 17).



Isothermal creep properties of polypropylene (homopolymer) at 20 deg C (68 deg F). (Ref. 16)

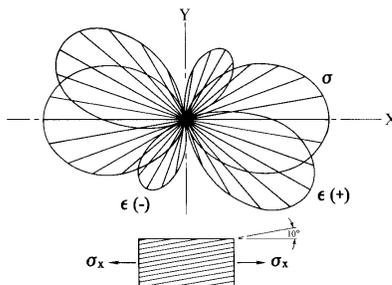
For most short-term testing of plastic and composite products under real or simulated service loads, the strain levels encountered are apt to be less than 1%, and can be considered "small" for data reduction purposes. Within this regime, the conventional definitions of strain can be employed with sufficient accuracy, and the strain distribution "at a point" is described by the usual transformation relationships, as manifested in Mohr's circle. Such being the case, principal strains are calculated from the measured strains in the customary manner.

The preceding remarks concerning strains at a point apply whether the material is isotropic or anisotropic. A continuously reinforced orthotropic composite, for example, is modeled (macromechanically) for design and stress analysis purposes as a homogeneous material with directionally varying mechanical properties. But the strain distribution about a point is a purely geometric function, unaffected by the mechanical properties; and the strains transform conventionally, as second-rank tensors. When a strain gage is installed in any direction on such a composite,

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the grid dimensions are (or should be) large compared to those characterizing the underlying inhomogeneities. As a result, the gage response represents the average strain under the grid (along the gage axis), and thus corresponds closely to the behavior of the theoretical (homogeneous) model. The same is true for each grid in a three-element rosette, which is generally required to determine the complete state of strain. Data reduction procedures – correction for transverse sensitivity and calculation of principal strains – are identical to those for isotropic materials (Ref. 18).

An interesting characteristic of orthotropic composites is that although both the strains and stresses at a point transform conventionally, according to the usual relationships, they do not, in general, do so together. That is, the principal strain directions do not coincide with those for the principal stresses except in certain special cases when the principal stresses act along the material axes. This may at first seem counter-intuitive to someone grounded in isotropic mechanics, but the effect can be readily demonstrated with an "off-axis" tensile test of an orthotropic material. As an example, illustrated below is a polar plot of the calculated normal stress and strain distributions for a 10 deg off-axis tensile specimen, as sometimes used to determine the shear modulus of a unidirectionally reinforced composite (Ref. 19). It can be seen that the principal axes for strain, in this instance, are about 30 deg away from the principal stress axes. Because of this behavior, calculation of principal stresses from principal strains is more complex than for the isotropic case, but the necessary relationships can be found in the standard reference texts on composite materials (Ref. 3).



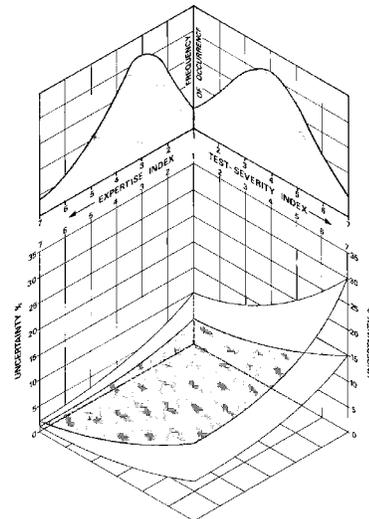
Polar representation of stress and strain distributions about a point in a 10 deg off-axis tensile test of a unidirectionally reinforced plastic.

Summary

The thesis advanced here is that accurate strain measurement on a plastic or composite test object will frequently call for much greater skill, expertise, and knowledge of mechanics than that typically required with the structural metals. Since the properties of plastic-based materials relevant to strain measurement and stress analysis often differ from those of metals by an order of magnitude

or more, error considerations tend also to differ – in both significance and type. In most cases, the potential errors are considerably larger with plastics and composites; and some error sources (e.g., hygroscopic effects on expansion and material properties) are altogether alien to the metals-oriented stress analyst.

Notwithstanding half a century of experience with strain gages applied to metals (and the current availability of high-precision strain gages and instruments) there are indications that the typical stress analysis laboratory may have difficulty in reliably achieving an accuracy of ± 10 percent. The following three-dimensional graph, for instance, represents the author's estimate of the expected uncertainty in terms of the test severity and the expertise of the strain gage user (Ref. 20). Although the graph is semi-intuitive in derivation, the extremities of the uncertainty surfaces correspond to calculable error magnitudes at the respective coordinates of test severity and expertise. It is interesting to note that results from a recent SEM round-robin test program are generally consistent with the predictions of the diagram (Ref. 21).



Probable uncertainty in strain measurement as a function of test severity and operator expertise.

The utility of the uncertainty graph for the immediate purpose is in visualizing the probable outcome of strain measurements on plastics or composites. Considering the previously described characteristics of these materials, the "test-severity index" (as a measure of impediments to accuracy) should probably range upward from about 4, and could readily exceed the limits of the diagram. Such being the case, accuracy can be expected to suffer at all levels of expertise; and, with inexperienced or careless practitioners, the data may not have sufficient reliability to justify their use in making engineering judgments.

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The preceding considerations may have long-term effects on the role of experimental stress analysis in the design and development of plastic-based mechanical products. Numerical methods (FEM, etc.) have already taken over large areas of what was once the exclusive territory of experimental stress analysis. This trend is apt to continue as the technology diffuses through the engineering community, and as moderately priced micro-computers gaining speed and capacity. To the degree that experimental stress analysts fail to prepare themselves for competently handling the more generalized attributes of plastics and composites, they can expect to relinquish ever more of their field to the numerical methods

Fortunately for the experimentalists, the need for laboratory and field testing should, if anything, rise with the continuing conversion from metals to structural plastics. Whether stress analysis is performed numerically or otherwise, the mechanical properties of the material must always be known; and these normally require experimental measurement. The characterization of a plastic or composite for engineering purposes necessitates considerably more extensive testing than is typical for metals primarily because of time, temperature, moisture, and aging effects on the material behavior. In addition, since numerical stress analysis is a modeling method (analogous to photoelasticity), experimental verification of product design adequacy is as necessary as ever, if not more so. These and other aspects of the metals-to-plastics conversion offer many new opportunities for the intelligent application of strain gage technology in product design and development.

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