Force, Weight, and Motion Measurement

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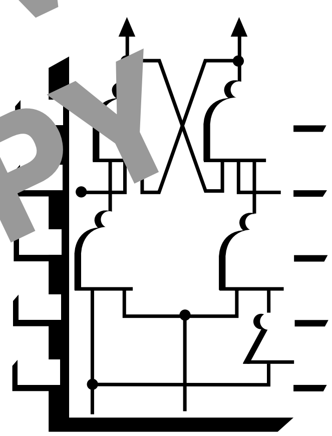
FORCE, WEIGHT, AND MOTION MEASUREMENT

Lesson One

Force, Stress, and Strain



TPC Training Systems

27401

Lesson

1 Force, Stress, and Strain

TOPICS

Force and Motion
Units of Force
Static Forces
Effects of Static Forces
Elasticity
Strain Gauges
Gauge Factor
Measurement Systems for Strain Gauges
Gauge Configurations
Other Force-Measuring Devices

OBJECTIVES

After studying this Lesson, you should be able to…

- Define force, stress, strain, and deformation in terms of the English and SI units used for their measurement.
- Describe the relationship between stress and strain (Hooke's law).
- Describe the operation and construction of various kinds of strain gauges.
- Identify the electrical circuits used with strain gauges.
- Describe the piezoelectric effect and the capacitance mat and discuss typical applications.

KEY TECHNICAL TERMS

Force 1.01 a pushing, pulling, or twisting
Stress 1.11 the resistance force per unit of area
Deformation 1.12 a change in dimension
Strain 1.13 the change in dimension divided by original dimension
Elastic limit 1.18 the maximum deformation the material can withstand and still return to its exact original shape when the force is removed
Strain gauge 1.21 a device in which resistance changes as an object deforms, thus indicating the strain (and consequent stress or load) on the object
Piezoelectric effect 1.48 phenomenon involving the production of voltage with deformation

The measurement of force is critical in many industrial applications. To ensure products that are reliable and structurally efficient, designers and manufacturers must determine the forces to which the objects will be subjected. This requires an unobtrusive measuring system that can be installed on the item of interest, allowing test engineers to measure accurately the loads and resultant stresses. Two instruments used for this task are strain gauges and devices using piezoelectric crystals. This Lesson deals with the theory and application of these instruments and others.

Force and Motion

1.01 If an object moves from rest, some *force* is causing that object to move. To move an object, you must apply a force—pushing, pulling, or twisting, for example. The force may be produced by electrical, mechanical, hydraulic, or pneumatic means, but force of some kind is necessary to move the object. However, the fact that an object is *not* in motion does not mean that no force is being applied. Equal and opposite forces may balance each other. If an object is at rest, it is in a condition of *static equilibrium*. That is, the sum of all the applied forces is equal to zero.

Units of Force

1.02 Force is measured in units that describe the magnitude of the force applied to an object. You must specify the *direction* in which the force acts, as well as its magnitude. Suppose you know only that two forces of equal magnitude act on an object. You can't tell if or how the object moves without knowing the direction in which the forces are acting.

1.03 In the English system of units, force is measured in pounds (lb). In the metric (SI) system, the unit of force is the newton (N). One N is the force needed to give a mass of one kilogram (kg) an acceleration of one meter per second squared. A force of 1 lb is equal to a force of 4.448 N.

Static Forces

1.04 An object does not move if the sum of all the forces acting on the object equals zero, in all directions. Figure 1-1 shows the forces acting on a rigid steel bar. The bar, supported by a scale at either end, weighs 4 lb.

1.05 The forces acting on the bar are W (its weight) and F_1 and F_2 (the forces acting upward at each scale to counterbalance the force W). The sum of forces F_1 and F_2 must be equal to W and opposite in direction. Otherwise the bar would accelerate. Therefore, the total force on the bar may be stated as:

$$F_1 + F_2 + W = 0, \text{ or } F_1 + F_2 = -W$$

Because the bar weighs 4 lb, $F_1 + F_2 = 4$ lb. Because one scale is placed at each end and the shape of the bar is uniform, $F_1 = F_2 = 2$ lb (half of W).

1.06 Now suppose a weight of 9 lb is hung from the bar, closer to Scale 2, as shown in Fig. 1-2 on the following page. Again, the sum of the forces equals zero, resulting in static equilibrium. The forces acting on the bar are the downward forces due to gravitation, W, and the upward forces from the scales counterbalancing W.

1.07 Because the 9-lb additional weight is closer to Scale 2, you would expect that scale to register more than Scale 1. In fact, both scales register the additional 9 lb in the ratio of $1/3$ to $2/3$, or:

$$F_1 = 2 \text{ lb weight of bar} + 1/3 \text{ of } 9 \text{ lb} = 5 \text{ lb}$$

$$F_2 = 2 \text{ lb weight of bar} + 2/3 \text{ of } 9 \text{ lb} = 8 \text{ lb}$$

$$F_1 + F_2 = 13 \text{ lb}$$

1.08 The calculations above are based on the behavior of bars like the one in Fig. 1-2. A bar or

Fig. 1-1. Steel bar on two scales

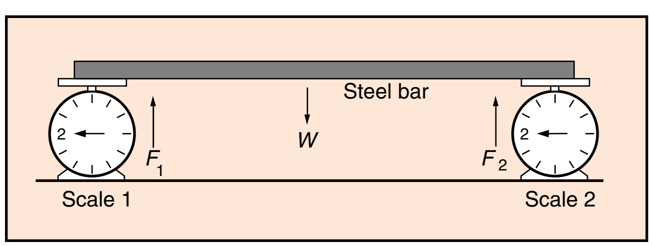


Fig. 1-2. Steel bar with a weight added

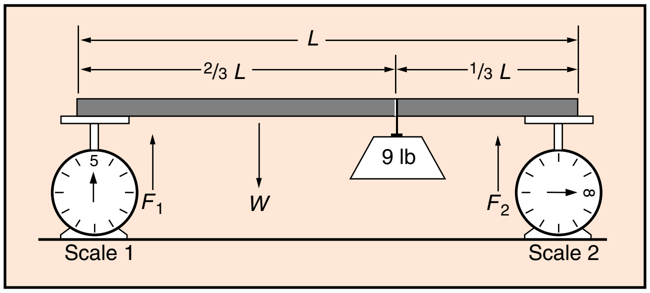
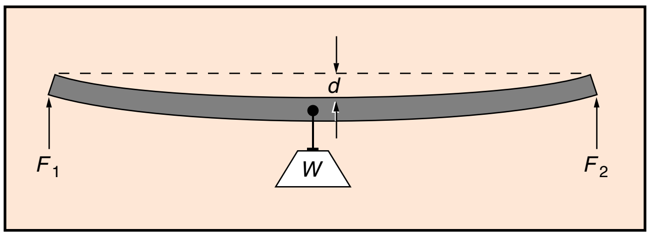


Fig. 1-3. Weight W causes this bar to bend



beam always deforms, or bends, under load. Figure 1-3 shows a weight suspended from a flexible bar. The force, W, causes the bar to bend along its longitudinal axis, and to deform a measurable distance, d. The deformation may be very slight when normal loads are applied. However, under an overload or sudden application of forces, for example, the deformation may be large enough to be unacceptable.

Application 1-1

A builder wanted to build quality condominiums but had to keep tight control on expenses. The amount and size of lumber used to support the typical floor and ceiling were critical. The choices included southern pine (2 × 12s on 24-in. centers or 2 × 10s on 16-in. centers), aluminum beams, and laminated wood. The maximum deflection at the center of the span had to be less than 0.0028 of the span to ensure that the ceiling under the beams would not crack. An analysis of the loads helped determine the proper size, spacing, and materials needed. Proper design then resulted in minimal deflection of the beams.

1.09 Figure 1-4 shows a steel bar in three different configurations. In each case, different forces are applied. The bar at the left in Fig. 1-4 is rigidly attached at one end with a force pulling along its longitudinal axis. This loading causes tensile stresses (*tension*) in the bar—the bar becomes longer. If the force and resulting deformation increase enough, the bar will permanently stretch or possibly fracture.

1.10 In the center of Fig. 1-4, the same bar is now gripped in a C-clamp. Force is applied along the longitudinal axis, but toward the center of the bar. Now the bar is under a compressive stress (*compression*). The bar will become shorter. The bar on the right in Fig. 1-4 is held rigidly at one end with a downward force acting to cut the bar where it is attached. This is an example of *shear* force. Shear stress is critical in the design of bolts, screws, and rivets, which can fracture (*shear*) if the applied force is too great.

Application 1-2

A manufacturer of outboard motors needs to protect the expensive gears, shafts, and other components from being permanently damaged if the propeller becomes caught in seaweed, sand, or other obstruction while the motor is running. Therefore a shear pin is built into the design. This pin is a solid piece of metal designed to shear, or fracture, if the propeller gets stuck while the motor is running. As torque is applied to the pin, its shape and material cause it to break. The shear pin acts like a mechanical fuse, protecting the more expensive components.

Effects of Static Forces

1.11 The preceding sections described four kinds of object deformation—bending, tension, compression, and shear. (Note that bending can cause a combination of simultaneous tension, compression, and shear in different areas of an object.) The body acted upon can return to its original shape because forces within the body resist the action of the external forces. A body in the act of resisting external forces is referred to as stressed. Stress is the amount of force per unit of area. In the English system, stress is measured in pounds per square inch, or psi. In the SI system, the units are megapascals (newtons per square millimeter), or MPa.

1.12 An object subjected to external forces deforms. *Deformation* is the change in shape, or dimension, of an object. For example, a cable resisting a load elongates, or stretches. If the external forces are compressive—in the foundation of a building, for example—the object compresses. If shear forces are applied—a wrench tightening a bolt, for example—the bolt deforms.

1.13 The units for measuring deformation indicate the change in dimension, usually length or volume. Deformation units are generally converted into strain. *Strain* may be expressed as the change in dimension divided by the original dimension—in./in. in the English system and mm/mm in the SI system. Strain may also be expressed as a percentage. For example, suppose a steel cable, originally 50 in. long, becomes 50.2 in. long while supporting a load of 200 lb. The strain on the cable is expressed mathematically as follows:

$$\frac{50.2-50}{50}=\frac{0.2}{50}=0.004 \text{ in./in. or } 0.4\%$$

Elasticity

1.14 The bar in Fig. 1-3 will return to its original position when the external force (caused by the application of the weight, *W*) is removed. This property of materials—the ability to deform under load and then return to the exact original shape when the load is removed—is referred to as *elasticity*.

1.15 This phenomenon is described by *Hooke's law*, which states that stress is directly proportional to strain. That is, a body that deforms will exert a force on the object that deforms it. This force is proportional to the amount of deformation as long as the deformation does not exceed a certain value.

1.16 Figure 1-5 on the following page shows graphs of four materials clamped in a tensile-force testing machine and stretched until they break. Wood and cast iron have minimal resistance to applied tensile forces, but steel has considerable tensile strength.

1.17 Different kinds of steel have different tensile-strength characteristics. For example, mild steel (low to medium carbon content—0.05 to 0.25% carbon) can stretch up to 3.9% before fracturing. Generally, as the carbon content of steel increases, its hardness and tensile strength also increase.

1.18 Points X and Y, where the graphs in Fig. 1-5 stop being a straight line, mark the *proportional limits* for hard and mild steel. The *elastic limit* (which may occur at some point on the graph beyond the proportional limit) is the maximum deformation the material can withstand and still return to its original shape when the load that caused the deformation is removed.

1.19 If an object deforms beyond the elastic limit, the deformation is permanent. It remains even when the load is removed. If the load continues to increase, eventually the material will fracture. This kind of fracture, a *ductile* fracture, shows considerable permanent deformation prior to fracture. In contrast, brittle materials—cast iron and ceramics, for example—fracture with little if any prior deformation.

1.20 On re-examining Fig. 1-3, you can see that the bottom of the bar is elongated and the top is shortened.

Fig. 1-4. This steel bar is subjected to three kinds of force

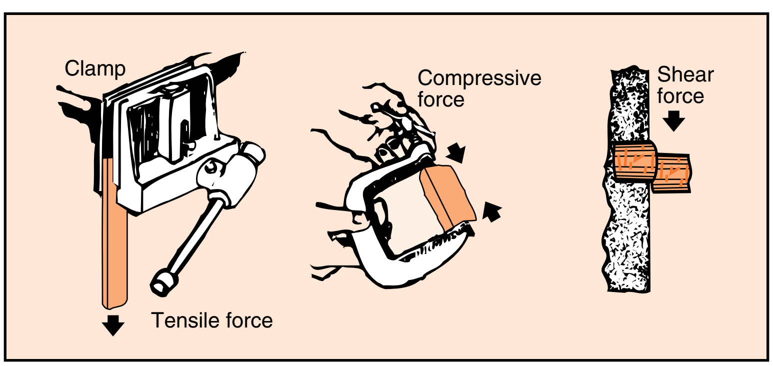
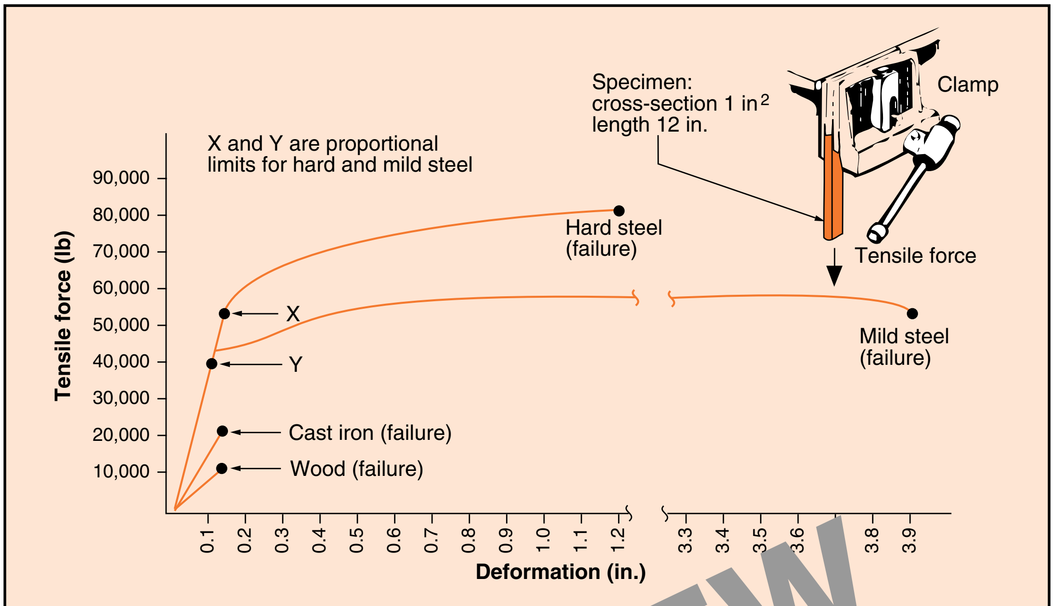


Fig. 1-5. Responses of four materials under stress



In effect, the bottom of the bar is under tension while the top is under compression. The deflection of the bar is exaggerated for illustrative purposes. In an actual situation, the deflection of the bar would be so slight it could not be seen by a casual observer.

Strain Gauges

1.21 A *strain gauge* is a transducer that changes its electrical resistance as its dimension changes. This device is widely used in load cells, scales, accelerometers, pressure gauges, torque and force gauges, and gyros. A common strain gauge is made from metal wire (or foil). As the wire undergoes slight extension and a decrease in its cross-sectional area, the resistance of the wire increases. Furthermore, the inherent resistivity of typical metals also increases with strain. These changes are small, but they can be measured by a sensitive electrical circuit. The wire must not be stretched beyond its elastic limit.

1.22 Figure 1-6 shows a simple resistance strain gauge. A wire is shaped into a flat grid (actually a

Fig. 1-6. Bonded strain gauge cemented on a steel beam

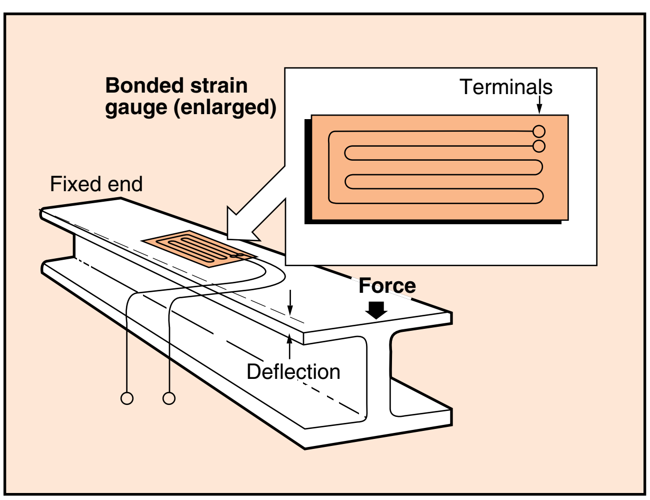
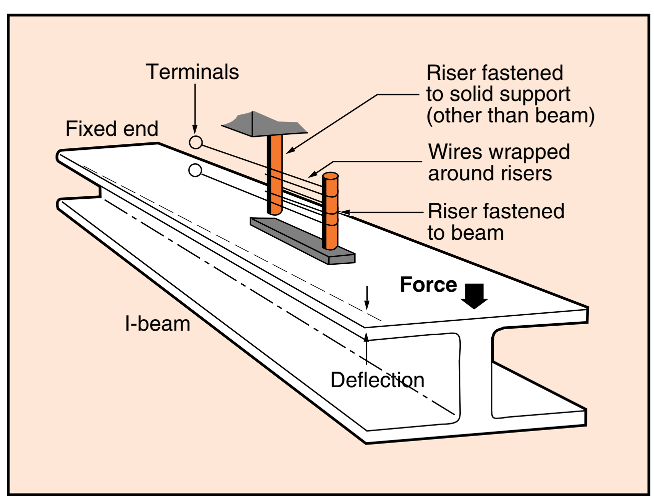


Fig. 1-7. Unbonded strain gauge mounted on a steel beam



thin metal foil is used) and bonded to a carrier sheet. The entire assembly is referred to as a *bonded strain gauge*. Initially the foil is one solid rectangular shape, but a chemical etching process removes much of it, leaving the wire-like grid. If the beam in Fig. 1-6 is to be put under load, with a stress resulting, the gauge must be bonded firmly to the beam, as shown.

1.23 The backing must be thin to transfer the strains of the object to the wire properly. The gauge assembly is attached to the object with a high-strength adhesive. In Fig. 1-6, the strain (and stress) of interest is longitudinal when the beam is under its normal transverse load. Therefore, the gauge must be applied to the beam in such a way that the wires stretch or compress in the longitudinal direction when the beam is loaded.

1.24 The beam deflects slightly downward as the load is applied to its free end. The bonded strain gauge, glued securely to the top surface of the beam, deforms much as the beam does. Because the beam is fixed at one end only, the top surface of the beam is under *tension* (it is increasing in length), while the bottom surface is under *compression* (it is decreasing in length longitudinally). The position of the strain gauge in Fig. 1-6 allows it to measure the amount of tensile strain and, by formulas, the compressive strain.

1.25 A second kind of resistance strain gauge is the *unbonded gauge*, which was used much more commonly in the past than it is today. This device consists of a stationary frame bolted or welded to the member under stress. The other part of the framework is securely fastened, but independent of the member under stress. Wires wound around the risers of the framework form a length of wire with a resistance value of R.

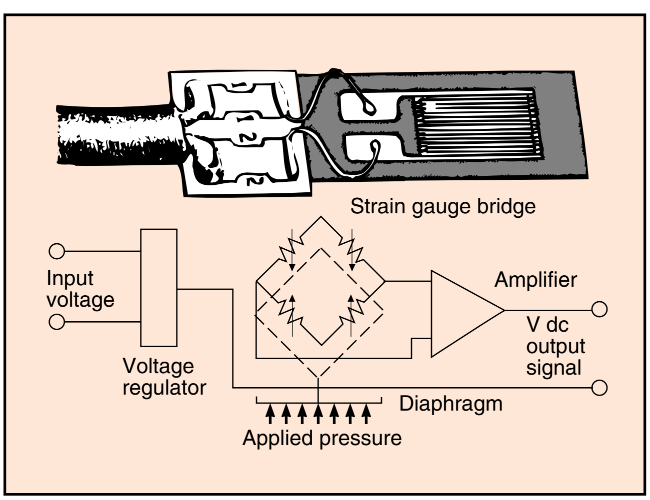
Table 1-1. Examples of strain gauges from one manufacturer

Characteristic	Bonded	Unbonded
1. Gauge factor (sensitivity)	1.7	4.0 and higher
2. Temperature effects	Use compen-sating gauge	Use compen-sating gauge
3. Unstressed gauge resistance	About 120 Ω	Can be 600 Ω
4. Wire in grid	Bonded to carrier sheet	Vulnerable to damage
5. Operational factors:		
a. Temperature	200°F max.	500°F max.
b. Repeatability	Within 0.25%	Within 0.25%
c. Hysteresis	Negligible	Negligible
d. Displacement	0.001 in.	0.002 in.
6. Maximum current	[illegible] mA	1.0 mA

1.26 As shown in Fig. 1-7, the wires elongate as force is applied to the beam, and the total resistance of the wires increases in proportion to the amount of force. An ohmmeter connected to the terminals will register a new value of total resistance that is directly related to the wire's change in length.

1.27 Figure 1-8 shows a bonded strain gauge that is about the size and weight of a postage stamp. The solder tabs at the left of the gauge, used to connect the gauge to separate terminal strips, help protect the device from mechanical forces if the lead wires are pulled. Table 1-1 compares some characteristics of one manufacturer's bonded and unbonded strain gauges.

Fig. 1-8. Bonded strain gauge



The Programmed Exercises on the next page will tell you how well you understand the material you have just read. Before starting the exercises, remove the Reveal Key from the back of the book. Read the instructions printed on the Reveal Key. Follow these instructions as you work through the Programmed Exercises.

1-1. A force of 1 lb is equal to a force of 4.448 _______.	1-1. N or NEWTONS Ref: 1.03
1-2. A bar attached at one end and under tensile stress becomes _______.	1-2. LONGER Ref: 1.09
1-3. A suspended bar under compressive stress becomes _______.	1-3. SHORTER Ref: 1.10
1-4. What kind of stress is critical in the design of metal fasteners?	1-4. SHEAR Ref: 1.10
1-5. Stress is _______ per unit of area, and deformation units are converted to _______.	1-5. FORCE; STRAIN Ref: 1.11, 1.13
1-6. A material's ability to return to its original shape when the load is removed is referred to as _______.	1-6. ELASTICITY Ref: 1.14
1-7. The relationship between stress and strain is described by _______.	1-7. HOOKE'S LAW Ref: 1.15
1-8. A strain gauge changes its ________ as its dimension changes.	1-8. RESISTANCE Ref: 1.21

Gauge Factor

1.28 The *gauge factor* or *sensitivity* of a strain gauge is the ratio of the relative change in resistance to the relative change in the length of the wire. It is expressed as:

$$\frac{\Delta R / R}{\Delta L / L}$$

where Δ = Greek letter *delta*, meaning change

R = initial resistance of gauge (in ohms)

L = initial gauge length

1.29 The foil diameter is about 0.002 in. (0.05 mm). The length of the wire and its electrical resistance are both chosen to work well in a small gauge. A typical unstressed gauge has a resistance of 120 Ω and is designed to carry a current of 25 mA. (Other standard strain gauges have resistances of 350 Ω, and amplifier bridges allow you to select either 120 or 350 Ω.) Strain gauges are also available with resistances of 50 to 5000 Ω and currents other than 25 mA.

Measurement Systems for Strain Gauges

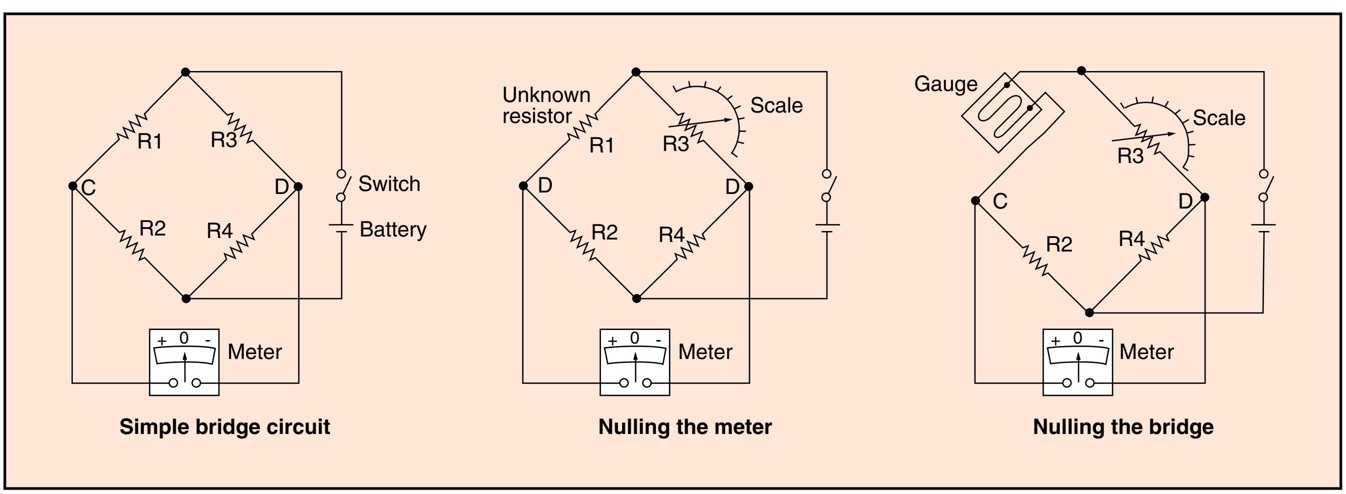
1.30 Several instrument manufacturers supply indicators calibrated for direct use with strain gauges. To match the gauge and the indicator to a specific application, the scale can be calibrated to read directly in units of force (lb or N), stress (psi or MPa), or displacement (in. or mm).

1.31 The change in a strain gauge's resistance during a test run or during field measurements is very small, about 0.2% or less. For example, a 120-Ω gauge changes its resistance to 120.24 Ω. Because a standard ohmmeter is not sensitive enough to measure this change, a special electrical circuit must be added.

1.32 Figure 1-9 shows three *Wheatstone bridge circuits*. The circuit on the left consists of resistors R1, R2, R3, and R4. A battery connected as shown causes an electric current in the resistors, part through R1 and R2 and part through R3 and R4. When the ratio of the resistances of R1/R2 equals the ratio of the resistances of R3/R4, points C and D are at an equal electrical potential, and the current through the meter is zero. However, if the ratio of resistances of R1/R2 is not equal to that of R3/R4, there is a current in one direction or the other and the ammeter does not read zero.

1.33 A Wheatstone bridge circuit is often used to measure resistance. Suppose the resistance of R1 is unknown and R2 and R4 are precision resistors of known value. The circuit in the center of Fig. 1-9 shows R3 as an adjustable resistor. When the switch is closed, the meter deflects in either the positive or negative direction, depending on the setting of R3. To find the value of R1, resistor R3 is adjusted until the following ratio of resistances is achieved:

Fig. 1-9. Bridge measuring circuits



$$R_1 = R_2 \times \frac{R_3}{R_4}$$

At this setting, the current through the meter is zero.

1.34 This procedure is referred to as balancing, or *nulling the meter*—that is, adjusting resistor R3 to obtain zero current flow in the meter circuit. If the resistance values of R2 and R4 are known and the value of R3 can be read on a meter, then the unknown resistor value can be determined as follows:

$$R_1 = R_2 \times \frac{R_3}{R_4}$$

When the current is zero and the value of R3 is read from the scale, the value of R1 can be calculated.

1.35 On the right in Fig. 1-9, the strain gauge is placed in the bridge circuit as the unknown resistance, R1. To measure strain, the gauge is put in place on the unstressed member and the bridge is balanced with the resistance value of the strain gauge (a procedure referred to as *nulling the bridge*). In this example, the gauge's resistance value is 130.00 Ω. Force is then applied to the member, the member deforms, and the strain gauge changes in resistance.

1.36 When the switch is closed, the bridge is unbalanced—that is, current flows in the meter circuit. The bridge is then nulled again (so that the meter reads zero) by adjusting R3. Suppose the new point of balance for the bridge shows that the gauge resistance has decreased from 130.00 Ω to 129.91 Ω.

1.37 When the gauge was purchased, it was accompanied by a tag certifying its sensitivity (gauge factor), or how much change in resistance could be expected for each fraction of a change in gauge length. If you know the sensitivity, you can calculate the strain for this gauge as follows:

$$\text{Sensitivity} = \frac{\Delta R / R}{\Delta L / L}$$

where ΔR = 0.09 Ω

initial R = 130 Ω

ΔL = change in length of the gauge (unknown)

L = initial length

1.38 For this particular example, the sensitivity (the gauge factor) is 1.7. The total strain of the gauge can be found by using the gauge-factor relationship as follows:

$$1.7 = \frac{0.09/130}{\Delta L / L}$$

$$\frac{\Delta L}{L} = \frac{0.09/130}{1.7}$$

$$= 0.0004 \text{ in./in.} = 0.04\%$$

That is, the strain at the gauge is 0.0004 in./in. This value can also be written as 400 × 10^{-6} in./in. or 400 microstrain (400 μS).

1.39 If you know the strain, you can find the stress from tables or from curves like those in Fig. 1-5. You can also use Hooke's law and a value called the *modulus of elasticity*, which is known for each material:

Stress = modulus of elasticity × strain

If the tensile test specimen shown in Fig. 1-5 had an original length of 250 in., and its change in length was 0.1 in., the strain would be 0.0004 in./in. (which is 0.04%). The modulus of elasticity of steel (hard or soft) is about 30 million psi. Therefore, using the above relationship between stress and strain, the stress under these conditions is:

$$\text{Stress} = 30{,}000{,}000 \text{ psi} \times \frac{0.1 \text{ in.}}{250 \text{ in.}}$$

$$= 30{,}000{,}000 \text{ psi} \times 0.0004$$

$$= 12{,}000 \text{ psi}$$

If the specimen has a cross-sectional area of 1 in^2, the load in lb is:

Load = stress × area

$= 12{,}000 \text{ psi} \times 1 \text{ in}^2$

$= 12{,}000 \text{ lb}$

Gauge Configurations

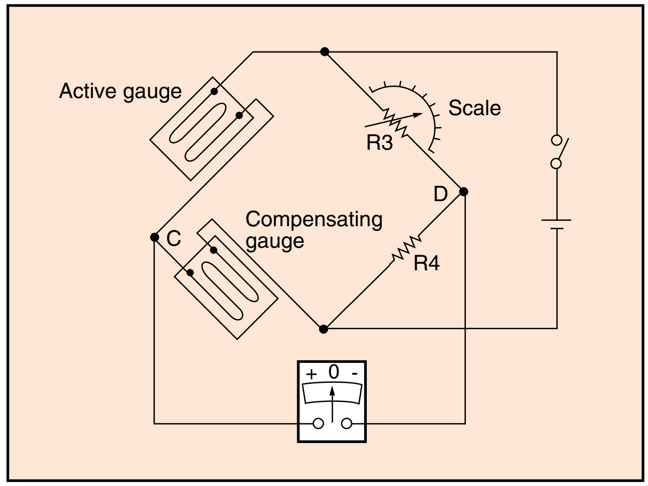
1.40 The strain-gauge application described in paragraph 1.35 has one serious defect. The very small wire used in the gauge changes resistance by only 0.2% or less for a typical application. Unfortunately, the resistance changes in the same or greater range for a temperature change of a few °F.

1.41 To cancel out the effect of temperature change, a second gauge, called a *compensating gauge*, is added to the circuit in Fig. 1-10. The compensating gauge is mounted on an unstressed piece of the same material as the member under stress. To minimize temperature variations that might affect the reading, the compensating gauge and strain gauge should be located as close together as possible. Of course, both gauges should be of the same kind and as close in resistance as possible.

1.42 With the arrangement just described, changes in resistance caused by temperature alone are the same for both arms of the bridge network. This satisfies two requirements.

- The ratio $R_1/R_2 = R_3/R_4$ is not altered by temperature because both gauges are under the same temperature conditions.

Fig. 1-10. Compensating gauge installed in a bridge circuit



- The change in resistance registered by the bridge circuit is due to strain only.

1.43 If two strain gauges are bonded to a member under stress, as shown on the left in Fig. 1-11, and connected electrically into the bridge circuit as shown, the sensitivity of the bridge circuit is doubled. That is, for the same load, the bridge output is twice as great. The reason is that Gauge 2 undergoes the same strain (or change in resistance) as Gauge 1. Because the gauges are in opposite arms of the Wheatstone bridge,

Fig. 1-11. Two gauges in a bridge circuit

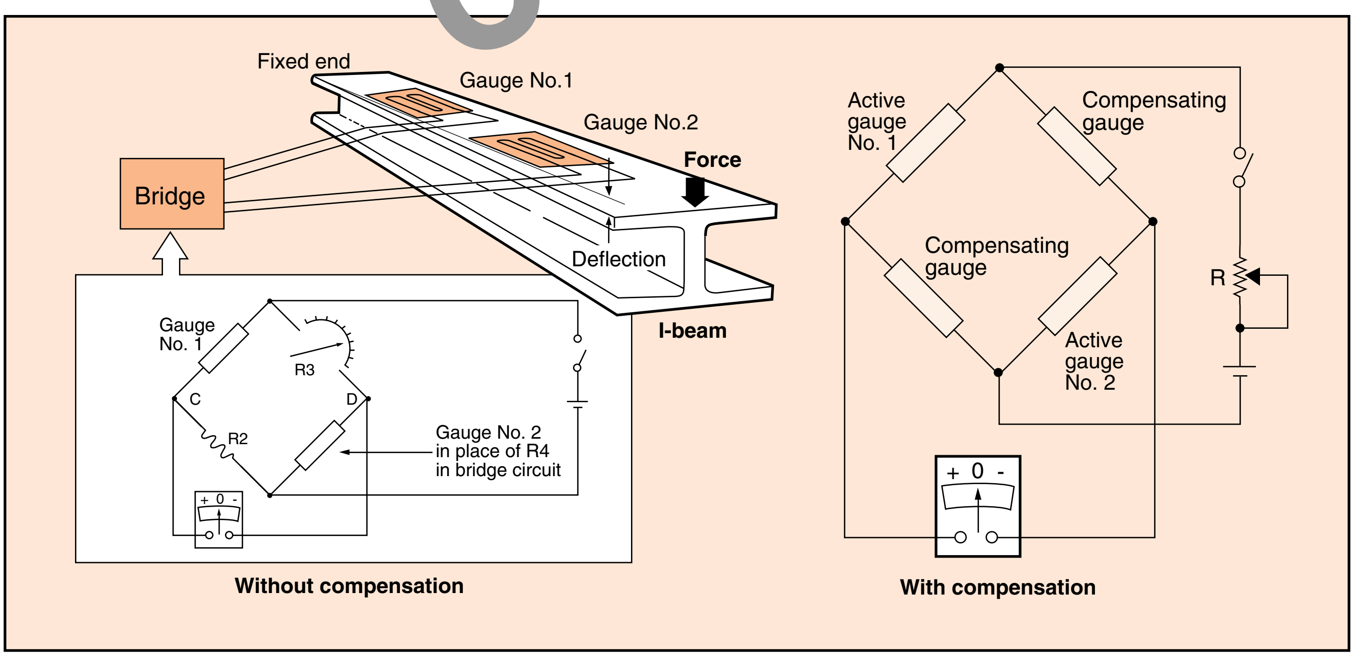
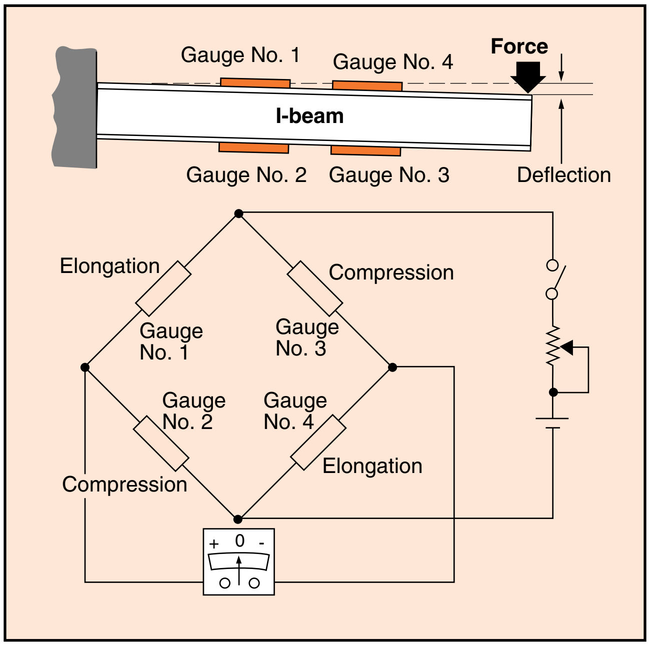


Fig. 1-12. Application of a complementary bonded strain gauge



the current will double for the same amount of beam deflection. This arrangement does not provide temperature compensation, however. If temperature compensation is desired, two compensating gauges are connected as shown on the right in Fig. 1-11 on the previous page.

1.44 Suppose the I-beam in Fig. 1-11 is in tension in the top flange and in compression in the bottom flange, as is normal for a beam under load. Four active strain gauges could be installed and wired as shown in Fig. 1-12. In this situation, the bridge output is four times that of a bridge with a single active arm. This arrangement, referred to as a *full bridge circuit*, provides automatic temperature compensation.

Other Force-Measuring Devices

1.45 In addition to the strain gauge, several other devices can detect deformation. The following are discussed in the paragraphs below:

- carbon pile
- pressure-sensitive wire
- piezoelectric gauges
- capacitance mats.

1.46 **Carbon pile.** Carbon granules contained in a cup are squeezed together when a force is applied. As force is increased, more contact is made between the granules and resistance decreases. Because the carbon pile loses accuracy if subject to mechanical vibration and variations in temperature, its use is limited to experiments and demonstrations.

1.47 **Pressure-sensitive wire.** A very thin coil of wire, made of 30% gold and 70% chromium, can be connected to measure extremely large forces. The wire, about 0.0002 in. (0.05 mm) in diameter, is wound on a form so that one turn does not touch the other. This arrangement exposes the maximum wire surface to the pressure (usually liquid) in the container. As pressure increases, the cross-sectional area of the wire decreases. A decrease in cross section increases the resistance of the wire. Therefore, a change in resistance indicates a change in pressure on the wire.

1.48 **Piezoelectric gauges.** Certain crystals (quartz, for example) produce a small voltage as they undergo deformation. This phenomenon is called the piezoelectric effect. The voltage produced by a piezoelectric device is related to the change in shape of the crystal, which in turn is related to the force applied. Most piezoelectric transducers are made of single-crystal quartz, which is very stable.

1.49 The frequency response of this kind of transducer is excellent—an advantage in measuring shock and vibration, but a potential problem because unwanted forces may be recorded. Advantages of the piezoelectric transducer are that force is directly proportional to output and that the transducer can be manufactured in very small sizes. Some of the problems include its small output signal (20 mV or less) and its inability to withstand high temperatures and humidity.

1.50 **Capacitance mat.** The capacitance mat is a rubbery material containing a grid of vertical and horizontal wires connecting many embedded capacitors. As applied forces change the thickness of the mat, its capacitances also change. By measuring the capacitances, you can determine the force(s) applied.

1.51 For example, a manufacturer of athletic footwear might want to see how new sole designs affect the load distribution under the foot. (The forces on the sole are directly related to the forces on the skeletal system while a person is running.) An insole-shaped capacitance mat with 20, 30, or 40 outputs is inserted into the sole of the sneaker and a test subject wears the sneaker while running, jumping, and so on. Instrumentation from the mat records the forces and transmits data to a data-acquisition system for lab tests, or to portable equipment in a backpack for field tests. Analysis of the forces allows the manufacturer to determine experimentally what the load distribution is under the wearer's foot.

Application 1-3

A tennis racket manufacturer needed to know the effect of new racket designs and materials on the forces transmitted to the handle and thus to the player's hand and arm. To determine these forces, strain gauges were attached to several locations on the racket frame and handle. (The gauges were protected from shock and vibration during the testing procedure.) A portable instrumentation system was used that consisted of the bridge completion circuitry, signal conditioning, batteries, and recording device (a small tape recorder). The test subject was instructed to hit tennis balls at varying levels of power while the forces were recorded. The manufacturer was able to improve the racket design based on the information from the tapes.

Application 1-4

The US Air Force needs to know the forces that a typical jet fighter encounters in normal flight maneuvers. Various areas of the aircraft frame are instrumented with strain gauges. A self-contained signal-conditioning system is placed on the aircraft, as is a recording device. The pilot is instructed to fly in a certain manner. After the aircraft has landed, technicians analyze the forces measured by the strain gauges attached to the structural members.

1-9. The ratio of the relative change in resistance to the relative change in length is called the strain gauge's ________ or ________.	1-9. GAUGE FACTOR, SENSITIVITY Ref: 1.28
1-10. Strain gauges can be calibrated to read ________ in lb or N, ________ in psi or MPa, or ________ in in. or mm.	1-10. FORCE; STRESS; DISPLACEMENT Ref: 1.30
1-11. A Wheatstone bridge circuit is often used to measure ________.	1-11. RESISTANCE Ref: 1.33
1-12. The gauge used to offset unwanted temperature effects is called a(n) ________.	1-12. COMPENSATING GAUGE Ref: 1.41
1-13. A full bridge circuit has an output ________ times that of a single-arm bridge and provides automatic ________ compensation.	1-13. FOUR; TEMPERATURE Ref: 1.44
1-14. A small voltage can be produced by causing a certain kind of crystal to ________.	1-14. DEFORM Ref: 1.48
1-15. The output signal of a piezoelectric transducer is ________ or less.	1-15. 20 mV Ref: 1.49
1-16. As applied force changes the ________ of a capacitance mat, its capacitance also changes.	1-16. THICKNESS Ref: 1.50

Answer the following questions by marking an "X" in the box next to the best answer.

1-1. A force of 1 lb is equal to a force of 4.448

- ☐ a. mPa
- ☐ b. N
- ☐ c. Pa
- ☐ d. psi

1-2. If you are standing on a stool that has straight legs, the forces exerted on the legs of the stool are mainly of what kind?

- ☐ a. Compressive
- ☐ b. Lateral
- ☐ c. Shear
- ☐ d. Tensile

1-3. The internal force in a body that resists external forces is referred to as

- ☐ a. reluctance
- ☐ b. resistance
- ☐ c. strain
- ☐ d. stress

1-4. If a bar 12 in. long is compressed 0.10 in., the unit deformation is ________ in./in.

- ☐ a. 0.00833
- ☐ b. 0.00600
- ☐ c. 0.005
- ☐ d. 0.04

1-5. Hooke's law states that a body acted upon by external forces will

- ☐ a. deform in proportion to the applied force
- ☐ b. deform permanently to some extent
- ☐ c. resist deformation if it is tough enough
- ☐ d. usually break rather than deform

1-6. Unlike brittle materials, ductile materials

- ☐ a. break without deforming
- ☐ b. can compress but not stretch
- ☐ c. deform before breaking
- ☐ d. have no elastic limit

1-7. The sensitivity of a strain gauge is equal to $\Delta R/R$ divided by

- ☐ a. $\Delta L/L$
- ☐ b. $\Delta L/RL$
- ☐ c. $\Delta R/L$
- ☐ d. $\Delta R/RL$

1-8. A Wheatstone bridge circuit is used with a strain gauge in order to

- ☐ a. allow high temperature measurements
- ☐ b. help reduce electrical noise
- ☐ c. increase the sensitivity of the instrumentation
- ☐ d. permit the use of a recording device

1-9. One or more compensating gauges are added to a strain gauge circuit to offset the effect of

- ☐ a. changes in pressure
- ☐ b. changes in temperature
- ☐ c. high humidity
- ☐ d. vibration

1-10. A disadvantage of the piezoelectric gauge is its

- ☐ a. irregular response to force
- ☐ b. large output signal
- ☐ c. large size
- ☐ d. sensitivity to high temperatures and humidity

SUMMARY

An object that is subjected to one or more forces can deform. The kind of material, the supporting structure, and the applied forces all affect the kinds of deformation the object undergoes. The direct relationship between applied forces and resulting deformation of an object is stated in Hooke's law. If the deformation can be measured accurately while the object is under load, the applied forces can be calculated.

Strain gauges are used to determine the strain on materials under applied forces. Gauges applied in several locations determine the total strain on the material. The electrical resistance of the strain gauge changes as it is deformed, so a measured resistance change indicates the strain and load. Other techniques used to measure strain (and load) include the carbon pile, pressure-sensitive wire, piezoelectric material, and capacitance mat.

Answers to Self-Check Quiz

1-1. b. N. Ref: 1.03

1-2. a. Compressive. Ref: 1.10

1-3. d. Stress. Ref: 1.11

1-4. a. 0.00833. Ref: 1.13

1-5. a. Deform in proportion to the applied force. Ref: 1.15

1-6. c. Deform before breaking. Ref: 1.19

1-7. a. $\Delta L/L$. Ref: 1.28

1-8. c. Increase the sensitivity of the instrumentation. Ref: 1.31, 1.32

1-9. b. Changes in temperature. Ref: 1.41

1-10. d. Sensitivity to high temperatures and humidity. Ref: 1.49