Strain Gauges

Strain

- In many aerospace applications it is useful to measure strain

$$strain = \frac{\Delta L}{L}$$

From it we can also derive;

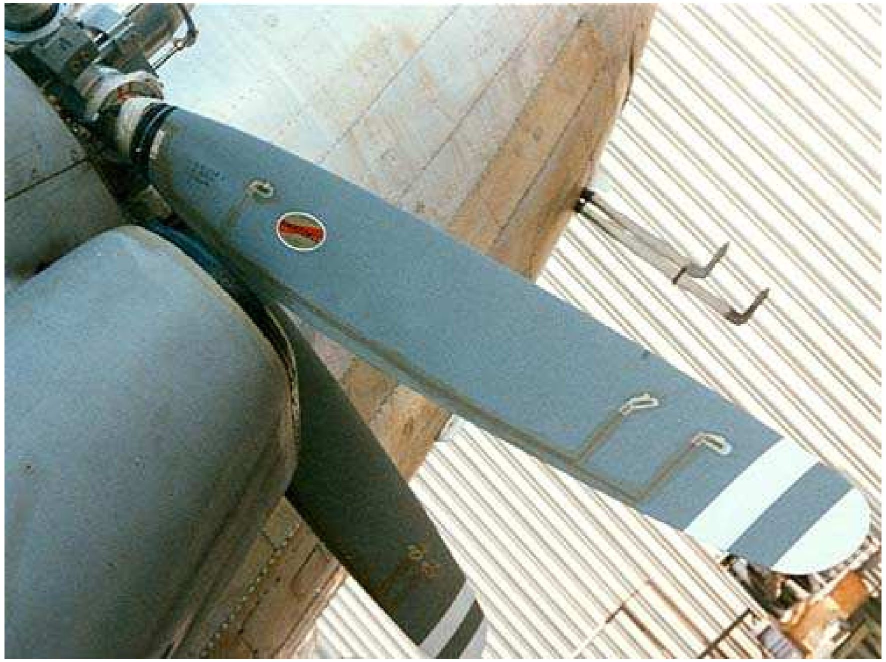
- Displacement
  - by knowing the geometric relationship between strain and displacement for a structure
- Force
  - by knowing the stiffness of the structure

General applications

- A load cell is a structure designed such that forces in a particular axis can be inferred from the measured strain a part of that structure. Used for electronic balances

- Strain gauges are also extensively used to monitor civil structures, monitoring loading and/or cracking

Aerospace applications



www.airplanetest.com

www.hbm.com

- Strain gauges mounted on propellers to monitor loads in flight

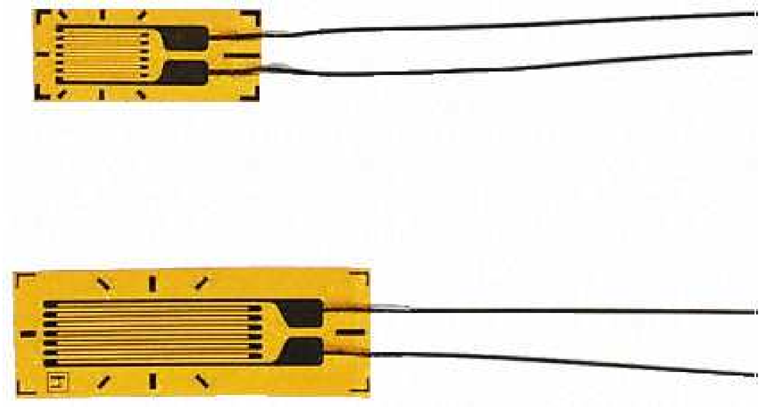
Aerospace applications

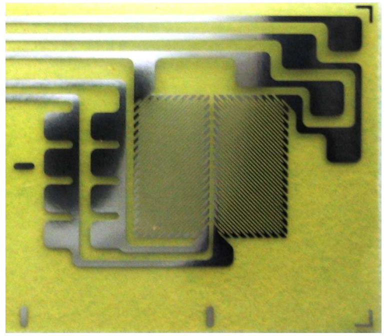
- Wind turbine blade testing

www.ara.co.uk

- Wind tunnel force balances: Multi-degree of freedom load cells

Metallic strain gauges



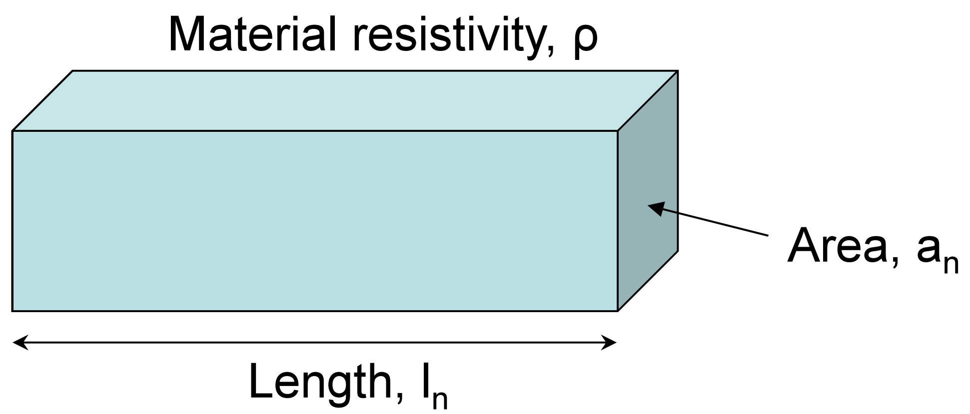


- The most common strain gauge is the metallic foil gauge.
- A thin metallic strip, encapsulated in a polymer sheath, is tightly bonded to the host structure such that as the structure elongates or contracts so will the gauge.
- The resistance of the gauge is related to its geometry and so as the structure moves, the resistance changes.
- Converts change in length into a change in resistance

Metallic foil gauges – simplistic physics

- Metallic materials have free electrons in their atomic structure – electrons that are not caught in covalent bonds with neighbouring atoms.
- These electrons are free to travel and conduct charge when exposed to an electric field.
- However the electrons must negotiate the lattice structure of the conductor. The structure impedes the progress of the electrons and gives rise to the phenomena of resistance (it's a bit more complex than this but lets not open that can of worms!).
- If the path is made longer resistance increases. Conversely if the cross section of the path is increased, resistance decreases.
- Temperature also has an effect. In metals the increased vibrations of the lattice structure at higher temperatures increases resistance. More of this later.

Metallic foil gauges - electrical



$$R_n = \rho \frac{l_n}{a_n}$$

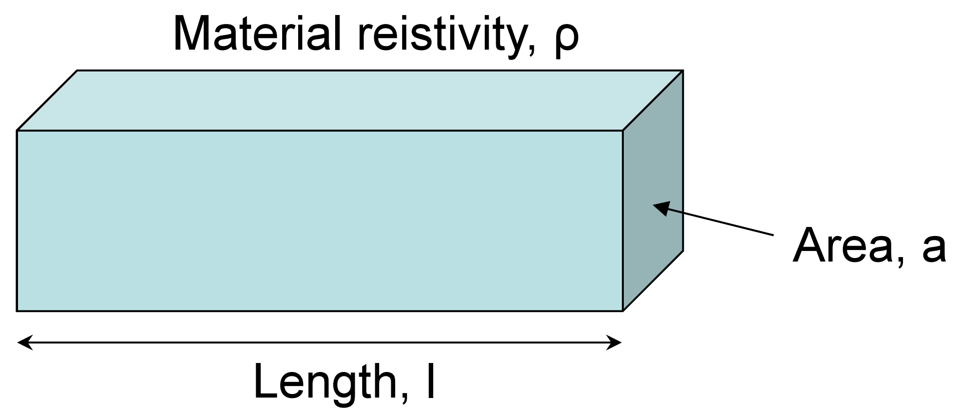
- Resistance of a simple prism is given by the resistivity of the material, ρ, multiplied by length, l, divided by area, a. (Where current flows along the length)

Metallic foil gauges - electrical

$$R_{st} = \rho \frac{l_{st}}{a_{st}}$$

- After stretching the resistivity of the material is normally the same. The new length and area are used to calculate new resistance.

Metallic foil gauges - electrical

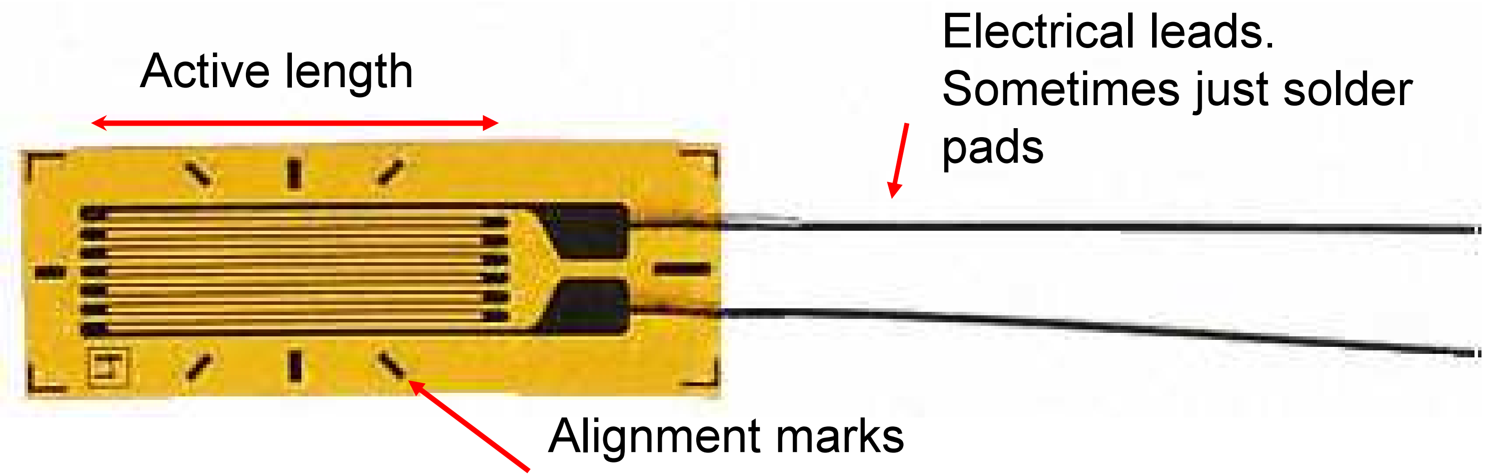


$$\Delta R \big/ R = GF \, \Delta l \big/ l$$

$$\Delta R \big/ R = GF * strain$$

- The gauge factor is defined as the ratio between the relative change in resistance and the strain (It incorporates Poisson ratio).
- Most foil gauges have GF~2
- l is the unstrained length; R is the unstrained resistance

Metallic strain gauges



- A practical strain gauge is made up of many ‘strips’ of an alloyed metal folded back upon each other to increase the effective length.
- The nominal resistance can be standardised to one of several values. 120Ω is the most common but they can be higher or lower.
- Typical strain measuring range is ~ +-3%
- They are normally temperature compensated for a particular substrate – i.e. they are designed to match the thermal expansion of the material, with differing gauges for steel and aluminium.

Metallic foil gauges - electrical

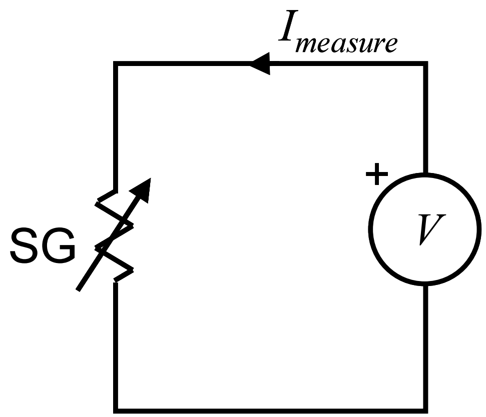
- The input variable (length) modulates a parameter (resistance) in the electrical domain.
- We need a additional system to convert resistance to voltage.

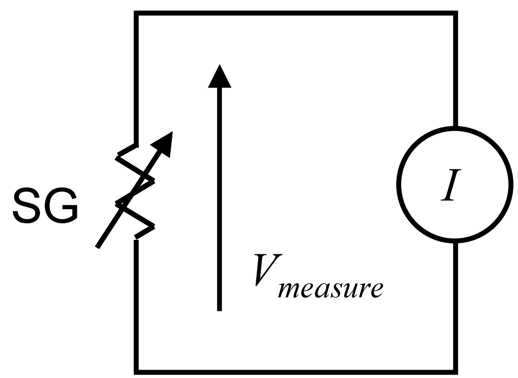
$$V = IR$$

- From Ohms law we know that resistance is the constant that relates Voltage and Current.

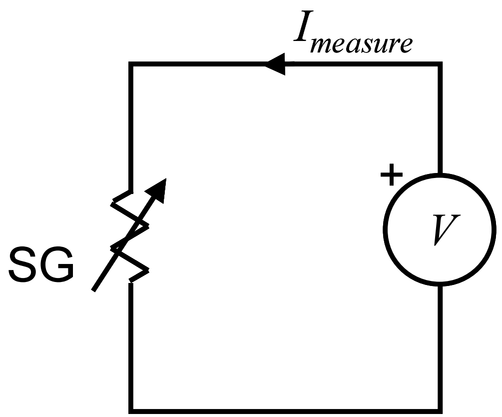
Metallic foil gauges – direct measurement

- The input variable (length) modulates a parameter (resistance) in the electrical domain.
- We need a additional system to convert resistance to something we can measure.
- We could apply a voltage and measure current, or apply a current and measure voltage





Metallic foil gauges – direct measurement



- Let's consider this measuring system and its output over a modest +/-2% maximum strain.
- V=12V, GF=2, R_n=120Ω

$$I = \frac{V}{R_n + \Delta R}$$

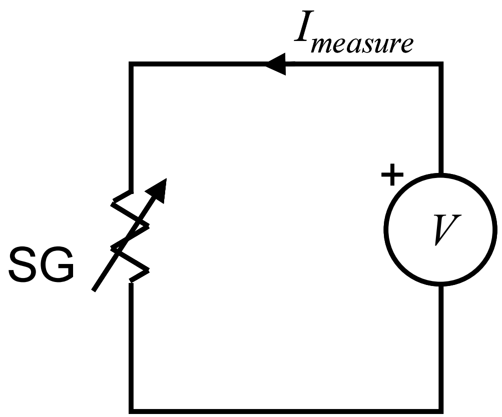
$$\varepsilon = \frac{1}{GF}\left(\frac{V}{IR_n} - 1\right)$$

$$I_{\varepsilon=0} = \frac{12}{120} = 0.1A$$

$$I_{\varepsilon=2\%} = \frac{12}{120+4.8} = 0.096A$$

$$I_{\varepsilon=-2\%} = \frac{12}{120-4.8} = 0.104A$$

Metallic foil gauges – direct measurement



- Let's consider this measuring system and its output over a modest +/-2% maximum strain.
- V=12V, GF=2, R_n=120Ω

- Max value to be measured = 0.104 A
- Resolution of 1% in each direction = 0.004/100 = 0.00004A

- Resolution as percentage of max = 0.038%
- This is can be challenging!

Important idea

- It is difficult to design a system to achieve a high resolution over a large range.

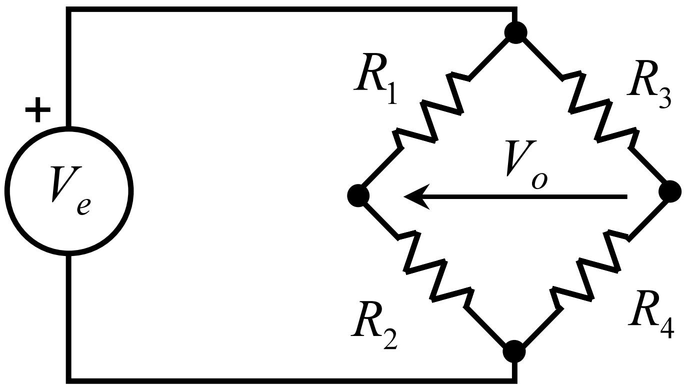
- *Why?*

Direct measurement - problems

- Direct measurement has several potential problems.
- Accurate current/voltage sources and measurement are possible (within limits), although not always convenient.
- Accuracy problems are being exacerbated because we really want to measure *change* rather than *absolute* resistance.

The Wheatstone bridge

- This type of measurement problem is common place and hence solutions exist.
- Using a ‘bridge’ we can measure resistance relative to a known value.

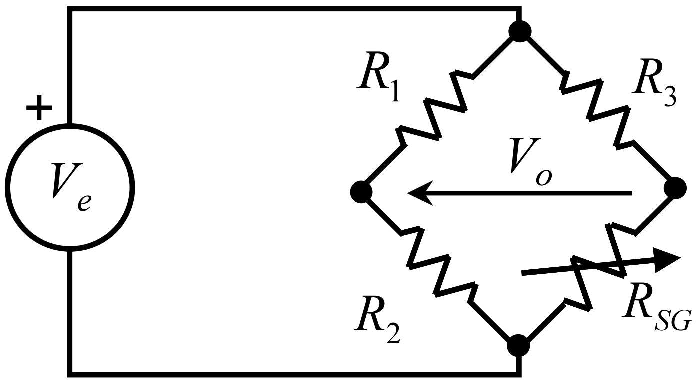


$$V_o = V_e\left(\frac{R_4}{R_4 + R_3} - \frac{R_2}{R_1 + R_2}\right)$$

- This type of circuit was popularised by Sir Charles Wheatstone, hence the common name ‘Wheatstone bridge’

The Wheatstone bridge

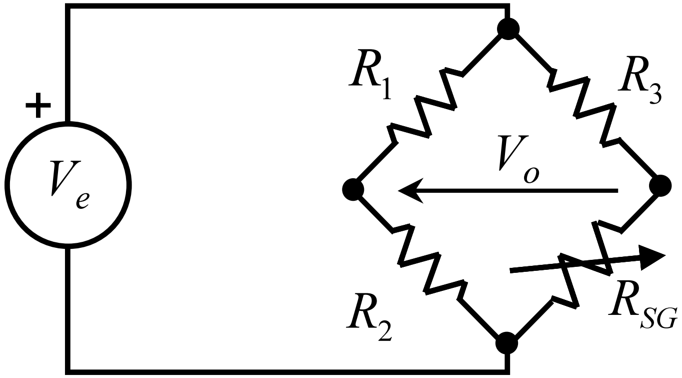
- This type of measurement problem is common place and hence solutions exist.
- Using a ‘bridge’ we can measure resistance relative to a known value.



$$V_o = V_e\left(\frac{R_{SG}}{R_{SG}+R_3} - \frac{R_2}{R_1+R_2}\right)$$

- This circuit will measure the difference between R_2 and R_{SG}.

The Bridge



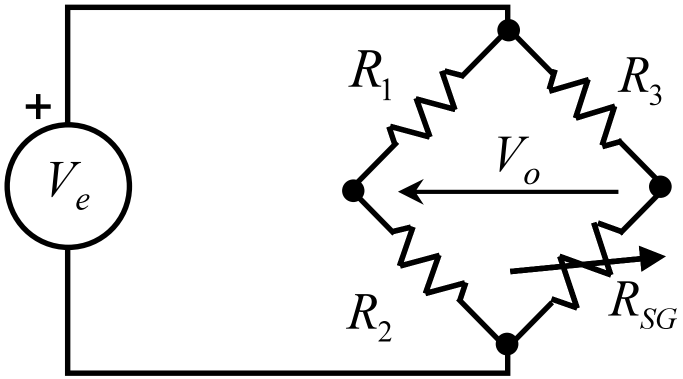
$$V_o = V_e\left(\frac{R_{SG}}{R_{SG}+R_3} - \frac{R_2}{R_1+R_2}\right)$$

$$V_o = V_e\left(\frac{R_n+\Delta R}{(R_n+\Delta R)+R_n} - \frac{R_n}{R_n+R_n}\right)$$

- Set R_1 R_2 R_3 = R_n *(unstrained)*

$$V_o \approx \frac{V_e}{4}\left(GF\frac{\Delta l}{l}\right)$$

The Bridge



$$V_o \approx \frac{V_e}{4}\left(GF\frac{\Delta l}{l}\right)$$

$V_{o,\varepsilon=0} = 0$

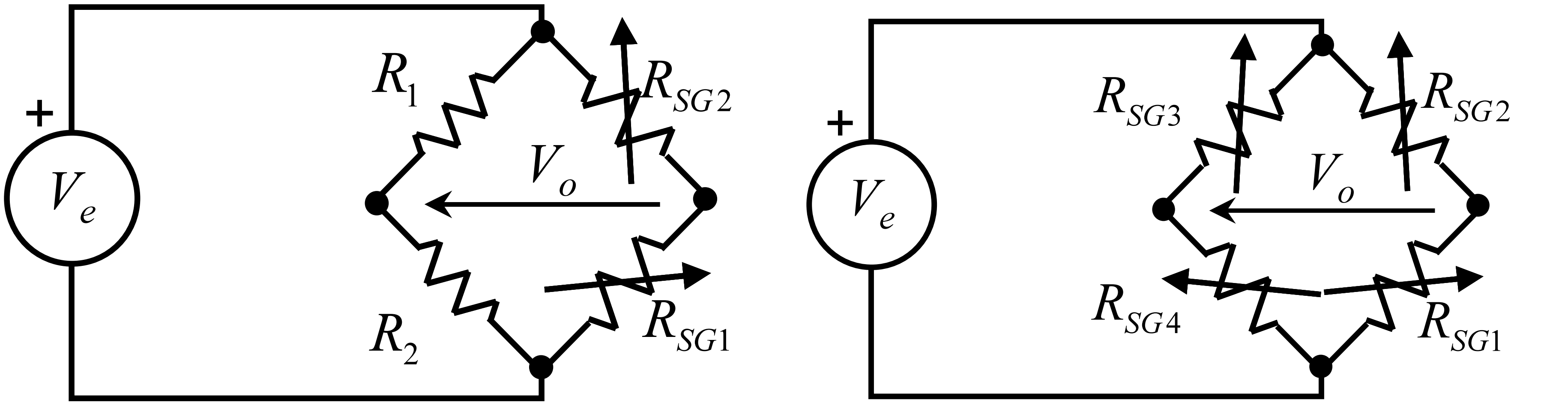
$V_{o,\varepsilon=0.02} = 0.01V_e$

$V_{o,\varepsilon=-0.02} = -0.01V_e$

- Max to be measured = $0.01V_e$
- Resolution of 1% = 0.01/100 = $0.0001V_e$
- Resolution as percentage of range = 1%

- Now we have removed the offset, if we want to measure with 1/100th of full range of strain we only need a meter capable of 1% resolution – much easier than before. *(resolution is 26 times less than required in our previous example)*

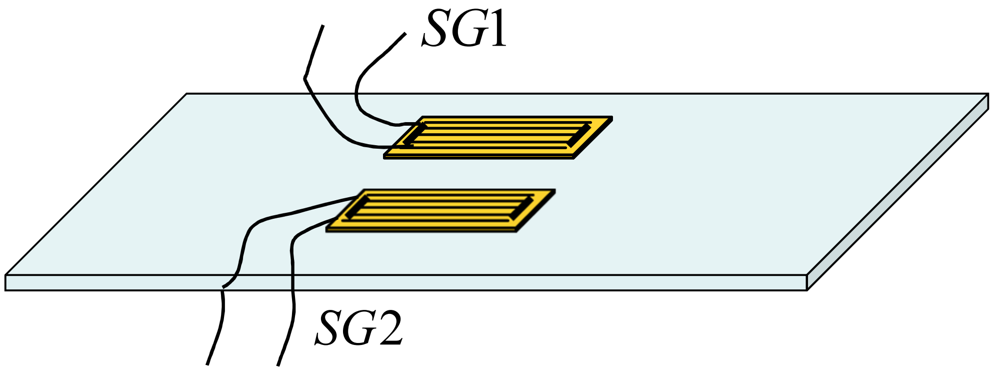
The Bridge – combining gauges

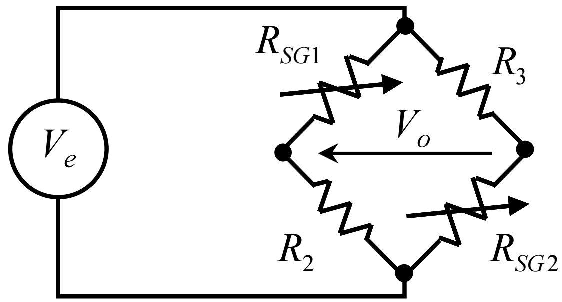


- The bridge can be made up with more than one ‘active’ element.
- A bridge with one active element is a ‘quarter’; two active elements make a half bridge; four a full bridge

Useful strain gauge connections

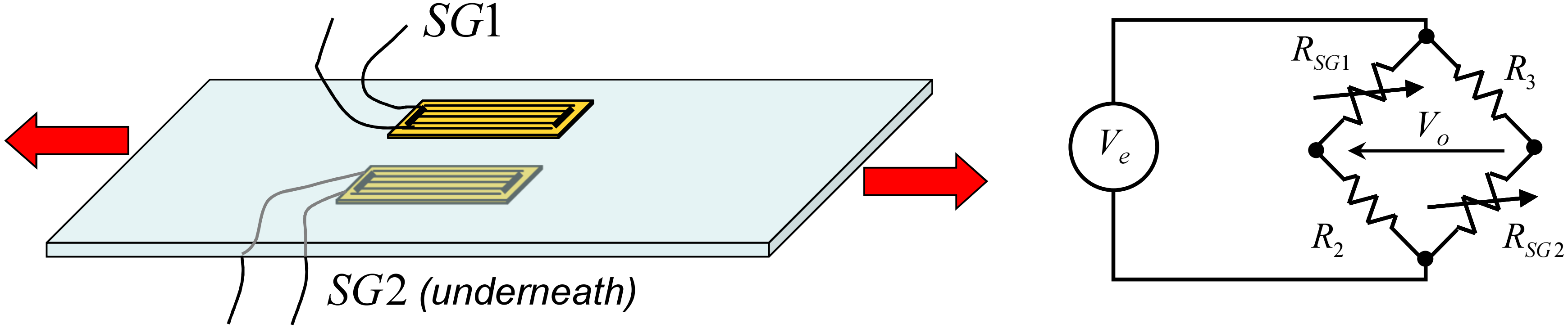
- Strain gauges can be combined - on the subject and in the bridge – to give a variety of useful behaviours.



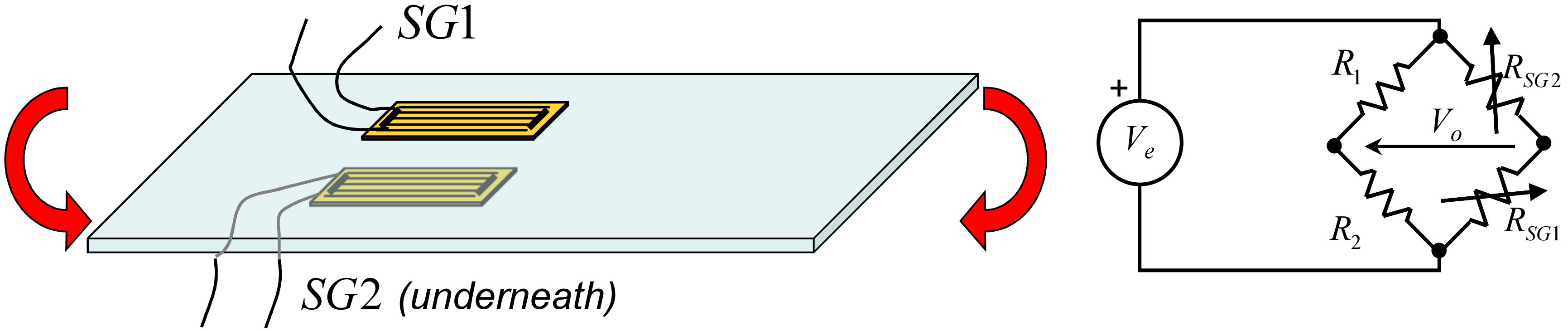


- **SGs combined to double sensitivity**

More useful strain gauge connections

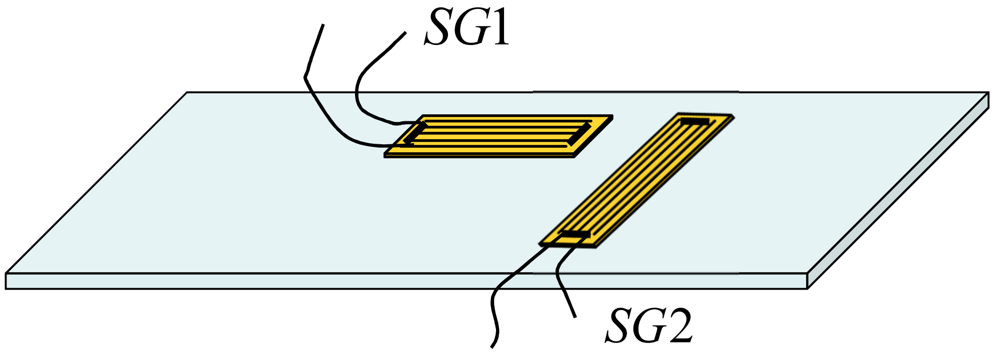


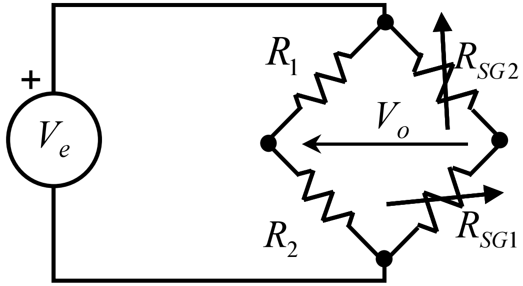
• **Doubles sensitivity, measures tensile strain, eliminates bending strain**



• **Doubles sensitivity, measures bending strain, eliminates tensile strain**

More useful strain gauge connections

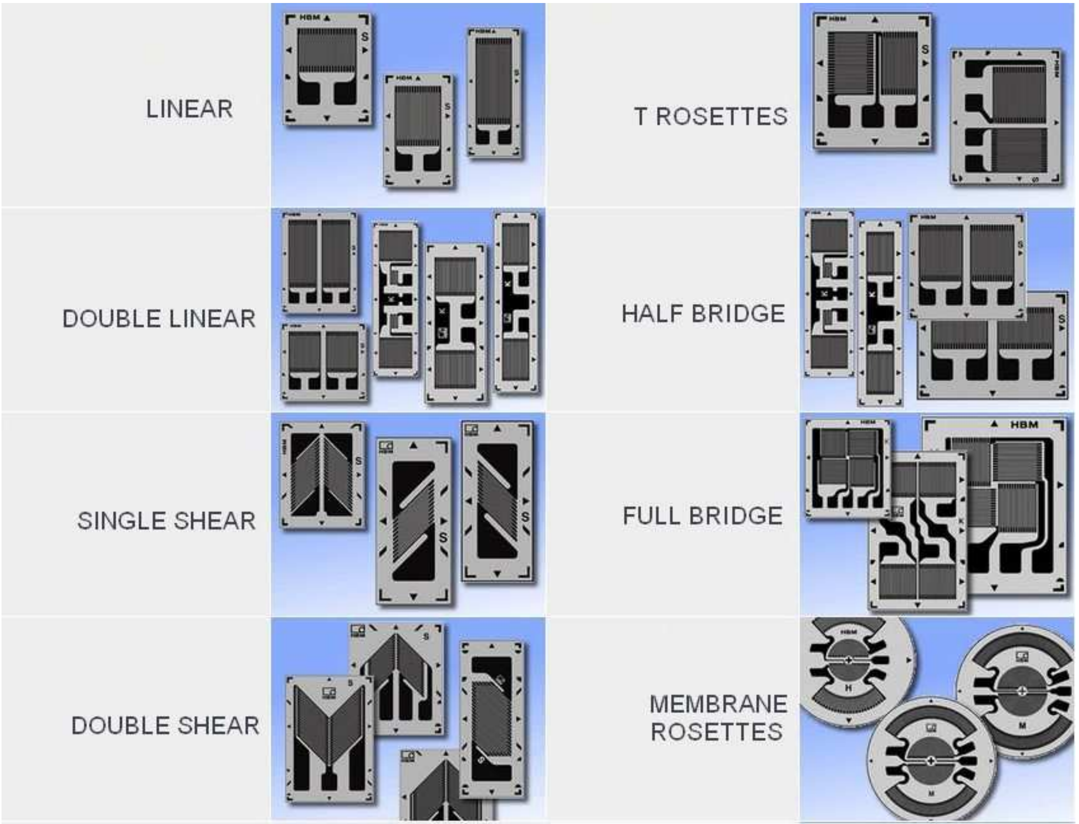




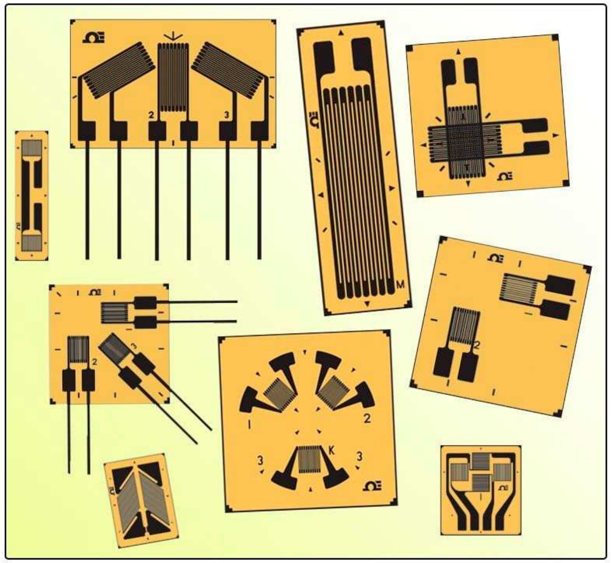
- **Provides temperature compensation**

- Most materials expand as they heat up.
- Where the temperature change is modest, the SG may be sufficiently compensated through its design.
- Alternatively, further SG are used which are positioned such that they only respond to strain due to temperature effects.
- The output is combined in the bridge to cancel temperature-induced strain measurements

SG Rosettes



- SG's are often packaged with multiple elements to aid sensing in multiple axes and/or to provide isolation from unwanted strain components or temperature effects.



Bridge problems

- The ¼ bridge with voltage excitation doesn't quite measure strain.

We want:

$$V_o \propto \frac{\Delta R}{R}$$

But we get:

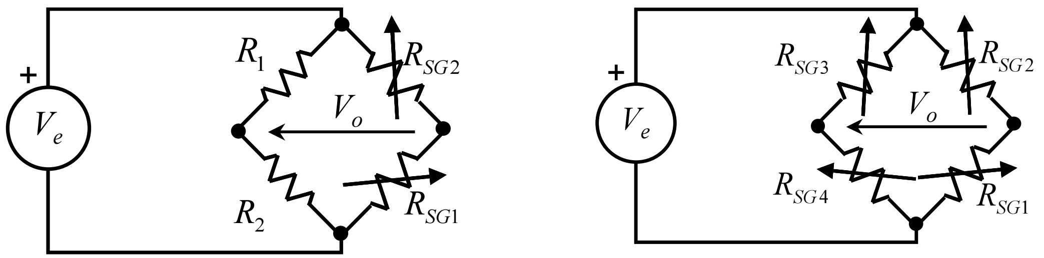
$$V_o \propto \left(\frac{\Delta R + R_n}{\Delta R + 2R_n} - 0.5 \right)$$

- Error is about 0.5% of indicated strain value, so absolute error is low for low strains and worse at higher levels.

Bridge problems

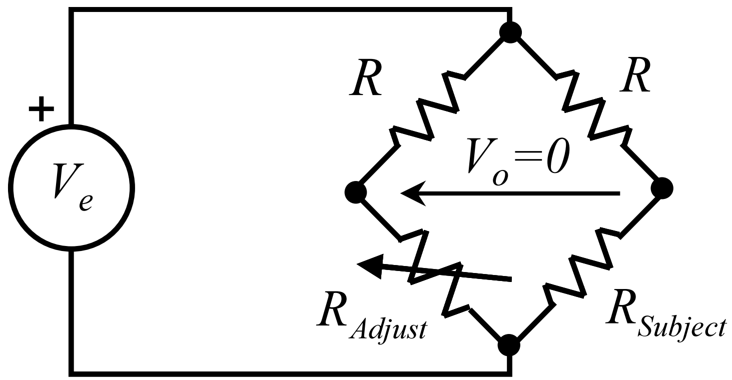
- The ¼ bridge with voltage excitation doesn’t quite measure strain.

- *Apply a pre-determined correction factor.*
- *Use current source to excite bridge (reduces but does not eliminate error)*
- *Use a bridge topology that maintains a constant current in each leg, e.g. arrangements of;*



Null sensing

- When the bridge was first invented it wasn't used in the way we have described so far….



- The resistance of the subject was determined by adjusting a resistance on the opposing leg so that the measured voltage was equal to zero.
- With zero measured voltage, the adjustable resistance must be of equal value to the subject.

Important idea

- Null sensing - where we ‘force’ some variable to zero and measure the effort required; the value of effort is then used as a proxy for what we want to actually measure - is used in many applications.

- *Some measurements may not be possible to do directly*
- *It can shift the requirement for high accuracy onto parts of the measurement system that are easier to make accurate,*
- *It reduces the range required by some sensors,*

  i.e. in the previous example only accurate indication of zero volts is required, it is the adjustable resistor that must be accurate.

Other strain gauges

- Although foil strain gauges are by far the most common way to measure strain, other techniques exist.
- Using a totally different approach, vibrating wire strain gauges measure the frequency of vibration of a wire under tension – like a guitar string.
- Semiconductor SGs exploit a similar effect to metallic foil gauges (resistance of material changing due to deformation) but have much higher gauge factors (~200). The gauge factor varies with strain so extensive calibration is required. They are much cheaper to produce than foil gauges.

Strain Gauges