Introduction to Strain and Strain Gages

- Bridge110

Here at Madgetech we are no strangers to the world of measurement and data recording. We design and build a full line of products to meet a wide range of data logging requirements. With the release of the Bridge110, we have introduced ourselves into the realm of strain measurement. The intent of the Bridge110 was to make strain measurement easy and accessible to everyone no matter what their experience level, and we feel as though we have succeeded.

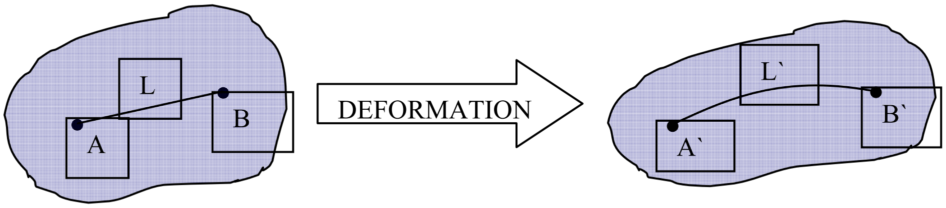
This application note was written for use in conjunction with the Bridge110. It is designed to give the user a good working knowledge of strain and strain gages. After reading this we hope that you feel more comfortable and confident working with strain gages.

TABLE OF CONTENTS

INTRODUCTION TO STRAIN

What is Strain?

When forces are applied to an object they can change its size and shape. This is called deformation. This deformation can be described by a dimensionless measurement called strain. For most practical purposes we can define strain as follows:



Suppose a body exists with two points within the body, A and B which are a distance L apart from each other. Forces are applied to the body and it deforms such that A becomes A` and B becomes B` and the distance between them becomes L`. The strain (ε) is then defined by the limit expressed below (Eqn.1), and can be approximated by Eqn.2.

Equation 1

$$\varepsilon := \lim_{B \to A} \frac{L' - L}{L} \to \frac{(L' - L)}{L}$$

so

Equation 2

$$\varepsilon := \frac{\Delta L}{L} \quad \text{where} \quad \Delta L := (L' - L)$$

Simple dimensional analysis shows that strain has no units (both numerator and denominator have the same units of length). However, in practice we refer to strain as its own dimensionless unit for convenience (e.g. $\varepsilon = m/m$ or in/in). Typically, measured values of strain are very small. So it is most common to refer to a value of strain in "micro-strain" (e.g. $\mu\varepsilon = \mu m/m$ where $\mu m = 10^{-6} m$)

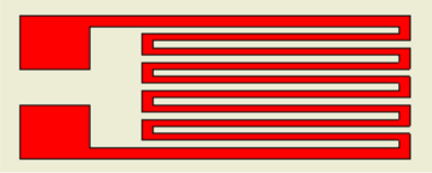
Why is Strain Important?

Strain is very important in the world of engineering because of its relations to other, more important, parameters. Strain has a direct relationship to stress based on material properties. This means that if we know the material properties and measure the strain we can calculate the stress (which becomes very important in structural analysis). Conversely, if we apply a known stress and measure the strain we can calculate the material properties (which is very important in materials testing). With the advent of the strain gauge measuring strain has become relatively easy. In addition, strain can be measured when the other parameters (e.g. stress or material properties) cannot.

What is a Strain Gage?

A strain gage is simply a pattern of thin wires or foil. It works on the principle that when the wire is put under strain (either elongated or shortened) it changes its electrical resistance measured in Ohms. The resistance of a wire (R) is a function of three parameters, all of which are effected by strain.

$$R = \rho \cdot \frac{L}{A}$$



The length (L) varies directly with strain (by definition). The area (A) varies inversely with strain (due to Poisson's Ratio*). The electrical resistivity of the material (ρ) will also vary depending on the material of the wire. Using this formula we know how the gage's resistance will change with strain. We can quantify this knowledge with a value called the Gage Factor (G_F) sometimes called sensitivity (S).

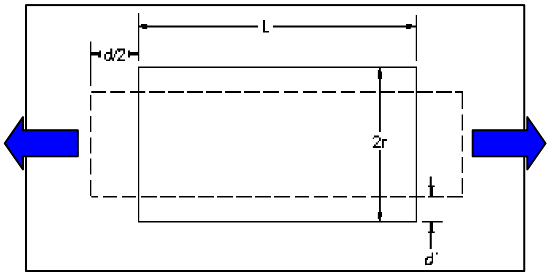
$$G_F = 1 + 2 \cdot \nu + \frac{\frac{d\rho}{\rho}}{\varepsilon}$$

Fortunately, most of us never have to compute this as it is provided by the strain gage manufacturer. With knowledge of the gage factor, the equation for finding strain is simplified.

$$\varepsilon = \frac{\Delta R}{G_F \cdot R}$$

* POISSON'S RATIO

When a member is subjected to an axial tensile force not only will it elongate, but it will also contract laterally. French scientist S.D. Poisson noticed that the ratio of these longitudinal and lateral strains (ε_{long} and ε_{lat}) was a constant, unique to the material of the member.

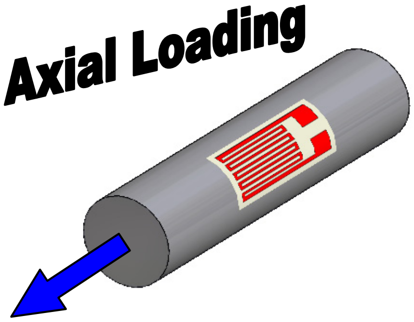


$$\varepsilon_{long} = \frac{\delta}{L}$$

$$\varepsilon_{lat} = \frac{\delta}{r}$$

$$\boxed{\nu = -\frac{\varepsilon_{lat}}{\varepsilon_{long}}}$$

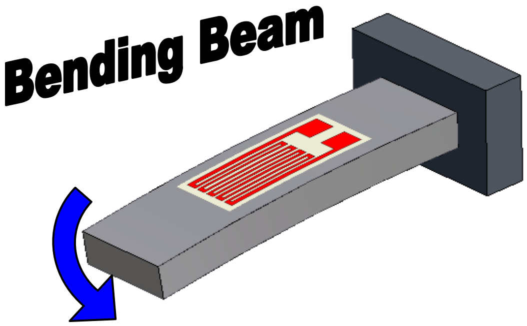
Where Can I Use A Strain Gage?



AXIAL LOADING

A member in tension or compression with a gage mounted parallel to the axis of the loading. Measurements can be made of total deflection, applied load, and stress.

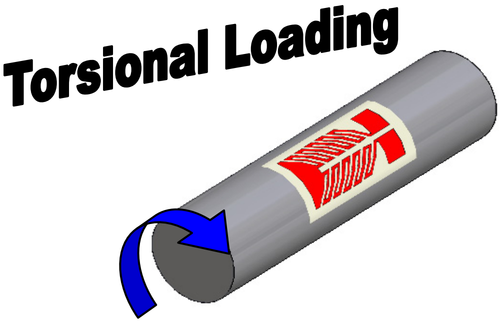
Ex. Columns, trusses, cables



BENDING BEAM

A member being bent by an applied moment or by a load exerted perpendicular to the beam. One side of the beam will be in tension while the other in in compression. Measurements can be made of stress, angular and linear deflection, and applied load / moment.

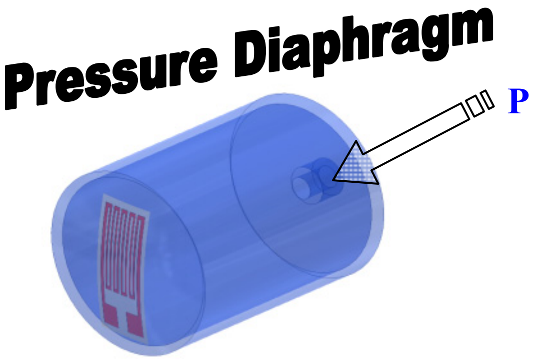
Ex. Leaf springs, cantilevered beams, rafters/ joists



TORSIONAL LOADING

A member in torsion with a gage mounted to it in the direction of the strain. Strain is in axes 45° to axis of torque and tangent to the member. Measurements can be made of stress, angular deflection, and applied torque.

Ex. Drive shafts, torsion rods



PRESSURE DIAPHRAGM

A pressure vessel with a gage mounted on a diaphragm (usually at the rear of the vessel.) Measurements can be made of fluid pressure inside the vessel.

Ex. Pressure transducers

Which Strain Gage Should I Use?

There are many different factors that come into choosing the correct strain gage for your particular application. The first step is analyzing all the different aspects of your application. Here are some example questions that should guide you in the right direction.

- What are you trying to measure?
    - ◊ Localized strain or average strain?
    - ◊ Strain in one known direction?
    - ◊ Principal strains in a known direction?
    - ◊ Principal strains in an unknown direction?
- Are the strain values expected to be high or low?
- Will the measured strain be mostly static or dynamic?
- Is it a high temperature application?
- Will the temperature vary much over the course of the test?
- How much space is available?
- Is the surface homogeneous?
- How much money are you willing to spend?
- How simple does the mounting process need to be?
- How critical is the accuracy of the readings?

Considering Gage Pattern

Uni-Axial strain gage should be considered if:

A single strain is to be measured and the direction is known or low cost is a priority (several uni-axial gages can cost less than a single bi- or tri- axial gage)

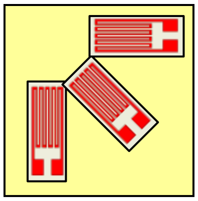
Uni-Axial Strain Gage

Bi-Axial (0˚, 90˚ T-Rosette) should be considered if:

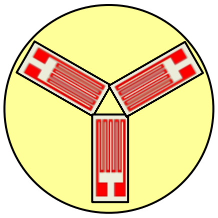
Principal strains ($\varepsilon_{1,2}$) are to be measured and direction is KNOWN (also applicable to torques)

Bi-Axial (0°, 90° T-Rosette) Strain Gage

Tri-Axial/ Three-Element (0˚-45˚-90˚ rectangular rosette, 0˚-120˚-240˚ delta rosette) should be considered if:



0˚-45˚-90˚ Rectangular Rosette

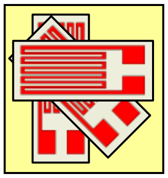


0˚-120˚-240˚ Delta Rosette

Principal strains ($\varepsilon_{1,2}$) are to be measured and direction is UNKNOWN

Stacked gage configuration should be considered if:

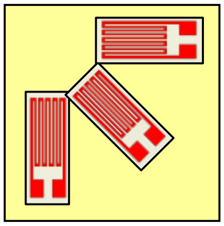
- There isn't much space available for mounting



Stacked Strain Gage Configuration

- Localized strain is to be measured
- A large strain gradient exists

Planar gage configuration should be considered if:



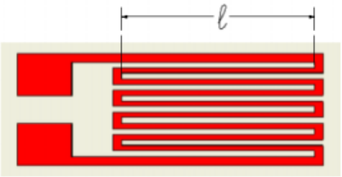
Planar Gage Configuration

- Heat effects are likely to be an issue
- Accuracy and stability are critical

Considering Gage Length

Strain Gages are typically recommended to be 3mm to 6mm

Use a **Shorter gage** (l ≤ 3mm) if:



- There isn't much space available for mounting
- Localized strain is to be measured (ex. Near a fillet, hole, notch etc.)
- As a rule l ≤ r/10, where r is the radius of the hole or fillet
- A large strain gradient exists
- Accuracy of the measurement is less critical

Use a **Longer gage** (l ≥ 6mm) if:

- Easier installation is a priority
- Heat effects are likely to be an issue
- Accuracy and stability are critical
- The surface is non-homogeneous (l ≥ 2x size of homogenuities)
- Low cost is a priority (5-12mm are usually cheapest)

Considering Wire Material

There are a number of different metal alloys that are used in strain gauges. Each one has it's own unique properties that makes it more suitable for some specific application. On the following page you are provided with the properties of four of the most common materials used in foil/wire gages. In addition, the properties of common semi-conductor gages are provided.

CONSTANTAN

Nickel/Copper Alloy   Gage Factor ~ 2.1

- Most common material in gages, and therefore low cost
- Better suited to static strains rather than dynamic
- Gage factor remains nearly constant even through large deformations
- Exhibits self-temperature compensation
- Temp range -30˚C to 193˚C (though can experience a lot of drift above 65˚C)

KARMA

Nickel/Chromium/Iron/Aluminum   Gage Factor ~ 2.0

Very similar characteristics to Constantan with these exceptions:

- Best suited to low temperature environments (as low as -265˚C)
- More stable over extended periods of strain
- Very difficult to solder

ISO-ELASTIC

Iron/Nickel/Chromium/Manganese Alloy   Gage Factor ~ 3.6

- High sensitivity
- High resistance
- Well suited for dynamic strain readings (has a good fatigue life)
- Does not exhibit temperature compensation
- Non-linear response beyond ~5000με

PLATINUM BASED ALLOYS

Commonly alloyed with Tungsten or Iridium   Gage Factor ~ 4.0 to 5.1

- High sensitivity
- Well suited to high temperature environments (in excess of 230˚C)

SEMI-CONDUCTOR GAGES

Gage Factor ~ 70 to 135

- Very high sensitivity (~50x that of wire)
- High resistance
- Typically more expensive than wire
- Can be made smaller than wire/foil gages for lower cost
- More likely to drift with temperature changes
- Resistance doesn't change linearly with strain (making data analysis more difficult)
- Typically have lower strain limits than a comparable wire gauge

Considering Backing Material

POLYMIDE

- Most common backing material, and therefore low cost
- Better suited to static strains rather than dynamic
- Capable of large elongations and is very flexible
- Not suitable in extreme temperature conditions

EPOXY

- Minimizes errors caused by the backing
- Brittle and require special skill to install
- Maximum elongation is limited

GLASS FIBER ENFORCED EPOXY

- Performs well over widest temperature range (up to 400˚C)
- Well suited to dynamic strains and fatigue loading
- Maximum elongation is limited

STRIPPABLE BACKING

- Backing is removed during installation and the adhesive serves as an insulator between the gage and the mounting surface.
- Best for use in extremely high temperature applications
- Installation requires special skill

Considering Adhesives

CYANOACRYLATE CEMENT

- Very common / Industry standard
- Fast bonding ~10min
- Gentle clamping required for 1-2 minutes
- Does not last for extended periods of time (months)

EPOXY

- Exhibits high bonding strength
- Should be used when high strains (e.g. to failure) are to be measured
- Required a clamping pressure (~5 to 20psi) during cure
- Has a long cure time, can be decreased by applying heat (~120˚C)

CERAMIC CEMENT

- Well suited to extremely high temperature applications

INSTALLING A STRAIN GAGE

In order for your strain gage to read properly and reliably it must be installed correctly. This means first preparing the surface to which you will be bonding the gage later. The procedures for preparing the surface are simple and easy to follow, yet will result in consistent, strong, and stable bonds. The procedures outlined below are generalized for most metals. More specific surface prep instructions are available at:

Preparing the Mounting Surface

CLEAN SURFACE

Use a solvent (such as acetone or alcohol) to remove any grease or oils from the surface to which the stain gage will be bonded. This is to prevent any contaminants from being driven into the surface while performing subsequent steps. Clean an area significantly larger than the gage (4 to 6 inches on all sides) to prevent any contaminants from the surrounding area from being introduced into the gage area.

ABRADE SURFACE

Remove any oxidation, paint or coating from the surface finishing the abrading with a 400 grit silicone-carbide paper to ensure a proper texture for adhesion. A cross-hatched abrasion pattern is preferable. Be careful not to over-abrade the surface resulting in change of either dimensions or mechanical properties.

MARK LAYOUT LINES

Use a clean rule and a hard pencil or pen to mark the desired position of the gage. Perpendicular lines crossing at the center of the gage area is standard, so that they can be lined up with reference marks on the gage.

CONDITIONING

Scrub the area with a solvent or marketed conditioner with a cotton-tipped applicator until the tip no longer comes up discolored. Do not allow the conditioner to dry on the surface, use a gauze sponge to wipe it off in a single slow stroke, then again with a clean sponge in the opposite direction. This prevents dragging any of the contaminates back into the gage area.

NEUTRALIZING

(This step is optional though recommended.) Apply a proper neutralizer (for the material you are bonding to) with a cotton tipped applicator in order to balance the pH (~7.0) of the surface to ensure more stable bonding. Again dry the area with same technique described above (in Conditioning).

After the surface has been prepared, do not let it stand for more than a few minutes before bonding the gage to it. Have the gage ready and move quickly to the bonding procedure. Be sure not to touch the surface or the gage with you fingers as the oils will decrease bond integrity.

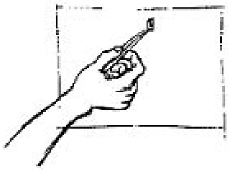
Bonding the Strain Gage

PREPARATION

Wash hands with soap and water. Clean the working desk area and all related tools with solvent or degreasing agent.

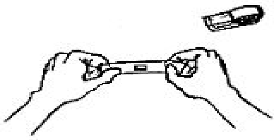
PREPARING GAGE

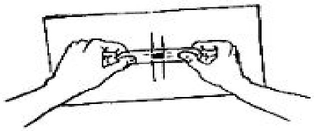
Carefully open the folder containing the gage. Use a tweezer, not bare hands, to grasp the gage. Avoid touching the grid. Place on the clean working area with the bonding side down.



TRANSFERRING GAGE

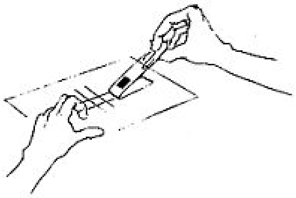
Use a proper length, about 15 cm (6 in), of cellophane tape to pick up the strain gage and transfer it to the gaging area of the specimen. Align the gage with the layout lines. Press one end of the tape to the specimen, then smoothly and gently apply the whole tape and gage into position.





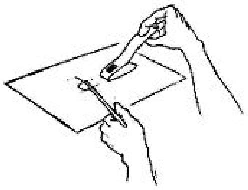
APPLYING CATALYST

Lift one end of the tape such that the gage does not contact the gaging area and the bonding site is exposed. Apply catalyst evenly and gently on the gage.



APPLYING ADHESIVE

Apply enough adhesive to provide sufficient coverage under the gage for proper adhesion. (Determining "sufficient" might require some trial and error iterations). Place the tape and the gage back to the specimen smoothly and gently. Immediately place thumb over the gage and apply firm and steady pressure on the gage for at least one minute.



REMOVING TAPE

Leave the tape in place at least two more minutes after the thumb was removed. Peel the tape from the specimen slowly and smoothly from one end to the other end.

****Note**: Some adhesives require mixing two compounds vigorously for a sufficient time, usually 5 minutes. Others require longer curing time up to 24 hours and/or higher temperature, usually by blowing hot air using a heat gun or placing in an oven. Some applications require higher clamping pressure as high as 350 kPa (50 psi). Please consult with the technical notes from the vendor for the right process parameters.

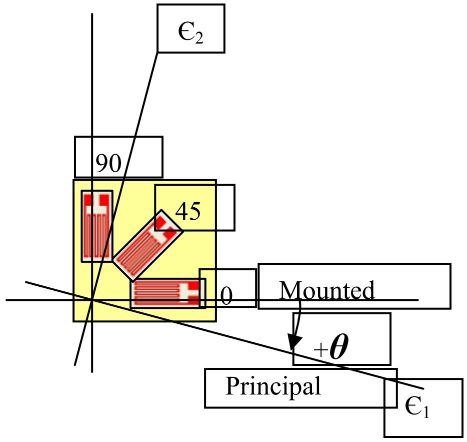
USING DATA AQUIRED FROM A STRAIN GAGE

When a strain gage is used properly it can provide a lot of information to the user, provided that the user has a basic understanding of stress-strain relationships. This next section is intended to provide the reader with that knowledge.

What Does The Data Mean?

As discussed earlier, the quantity that we are actually measuring is a change in voltage. Using Ohm's law (V=I x R) we can directly convert this reading into a change in resistance of the strain gage. From this, given the gage factor, we get our reading of strain (see page 2). This reading is the average amount of strain experienced over the length of the gage, in the direction that the gauge is mounted. In most cases the value of strain that is important to the user is maximum, or principal strains (ε_1 & ε_2) . For example, for a member in tension, the principal strains will be along the axis of loading (ε_1) and perpendicular to the axis (ε_2). If mounted correctly along the principal axis, these values can be read directly from either two separate gages or a bi-axial gage (although in the uni-axial tension case mentioned, ε_2 can be calculated easily by Poisson's Ratio.) If the principal axis are unknown, a tri-axial strain rosette must be used. From the three values of strain read from the rosette we can calculate both principal strains and their direction (relative to the rosette).

Rectangular Rosette

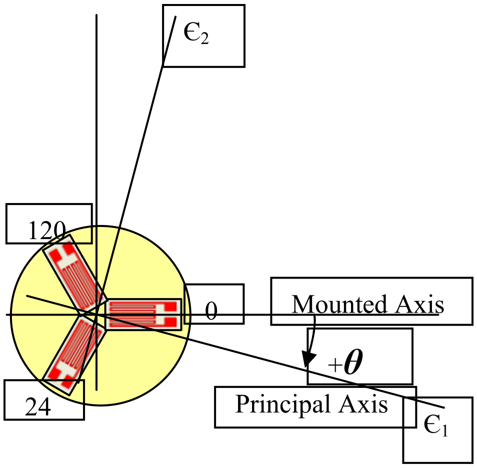


$$\varepsilon_1 := \frac{\varepsilon_0 + \varepsilon_{90}}{2} + \sqrt{\frac{\left(\varepsilon_0 - \varepsilon_{45}\right)^2 + \left(\varepsilon_{45} - \varepsilon_{90}\right)^2}{2}}$$

$$\varepsilon_2 := \frac{\varepsilon_0 + \varepsilon_{90}}{2} - \sqrt{\frac{\left(\varepsilon_0 - \varepsilon_{45}\right)^2 + \left(\varepsilon_{45} - \varepsilon_{90}\right)^2}{2}}$$

$$\theta := \frac{1}{2}\tan^{-1}\left(\frac{\varepsilon_0 - 2\varepsilon_{45} + \varepsilon_{90}}{\varepsilon_0 - \varepsilon_{90}}\right)$$

Equi-Angular Rosette



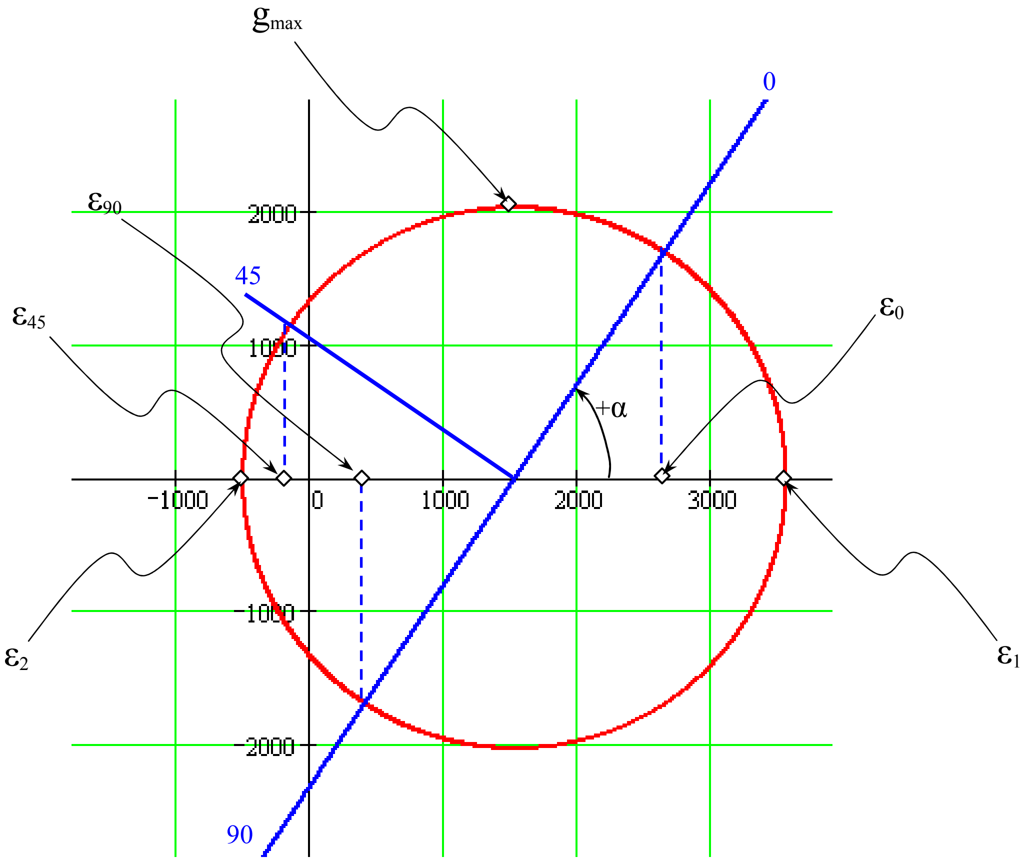
$$\varepsilon_1 := \frac{\varepsilon_0 + \varepsilon_{120} + \varepsilon_{240}}{3} + \sqrt{\frac{\left(\varepsilon_0 - \varepsilon_{120} - \varepsilon_{240}\right)^2}{9} + \frac{\left(\varepsilon_{120} - \varepsilon_{240}\right)^2}{3}}$$

$$\varepsilon_2 := \frac{\varepsilon_0 + \varepsilon_{120} + \varepsilon_{240}}{3} - \sqrt{\frac{\left(\varepsilon_0 - \varepsilon_{120} - \varepsilon_{240}\right)^2}{9} + \frac{\left(\varepsilon_{120} - \varepsilon_{240}\right)^2}{3}}$$

$$\theta := \frac{1}{2}\,\mathrm{atan}\left[\frac{\sqrt{3}\cdot\left(\varepsilon_{120} - \varepsilon_{240}\right)}{2\varepsilon_0 - \varepsilon_{120} - \varepsilon_{240}}\right]$$

Representing the Data In Mohr’s Circle

Mohr’s Circle is a common graphical representation for strains and stresses. In the case of strain we can display the values that we just calculated. Below is an example of this using values from a rectangular strain gage. In Mohr’s circle, the X-axis is the normal strain axis, and the Y-axis represents shear strain. The principal strains are where the circle crosses the normal strain axis, and the average strain is at the centerpoint. One must remember when plotting the circle that $\alpha = 2\theta$, thus the reason that the principal strains are shown to be 180˚ apart while in reality we know them to be perpendicular to each other. This can be seen in the projected axes of the strain gage as well (shown in blue). The measured values of strain are represented by the projection on the normal strain axis of where each of the gage axes intersects the circle.



Measured Values of μStrain

$\varepsilon_0 = 2.6 \times 10^3$

$\varepsilon_{45} = -200$

$\varepsilon_{90} = 450$

$\theta = 28.257$

Calculated Values of μStrain

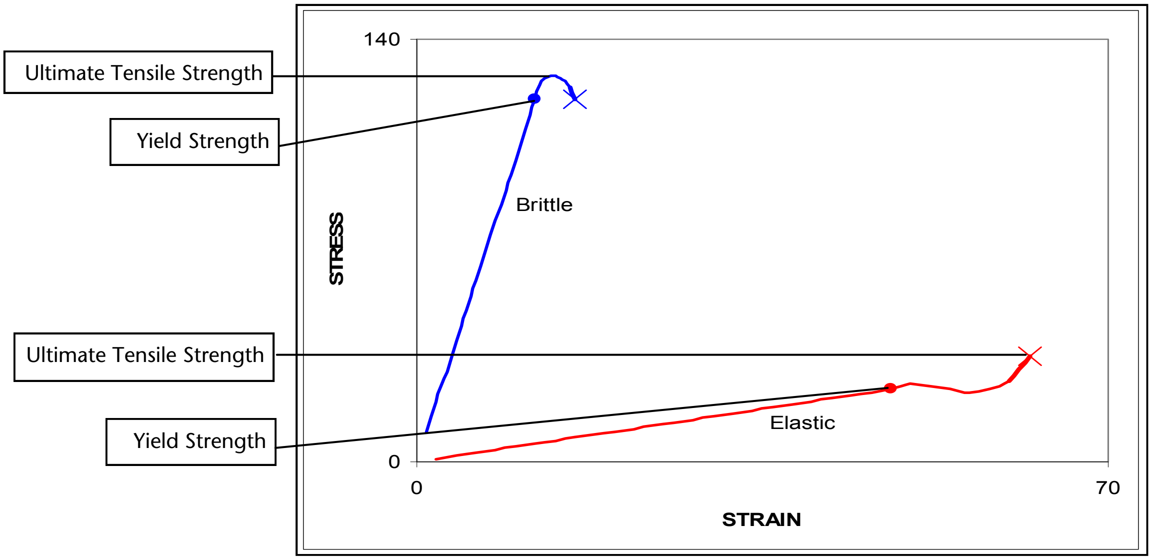
$\varepsilon_1 = 3.558 \times 10^3$

$\varepsilon_2 = -507.548$

$\gamma_{max} = 2.033 \times 10^3$

Stress– Strain Relationships

As stated earlier, strain is directly related to stress based on material properties. This means that if we know the material properties and measure the strain we can calculate the stress. In order to relate stress and strain, we must make the assumption that they vary linearly. However, stress and strain do not always vary linearly with one another. We can plot two members' stress-strain curves to demonstrate this fact. The curve in blue represents a strong yet brittle material (e.g. cast iron), and the curve in red represents a weaker but more elastic material (e.g. polyethylene). Each curve begins with a linear segment, this is the linearly-elastic region. The slope of this line corresponds to the material property known as the Modulus of Elasticity or Young's Modulus (E). At any point in this region, if the load is removed from the member, it will return to its original size. The end of this region is marked by the Yield Strength of the material, beyond which any deformations are permanent and the member eventually fails.



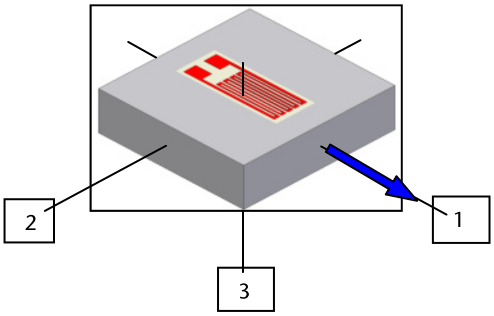
These curves are commonly generated by a testing machine (e.g. Instron) that measures load while straining a test piece. The exact shape of the curve will vary slightly due to inhomogenuities in the structure of the material, the speed at which it is loaded, etc. However, the slope of the line (E) remains a constant for a given material. In order to convert strains measured from gages we make the assumption that the material is not being stressed beyond its linearly elastic region.

Stress (σ) can be defined in two ways, as the force exerted on a member divided by its cross-sectional area, or by the strain multiplied by the material's Modulus of Elasticity.

$$\sigma = \frac{F}{A} \quad \text{or} \quad \sigma = E \cdot \varepsilon$$

As a strain gage is limited to measuring strain in the plane in which it is mounted we will only cover the two cases of uni-axial and bi-axial stresses. Formulas are given to convert the principal strains calculated earlier into the principle stresses. The state of stress is generally most important because it is what ultimately determines how and when the member will fail. Yield strength, ultimate strength and fatigue life are all based on stress.

Uni-Axial Stress



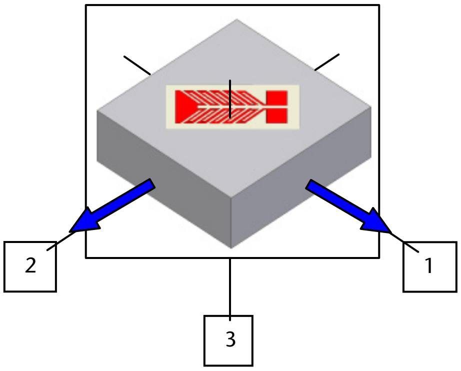
A single load is applied to axis 1 yielding a single stress. The materials' maximum principal strain is in the direction of axis 1. Strain is experienced in the other two axes due solely to Poisson's Ratio.

$$\sigma_1 = E \cdot \varepsilon_1$$

$$\sigma_2 = \sigma_3 = 0$$

$$\varepsilon_2 = \varepsilon_3 = \frac{-\nu \cdot \sigma_1}{E}$$

Bi-Axial Stress



Two loads are applied to different axes. They will yield two principal strains perpendicular to each other and two principal stresses corresponding to the strains (axes 1 & 2). Strain is experienced in the third axis due solely to Poisson's Ratio.

$$\sigma_1 := \frac{E}{1 - \nu^2} \cdot \left(\varepsilon_1 + \nu \cdot \varepsilon_2\right)$$

$$\sigma_2 := \frac{E}{1 - \nu^2} \cdot \left(\varepsilon_2 + \nu \cdot \varepsilon_1\right)$$

$$\sigma_3 := 0$$

$$\varepsilon_3 := \frac{-\nu}{1 - \nu} \cdot \left(\varepsilon_1 + \varepsilon_2\right)$$

The Pressure and Strain Handbook, Vol.29, Omega Engineering Inc.

Fundamentals of Machine Component Design, 3rd Edition, Robert C. Juvinall Kurt M. Marshek

Mechanics of Materials, Fourth Edition, R.C. Hibbeler