Designation: E1319 − 21

Standard Guide for High-Temperature Static Strain Measurement[1]

1. Scope*

1.1 This guide covers the selection and application of strain gages for the measurement of static strain up to and including the temperature range from 425 °C to 650 °C (800 °F to 1200 °F). This guide reflects some state-of-the-art techniques in high-temperature strain measurement.

1.2 This guide assumes that the user is familiar with the use of bonded strain gages and associated signal conditioning circuits and instrumentation as discussed in (**1**) and (**2**).[2] The strain gage systems described are those that have proven effective in the temperature range of interest and were available at the time of issue of this guide. It is not the intent of this guide to limit the user to one of the strain gage types described nor is it the intent to specify the type of strain gage system to be used for a specific application. However, in using any strain gage system including those described, the proposer shall be able to demonstrate the capability of the proposed strain gage system to meet the selection criteria provided in Section 5 and the needs of the specific application.

1.3 The devices and techniques described in this guide can sometimes be applicable at temperatures above and below the range noted, and for making dynamic strain measurements at high temperatures with proper precautions. The strain gage manufacturer should be consulted for recommendations and details of such applications.

1.4 The references are a part of this guide to the extent specified in the text.

1.5 The values stated in metric (SI) units are to be regarded as the standard. The values given in parentheses are for informational purposes only.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E6 Terminology Relating to Methods of Mechanical Testing

3. Terminology

3.1 *Definitions of Terms Common to Mechanical Testing:*

3.1.1 The terms calibration, elastic limit, error, gage factor, lead wire, modulus of elasticity, Poisson's ratio, and Young's modulus are used as defined in Terminology E6. Some important terms from E6 are reprinted here.

3.1.2 *gage factor—for strain gages*, the ratio between the unit change of strain gage resistance due to strain and the causing strain.

3.1.2.1 *Discussion*—The gage factor is dimensionless and is expressed as follows:

$$K = \frac{\frac{R - R_0}{R_0}}{\frac{L - L_0}{L_0}} = \frac{1}{\varepsilon}\frac{\Delta R}{R_0} \tag{1}$$

where:

K = gage factor,
R = strain gage resistance at test strain,
R_0 = strain gage resistance at zero or reference strain,
L = test structure length under the strain gage at test strain,
L_0 = test structure length under the strain gage at zero or reference strain,
ΔR = change in strain gage resistance when strain is changed from zero (or reference strain) to test strain, and
ε = the mechanical strain $\frac{L-L_0}{L_0}$

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[2] The boldface numbers in parentheses refer to the list of references at the end of this guide.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

3.1.3 *lead wire—for strain gages*, an electrical conductor used to connect a strain gage to its instrumentation.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *capacitive strain gage*—a strain gage whose response to strain is a change in electrical capacitance which 1s predictably related to that strain.

3.2.1.1 *Discussion*—Capacitive strain gages are also commonly referred to as capacitance strain gages.

3.2.2 *compensating strain gage*—a strain gage element that is subject to the same environment as the active strain gage element, and that is placed in the adjacent leg of a Wheatstone bridge to provide thermal, pressure, or other compensation in the strain gage system.

3.2.3 *electrical simulation*—a method of calibration whereby a known voltage is generated at the input of an amplifier, equivalent to the voltage produced by a specific amount of strain.

3.2.4 *free-filament strain gage*—a resistance strain gage made from a continuous wire or foil filament that is fixed to the test article along the entire length of the strain gage, and that is supplied without a permanent matrix.

3.2.4.1 *Discussion*—The matrix is an electrically nonconductive layer of material used to support a strain gage grid.

3.2.5 *integral lead wire*—a lead wire or portion of a lead wire that is furnished by a strain gage manufacturer as part of the strain gage assembly.

3.2.6 *resistance strain gage*—a strain gage whose response to strain is a change in electrical resistance that is predictably related to that strain.

3.2.7 *shunt calibration*—a method of calibration whereby a resistor or capacitor of known value is placed electrically in parallel with another resistor or capacitor in a circuit, causing a calculable change in the total resistance or capacitance that is predictably related to a specific amount of strain.

3.2.8 *signal conditioning circuit*—a circuit or instrument subsystem that applies excitation to a strain gage, detects an electrical change in the strain gage, and converts this change to an output that is related to strain in the test article.

3.2.8.1 *Discussion*—The signal conditioning circuit may include one or more of the following: bridge completion circuit, signal amplification, zero adjustment, excitation adjustment, calibration, and gain (span) adjustment.

3.2.9 *strain gage system*—the sum total of all components used to obtain a strain measurement.

3.2.9.1 *Discussion*—The strain gage system may include a strain gage; a means of attaching the strain gage to the test articles; lead wires; splices; lead-wire attachments; signal conditioning circuit and read-out instrumentation; data-logging system; calibration and control system; environmental protection; or any combination of these and other elements required for the tests.

3.2.10 *static strain*—a strain that is measured relative to a constant reference value, as opposed to dynamic strain, which is the peak-to-peak value of a cyclic phenomenon, without reference to a constant zero or reference value (Fig. 1).

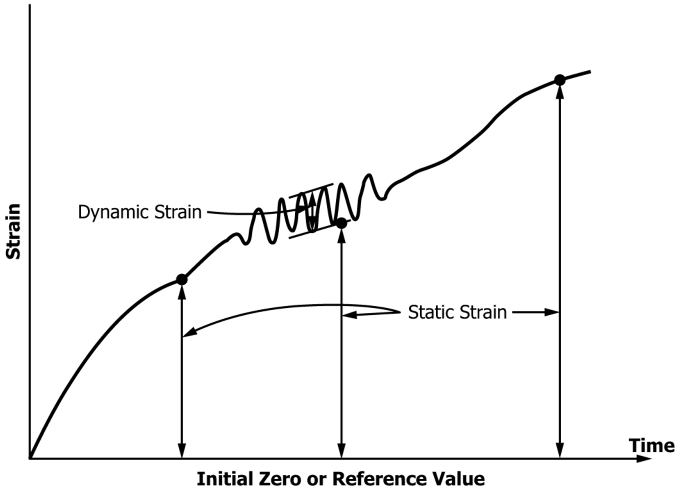


FIG. 1 Relationship Between Static and Dynamic Strain

3.2.11 *test article*—an item to which a strain gage system is installed for the purpose of measuring strain in that item.

3.2.12 *thermal compensation*—the process by which the thermal output of a strain gage system is counteracted through the use of one or more supplementary devices, such as a thermocouple or compensating strain gage.

3.2.12.1 *Discussion*—The counteraction may be integral to the strain gage system or may be accomplished by data processing methods, or both.

3.2.13 *thermal output*—the reversible part of the temperature-induced indicated strain of a strain gage installed on an unrestrained test article when exposed to a change in temperature.

4. Significance and Use

4.1 The use of this guide is voluntary and is intended for use as a procedures guide for selection and application of specific types of strain gages for high-temperature installations. No attempt is made to restrict the type of strain gage types or concepts to be chosen by the user. The provisions of this guide may be invoked in specifications and procedures by specifying those that shall be considered mandatory for the purpose of the specific application. When so invoked, the user shall include in the work statement a notation that provisions of this guide shown as recommendation shall be considered mandatory for the purposes of the specification or procedure concerned, and shall include a statement of any exceptions to or modifications of the affected provisions of this guide.

5. Strain Gage Selection Criteria

5.1 The factors listed in this section shall be considered when selecting a strain gage system for use in the temperature range specified in 1.1. The risk of compromising certain test objectives shall be evaluated.

NOTE 1—It is possible that no strain gage has all of the desired capabilities to meet all requirements of a particular test. Some test objectives will have to be modified to match the capabilities of the available strain gage selected. Guidelines for this evaluation are provided in Section 9.

5.2 *Operating Temperature:*

5.2.1 *Isothermal Tests*—Stability of the reference value with respect to time is essential when tests are to be made at constant temperature. The stability of the candidate strain gage system at the specified temperature shall be such that any shift that occurs in the reference value is tolerable for the duration of the test.

5.2.2 *Thermal Compensation and Transients*—The adequacy of the thermal compensation shall be considered when the measurement of strain during a thermal transient is required.

NOTE 2—Thermal output is a function of temperature, thus its value at a temperature depends not only on temperature, but on the temperature history followed in reaching that temperature. If significant hysteresis in the thermal response is present, large errors or uncertainties can result. This is especially true when the calibration procedure used to characterize the thermal output does not accurately reflect the temperature sequence to which the strain gages will be exposed during testing.

5.2.2.1 If the response time of the thermal compensation is exceeded, the resulting uncertainty shall be considered.

5.2.2.2 The ability of the strain gage system to withstand the transient without a detrimental shift of the reference value shall be verified. This is true whether or not strain is measured during the transient.

5.2.2.3 Any gage factor change as a function of temperature change shall also be considered.

5.2.3 *Pre-test Calibration:*

5.2.3.1 If thermal output calibration on the test article is not possible, strain gages shall be precalibrated on a similar material.

NOTE 3—Variations of up to 0.3×10^{-6}/°C are possible within a material. Often, rolling direction will influence thermal expansion coefficient.

5.2.3.2 Precalibrate resistance or capacitive strain gages using a calibration fixture made from material similar to the test article. The calibration fixture shall be made to precisely fit the strain gage, especially if curvature is involved. Mating parts shall be lapped together to provide uniform clamping pressure around the periphery of the strain gage weld area.

5.2.3.3 The calibration test should be repeated to ensure precise duplication of the calibration. Zero return should also repeat exactly.

NOTE 4—If calibration data does not repeat, either the calibration setup or the strain gages are faulty.

5.2.4 *Post-Test Calibration*—If a more precise thermal output calibration is needed, a post-test calibration should be conducted.

5.2.4.1 Remove the test strain gage (cut it out of the test article) and run a precision test on the test strain gage still attached to the test article material.

NOTE 5—The test article is relieved of all induced stresses (thermal, mechanical, residual) and is free to expand freely with temperature.

5.2.4.2 The strain gage integral lead wire should be exposed to thermal gradients similar to those that occurred during the test program.

5.3 *Duration of Test*—The ability of all parts of the strain gage system to function for the specified duration of test should be demonstrated; if multiple tests are required on the same test article, the capability and effect of strain gage replacement shall also be established.

5.4 *Strain Rate*—The time response of the candidate strain gage system shall be adequate to meet test requirements if rapid changes of load are anticipated.

NOTE 6—Limiting the loading rate of the test is one solution to accommodate limitations of the selected strain gage system.

5.5 *Environment*—Some strain gages are limited to specific operating environments and therefore, the strain gage system selected shall be capable of withstanding the environment in which it will operate. Such limitations shall be carefully considered when selecting the strain gage system to be used.

5.5.1 Factors such as pressure, vibration, radiation, magnetic fields, and humidity shall be considered.

5.5.2 The ambient and test environments of the elements of the strain gage system shall be considered in the selection of lead wires, connectors, instrumentation, and seals (when required).

5.6 *Strain Range:*

5.6.1 *Total Strain Range*—The maximum strain ranges of the candidate strain gage types shall be defined and shall be adequate for the test. Mechanical strain attenuators, when permissible, may be added to extend the strain range of a given strain gage system, subject to the limitation of 5.6.2.

5.6.2 *Resolution*—The ability of the candidate strain gage system to measure small increments of strain within the total strain range should be compared with the incremental strain measurement requirements of the test. When mechanical strain attenuators are used, the resulting loss of resolution shall be considered.

5.7 *Strain Gradient*—The length of the candidate strain gage establishes the length over which the unit strain is averaged. This factor shall be considered.

5.8 *Uncertainty Factor*—Uncertainty information that is available from the manufacturer shall be considered, in conjunction with conditions that are unique to the test, in order to estimate the total uncertainty.

5.9 *Space Requirements*—Working space for installation of the strain gage system shall be considered. Space adjacent to the installed strain gage should be provided for installation of room-temperature strain gages required for making in-place calibrations.

NOTE 7—If space on or adjacent to the test article is limited, the space requirements for the complete strain gage system can be a critical consideration in determining the suitability of a particular strain gage system.

5.10 *Effects of the Strain Gage on the Test Article*—If a weldable strain gage is to be used on thin sections, an evaluation of the reinforcing effect should be made.

NOTE 8—In most cases the reinforcing effect of the strain gage on the test article is negligible, particularly in the case of capacitive strain gages where the spring rate is extremely low. Technical data concerning this effect can be obtained from a strain gage manufacturer.

6. Characteristics of Available Strain Gages

6.1 The two basic types of strain gages used for high temperature static strain measurements are resistance strain gages and capacitive strain gages.

6.1.1 Resistance strain gages are usually small, low-profile units superbly suited for dynamic strain measurements and relatively short-term static measurements. Because high temperatures cause metallurgical instability, oxidation, relaxation, and phase change of the strain sensing materials, all of which affect resistance change, resistance gages are generally not used for long-term measurements.

6.1.2 Capacitive strain gages are devices that measure changes in geometry and are unaffected by temperature or temperature changes, oxidation, relaxation, creep, grain growth, or phase change. They are best suited for measuring creep strains, or for very long-term tests on applications where a relatively large strain gage can be used, and when the strain gage will not be subjected to high vibration, gravity, or acceleration forces, shock loading, or an electrically conductive atmosphere.

6.1.3 When selecting a specific strain gage for a given application, the strain gage system shall be qualified for the specific conditions under which it will be required to operate and for the characteristics it shall exhibit under service conditions. This section describes some of the capability of currently available strain gages, suitable for use in the specified temperature range, to meet the selection criteria of Section 5.

NOTE 9—Wire and foil free-filament strain gages are usable to approximately 400 °C (750 °F) under static conditions, and to approximately 1250 °C (2280 °F) for certain dynamic applications. However, the bonding methods used (ceramic cement, flame spray) are cumbersome and difficult to employ on large structures, particularly under field conditions. Ceramic cements require heat-curing and are generally unsuitable for large structures such as nuclear or fossil-fuel power-generating equipment. Flame spray is also difficult to use in the field. Free-filament strain gages, although useful for strain measurement on small articles under laboratory conditions, are, therefore, not included in this guide. This does not preclude the use of these strain gages for specific tests based on the selection criteria of Section 5.

6.1.4 The strain gages described in this section have been used at high temperature for sufficient time and with sufficient success to warrant consideration in this guide. Each type has unique features, advantages, and limitations that shall be carefully evaluated relative to the selection factors of Section 5.

6.2 *Bonded Weldable Resistance Strain Gage:*

6.2.1 This strain gage, shown in Fig. 2, consists of a free-filament strain gage ceramic bonded to a shim. While it is not usually sealed or intended for underwater use, some hermetically sealed strain gages are bonded to the shim with ceramic cements or flame sprayed ceramics. The following alloys are available: *(1)* self temperature compensated nickel chrome alloy sensors usable to 340 °C in quarter bridge (single element) configuration, *(2)* platinum tungsten and palladium chrome alloy sensors (dual element) compensated with platinum elements in half-bridge configuration, and *(3)* iron chrome aluminum alloys having low temperature coefficient are available in half- or full-bridge configuration for applications where active-dummy combinations (slow temperature changes) are usable.

6.2.2 Except for long-term stability, the bonded strain gage has excellent performance with minimal hysteresis, small zero shift, long fatigue life, and accurate gage factor among its salient features. An integral weldable terminal and integral high temperature cable are usually supplied with these units, especially when the strain gages are supplied precalibrated for apparent strain.

6.2.3 The thermal output of the dual element strain gages can be adjusted to produce a zero output at any two selected temperatures. The thermal output of the platinum tungsten strain gage is usually well within ±200 µm/m between 20 °C and 500 °C. The shape of the thermal output curve is influenced by the thermal expansion characteristics of the test material. Fig. 3 shows the bridge completion circuit for the dual element half-bridge strain gage. There are two methods of thermal compensation: *(1)* NASA method (**3**) and *(2)* the wire method (**4**).

6.2.3.1 With the NASA method, the strain gage is manufactured to fit a specific type of material with the platinum thermometer element resistance value selected to provide an almost perfectly balanced bridge. This permits a three-wire cable to be used without sacrificing inherent lead wire compensation. The five-wire system employs a thermometer element sufficiently high in resistance to compensate on virtually any material. This makes for universal thermal compensation on any material. The drawback of this universal system is that five wires are required. A shunt calibration resistor R_g placed across the thermometer element only shunts the output of the compensator. If the shunt calibration resistor were placed across the thermometer and lead wire, inherent lead compensation would be sacrificed.

6.2.4 The user may precalibrate the strain gage and cable system and determine the bridge completion resistor values using a set of equations provided with the strain gage, or the strain gage may be precalibrated at the factory (**5**) and supplied precalibrated with the bridge completion resistors included in a circuit attached to the cool end of the cable. The user needs

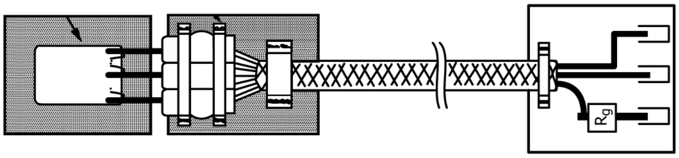


FIG. 2 Bonded Weldable Resistance Strain Gage

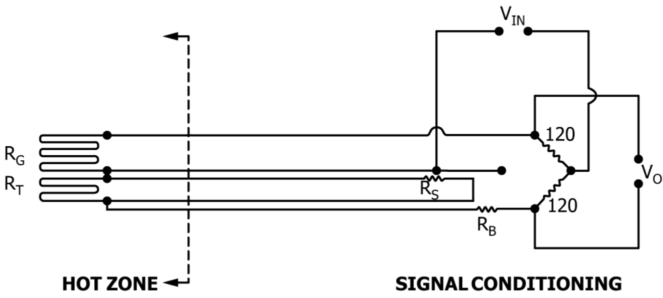


FIG. 3 Five-Wire Circuit

only to connect the strain gage as a full bridge transducer and insert the calibration curve into the data acquisition system.

6.3 *Hermetic Weldable Resistance Strain Gage*—This strain gage, which is shown several times the actual size in Fig. 4, is hermetically sealed and furnished with integral lead wires, and may be used in a variety of severe environments at high temperature. The strain tube is welded to a thin mounting flange, which is welded to the surface of the test article, thus providing transfer of strain from the test article to the strain gage. Although Fig. 4 shows stainless steel strain tube, mounting flange, and cladding of the integral lead wire, other materials are available to meet the requirements of specific applications; consult the manufacturer for available materials. Within limits, the thermal output of the strain gage due to temperature can be adjusted to produce a zero output at any two selected temperatures by inserting a thermal compensation resistor, R_{tc} in Fig. 5 in series with either the active or compensating strain gage element; the proper resistor is furnished by the manufacturer. Because of the added resistance in series with one of the strain gage elements, the bridge-completion resistors shall also be adjusted for balance by adding a balancing resistor (R_{bal} in Fig. 5) in the opposite half of the bridge. This resistor is also furnished by the strain gage manufacturer. The value of R_{bal} is based on the use of 120 Ω bridge-completion resistors to produce a balanced bridge when the strain gage is connected.

6.3.1 *Operating Temperature and Thermal Stability:*

6.3.1.1 The platinum tungsten element is essentially stable for short-term testing to 500 °C (days) with shorter excursions up to 580 °C (hours) without damage to the strain gage. Longer tests (weeks) can be run to up to 425 °C. Beyond these limits a capacitive strain gage should be used.

6.3.2 *Thermal Compensation and Transients*—Thermal output characteristics shall be considered for operation at varying temperatures.

NOTE 10—Information about the thermal output characteristics is furnished by the manufacturer for use of the strain gage on the material specified by the user.

6.3.2.1 For precise evaluation, the strain gage system shall be calibrated, with thermal output determined at the temperatures of interest. Temperatures should be measured by a thermocouple(s) mounted immediately adjacent to the strain gage.

NOTE 11—Thermal output and hysteresis of a test are usually repeatable under identical test conditions; however, even the slightest change in test conditions can result in a change of thermal output, hysteresis, or both.

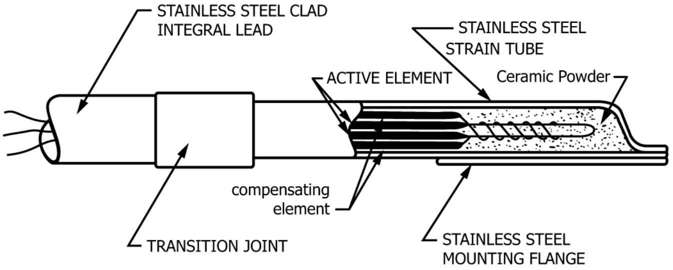


FIG. 4 Hermetic Weldable Resistance Strain Gage

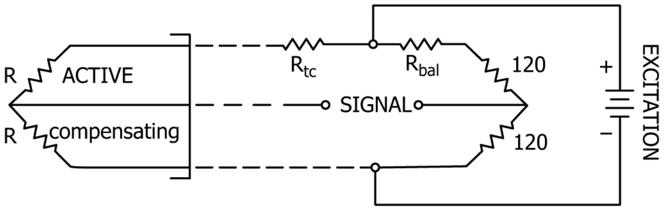


FIG. 5 Bridge Completion Circuit and Power Supply

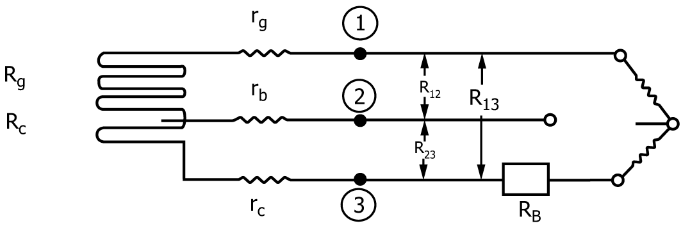
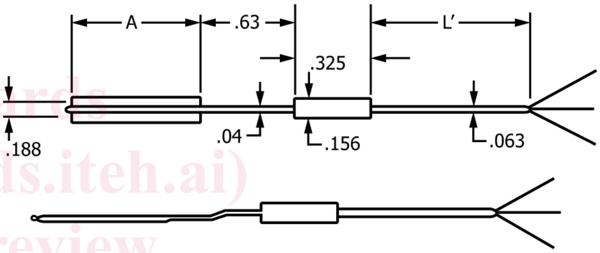


FIG. 6 Three-Wire Circuit

TYPE	SG 425	MG 425
DIM. A	1.09	.62



NOTE 1—All dimensions are in inches.

FIG. 7 Dimensions of Hermetic Weldable Resistance Strain Gage

6.3.2.2 To qualify the strain gage for thermal shock, laboratory tests should be made to determine the stability characteristics and the limits of thermal compensation.

6.3.3 *Electrical Requirements*—Bridge completion, as shown in Fig. 5, shall be made. While there are several standard strain gage systems with bridge completion capability available, for static strain measurement in the temperature range of this guide, an individual signal conditioning circuit should have the following features for each strain gage.

6.3.3.1 *Excitation Power Supply*—A power supply for providing constant DC voltage, continuously variable from 1 V to 15 V across a 120 Ω external load, shall be used. If more than one bridge circuit is excited by the same power supply, the electrical configuration shall provide electrical isolation of each circuit to protect it in the event of a direct short of the excitation of any of the adjacent circuits.

NOTE 12—Constant current excitation cannot be used with some of the thermal compensation techniques generally used with the hermetic weldable resistance strain gage..

6.3.3.2 *Balance Control*—Means shall be provided for balancing the bridge with a *T* balance resistor circuit across the completion half of the bridge. This means may be omitted if the data acquisition equipment automatically compensates for initial bridge unbalance.

6.3.3.3 *Shunt Calibration*—Shunt calibration capability should be provided on the completion half of the bridge. The active or compensating legs of the bridge should not be shunted, because of changes in the resistances of the lead wires with temperature. Multiple shunt calibration should be done.

6.3.3.4 *Signal Conditioning Circuit*—The signal conditioning circuit shall be capable of handling a half-bridge circuit with precision completion resistors, configured to permit the addition of series balance resistors to either leg. The signal conditioning circuit should be able to accommodate a half-bridge, five-wire configuration, with two additional leads, for remote sensing of the excitation voltage.

6.3.3.5 Means shall be provided for continuous monitoring of bridge excitations and bridge output. An amplifier may be used or omitted, depending on the input capability of the strain gage system used. Amplifier requirements are not covered in this guide; however, a good quality, stable amplifier with true differential input, and input impedance of not less than 10 MΩ and shunted by 750 pF when DC-coupled should be used.

6.4 *Differential Capacitance Strain Gage*—Fig. 8 identifies major elements of the strain gage and shows principal dimensions. Fig. 9 shows an isometric view. The compensating rod (1) is usually made of the same material as the test article (specified by user). The cylindrical excitation plates (2) are mounted coaxially on, but are electrically insulated from, the compensating rod. The sensing ring (3) is mounted coaxially with the excitation plates but is separated from them by an air gap. The attachment ribbons (4) (see the isometric view, Fig. 9) provide means for welding the strain gage to the test article. The alignment flexures (5) (see the isometric view in Fig. 9), maintain the coaxial alignment of the sensing ring relative to the excitation plates and compensating rod. Leads from the three capacitor plates are brought to a terminal (6) (in Fig. 9) which is also attached to the test article by spot welding. The complete strain gage system consists of a half-bridge differential capacitance strain gage, a capacitive signal conditioning circuit, and the interconnecting leads.

6.4.1 With this type of strain gage, strain in the test article causes linear movement of the excitation plates relative to the colinear sensing ring. Changes in capacitance result when more or less area of the sensing ring overlaps the respective excitation plates; the linear gap between the excitation plates and the annular gap between the excitation rings and the sensing rings remain constant. Thermal compensation is achieved by use of a compensating rod made from a material having thermal expansion characteristics similar to those of the test article. Both the strain gage and the test article are instrumented with thermocouples to obtain data for computing the corrections required if there is a temperature difference between the compensating rod and the surface of the test article. These thermocouples (7) are shown in Fig. 9 and are connected to the thermocouple terminals (8) which are spot welded to the test article. Factors affecting strain gage selection are discussed in the following paragraphs.

6.4.2 *Operating Temperature and Thermal Stability*—The strain gage operates effectively over the entire 425 °C to 650 °C (800 °F to 1200 °F) range covered by this guide. Average drift rates for long term tests (2000 h to 12 000 h) are typically from 0.01 (µm/m)/h to 0.05 (µm/m)/h at approximately 640 °C (1180 °F). Short term drift rates can be up to 1 (µm/m)/h during the first 100 h of operation.

6.4.3 *Thermal Compensation and Transients*—The strain gage has been used successfully at thermal transients of up to 17 °C/s (30 °F/s). For varying temperature conditions, thermal output should be generated in situ utilizing an integral surface thermocouple.

NOTE 13—Thermal output and hysteresis of a test are usually, within limits repeatable under identical test conditions. Even the slightest change in test conditions, however, can result in a change of apparent strain, hysteresis, or both.

6.4.4 *Life Expectancy*—Successful tests of more than 12 000 h duration have been reported. Cyclic fatigue data are not available **(6).**

6.4.5 *Strain Rate*—The strain gage is rated for less than 2 % nonlinearity to 30 000 µm/m at 21 °C (70 °F) **(7).**

6.4.6 *Environmental Factors Other Than Temperature*—The strain gage has usually been used in air at atmospheric pressure, but has performed satisfactorily in helium, hydrogen, nitrogen, and an air-argon mixture of unknown composition. The experimenter should consult the manufacturer before attempting to use the strain gage in gases other than those noted.

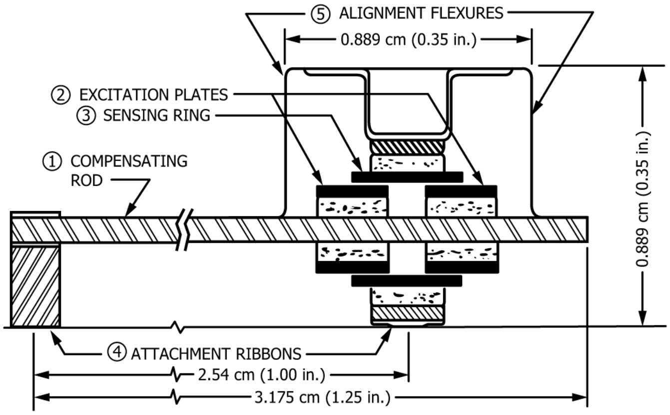


FIG. 8 Differential Capacitance Strain Gage