LECTURE NOTES

ON

EXPERIMENTAL STRESS ANALYSIS (BCCB13)

M.Tech II Semester

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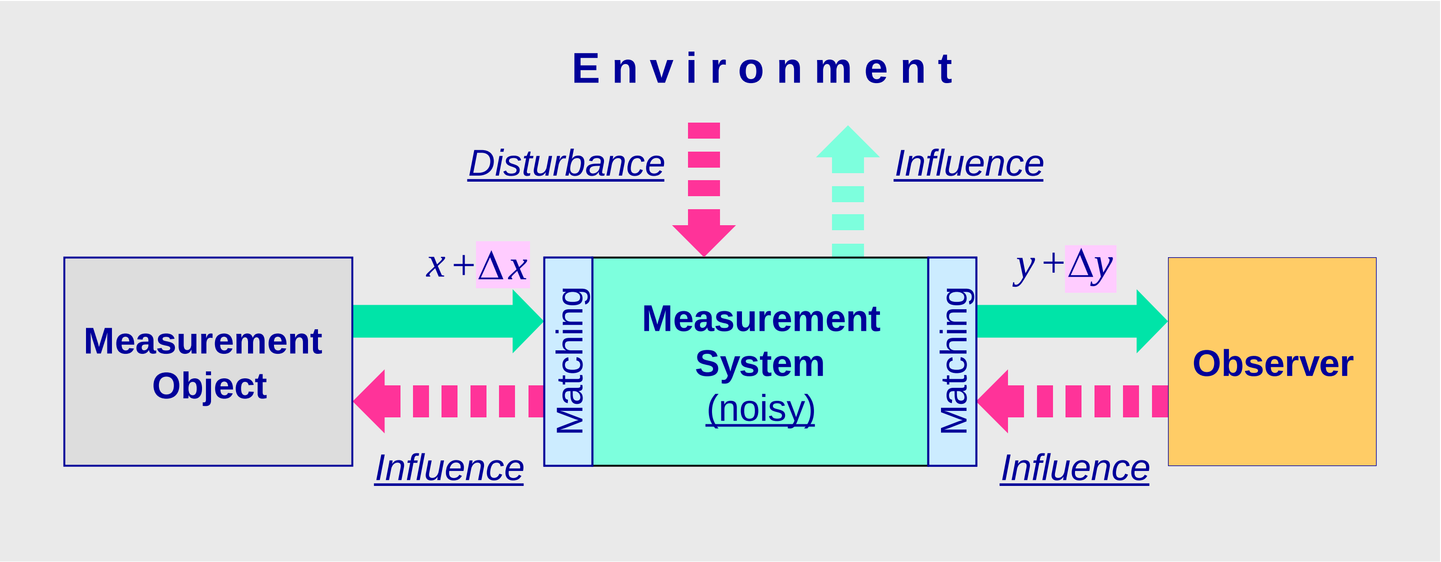
MECHANICALENGINEERING

MEASUREMENT THEORY FUNDAMENTALS

Generic scheme of a measurement



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1. Basic principles of measurements

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1.4. Types of measurements
1.5. Scaling of measurement results

1. BASIC PRINCIPLES OF MEASUREMENTS

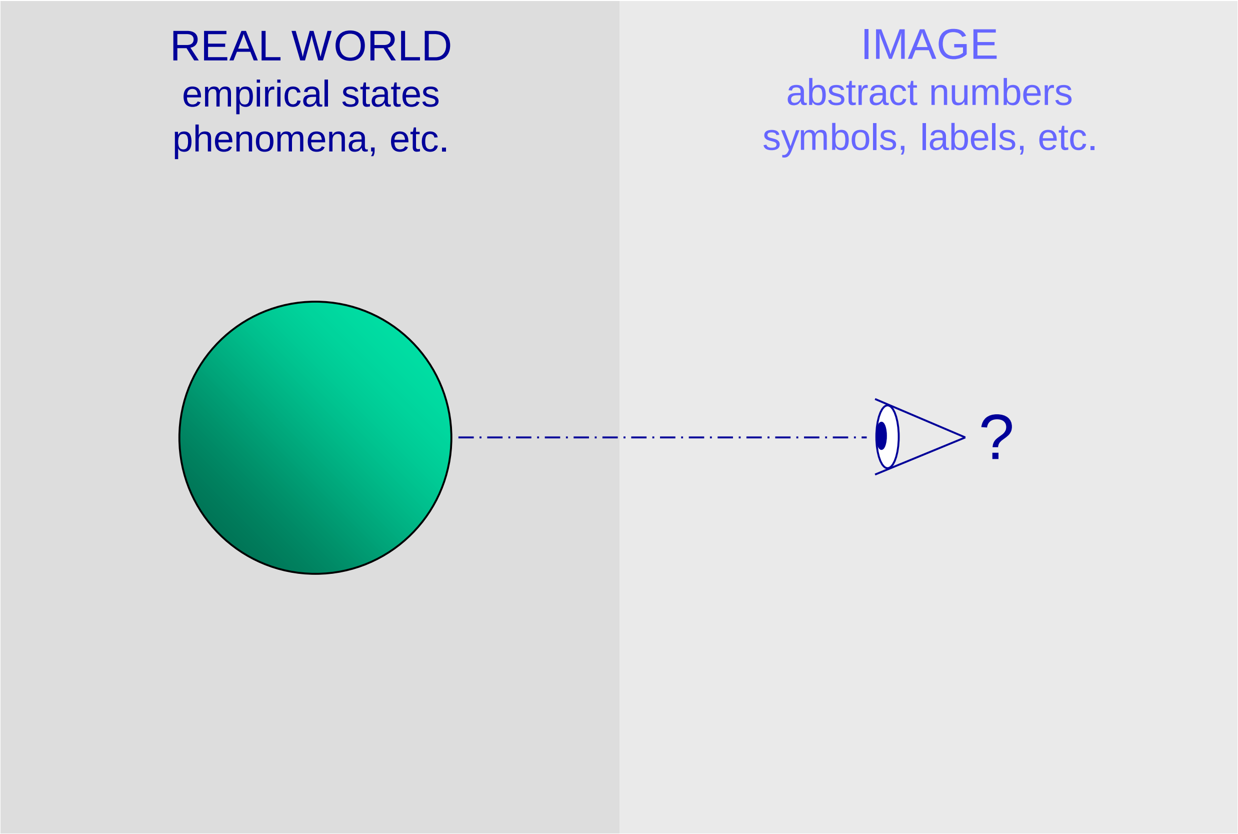
1.1. Definition of measurement

Measurement is the acquisition of information about
a state or phenomenon (object of measurement)
in the world around us.

This means that a measurement must be descriptive (observable) with regard to that state or object we are measuring: there must be a relationship between the object of measurement and the measurement result.

Reference: [1]

Illustration: Descriptiveness (observability) of a measurement



REAL WORLD
empirical states
phenomena, etc.

IMAGE
abstract numbers
symbols, labels, etc.

The descriptiveness is necessary but not sufficient aspect of measurement: when one reads a book, one gathers information, but does not perform a measurement.

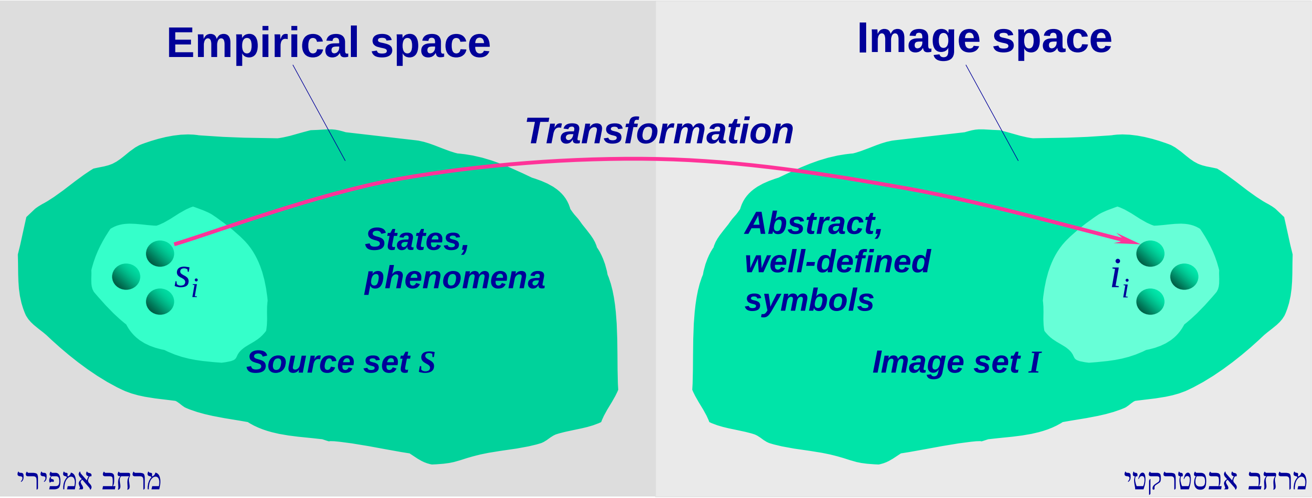
A second aspect of measurement is that it must be selective: it may only provide information about what we wish to measure (the measurand) and not about any other of the many states or phenomena around us.

This aspect too is a necessary but not sufficient aspect of measurement. Admiring a painting inside an otherwise empty room will provide information about *only* the painting, but does not constitute a measurement.

A third and sufficient aspect of measurement is that it must be objective. The outcome of measurement must be independent of an arbitrary observer.

Reference: [1]

In accordance with the three above aspects: descriptiveness, selectivity, and objectiveness, a measurement can be described as the mapping of elements from an empirical source set onto elements of an abstract image set with the help of a particular transformation (measurement model).



Source set and image set are isomorphic if the transformation *does copy* the source set structure (relationship between the elements).

Reference: [1]

1.2. Definition of instrumentation

In order to guarantee the objectivity of a measurement, we must use artifacts (tools or instruments). The task of these instruments is to convert the state or phenomenon into a different state or phenomenon that cannot be misinterpreted by an observer.

The field of designing measurement instruments and systems is called instrumentation.

Instrumentation systems must guarantee the required descriptiveness, the selectivity, and the objectivity of the measurement.

Reference: [1]

Example: Measurement as mapping

Empirical space

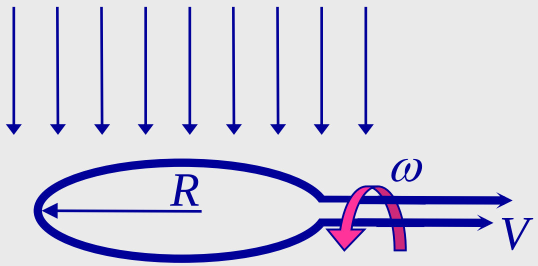
Image space

State (phenomenon):

Static magnetic field

Transformation

Abstract symbol, B



$B = f(R, \omega, V)$

Measurement model

Instrumentation

מרחב אמפירי

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$$v = -\frac{\mathrm{d}[B\cos(\omega t)A]}{\mathrm{d}t}$$

1.3. Why measuring?

Let us define ‘pure’ science as science that has sole purpose of *describing* the world around us and therefore is responsible for our perception of the world.

In ‘pure’ science, we can form a better, more coherent, and objective picture of the world, based on the information measurement provides. In other words, the information allows us to create models of (parts of) the world and formulate laws and theorems.

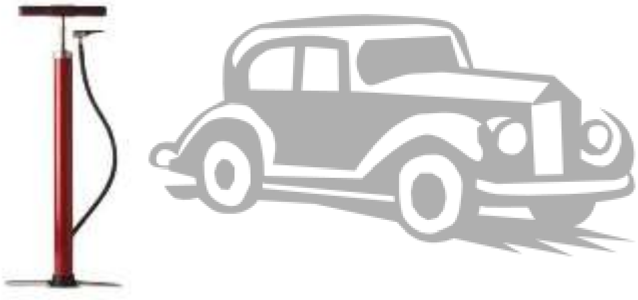
We must then determine (again) by measuring whether this models, hypotheses, theorems, and laws are a valid representation of the world. This is done by performing tests (measurements) to compare the theory with reality.

We consider ‘applied’ science as science intended to change the world: it uses the methods, laws, and theorems of ‘pure’ science to modify the world around us.

In this context, the purpose of measurements is to regulate, control, or alter the surrounding world, directly or indirectly. The results of this regulating control can then be tested and compared to the desired results and any further corrections can be made.

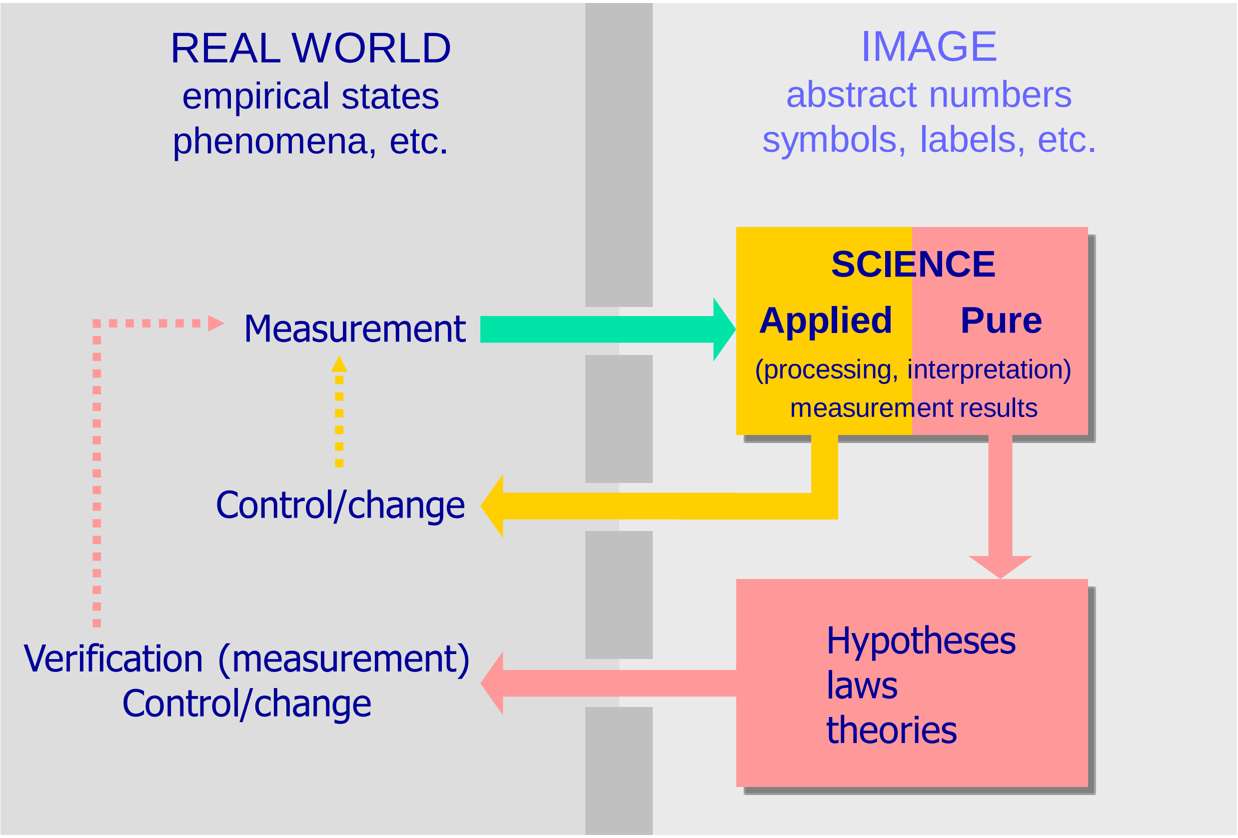
Even a relatively simple measurement such as checking the tire pressure can be described in the above terms:

1) a hypothesis: we fear that the tire pressure is abnormal;
2) perform measurement;
3) alter the pressure if it was abnormal.



Reference: [1]

Illustration: Measurement in pure and applied science



1.4. Types of measurements

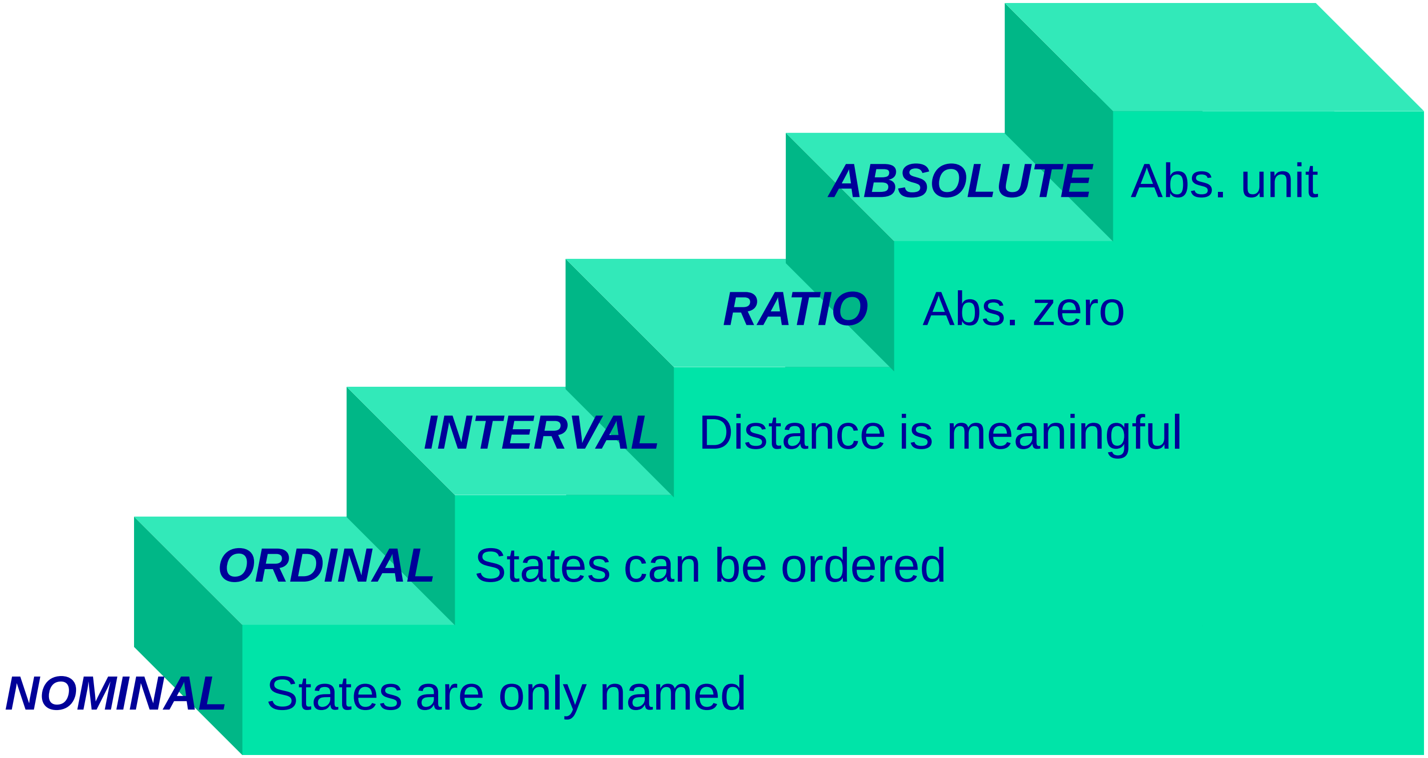
To represent a state, we would like our measurements to have some of the following characteristics.

- Distinctiveness: $A = B$, $A \neq B$.
- Ordering in magnitude: $A < B$, $A = B$, $A > B$.
- Equal/unequal intervals: $|A - B| < |C - D|$, $|A - B| = |C - D|$, $|A - B| > |C - D|$.
- Ratio: $A = k\,B$ (absolute zero is required).
- Absolute magnitude: $A = k_a REF$, $B = k_b REF$ (absolute reference or unit is required).

These five characteristics are used to determine the five types (levels) of measurements.

Reference: [1]

Illustration: Levels of measurements (S. S. Stevens, 1946)



ABSOLUTE Abs. unit

RATIO Abs. zero

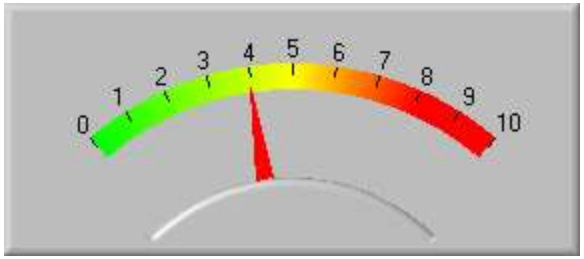
INTERVAL Distance is meaningful

ORDINAL States can be ordered

NOMINAL States are only named

1.5. Scaling of measurement results

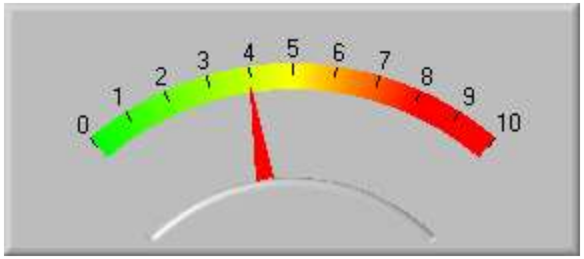
A scale is an organized set of measurements, all of which measure one property.

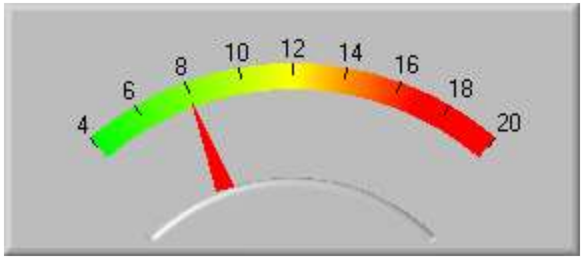


The types of scales reflect the types of measurements:

1. *nominal* scale,
2. *ordinal* scale,
3. *interval* scale,
4. *ratio* scale,
5. *absolute* scale.

A scale is *not* always unique; it can be changed without loss of isomorphism.





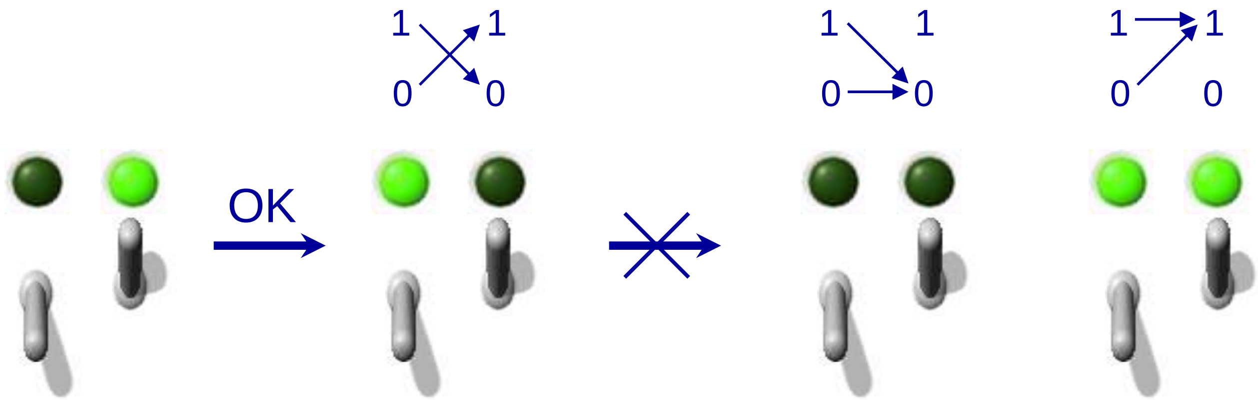
Note that a high-level scale should *usually* allow all the lower-scale measurements.

1. Nominal scale

Examples: numbering of football players, detection and alarm systems, etc.

Any one-to-one transformation *can** be used to change the scale.

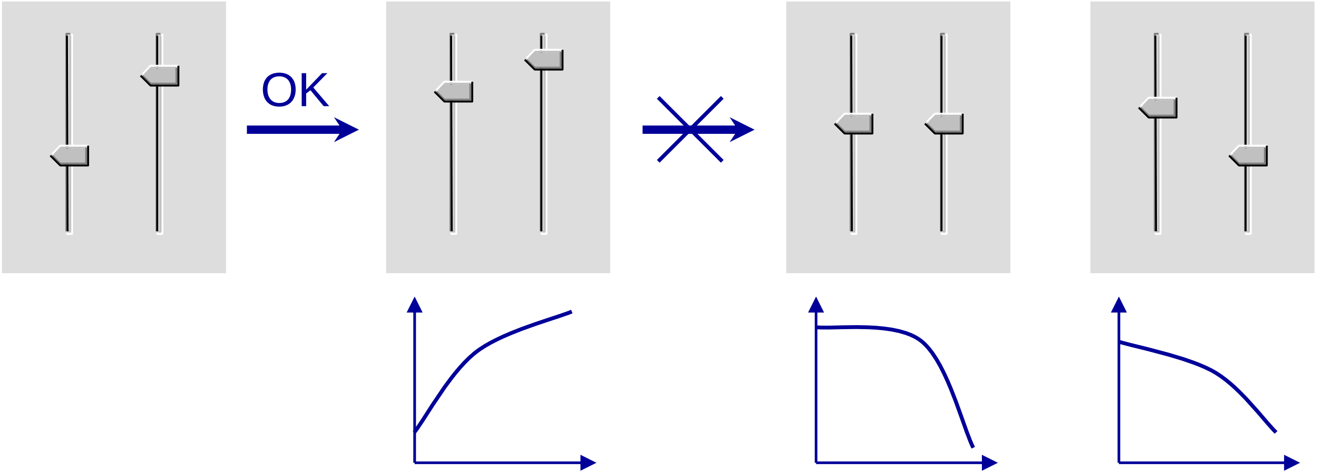
*Stevens did not say that transformations that are not 'permissible' are prohibited. http://mu.dmt.ibaraki.ac.jp/yanai/neu/faq/measurement.html#exmpls



2. Ordinal scale

Examples: IQ test, competition results, etc.

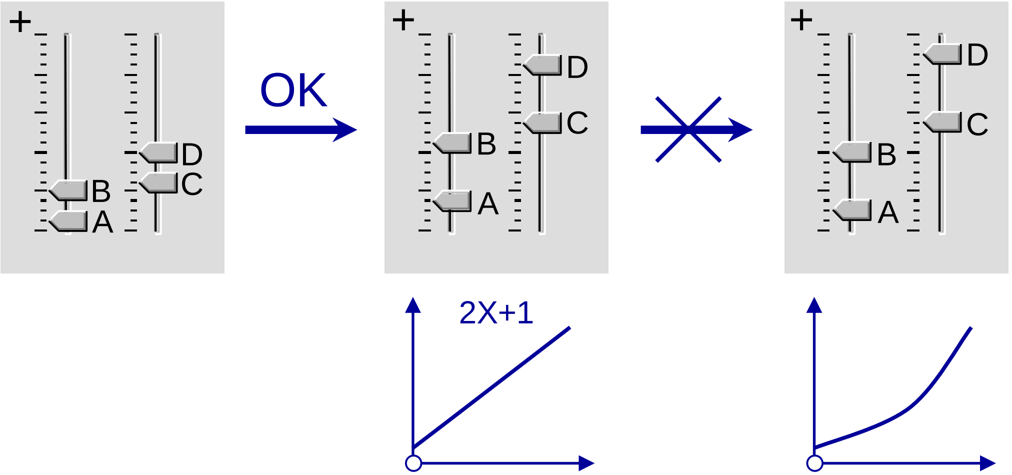
Any monotonically increasing transformation, either linear or nonlinear, can be used to change the scale.

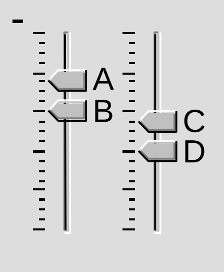


3. Interval scale

Examples: time scales, temperature scales (C, F), etc., where the origin or zero is not absolute (floating).

Any increasing linear transformation can be used to change the scale.



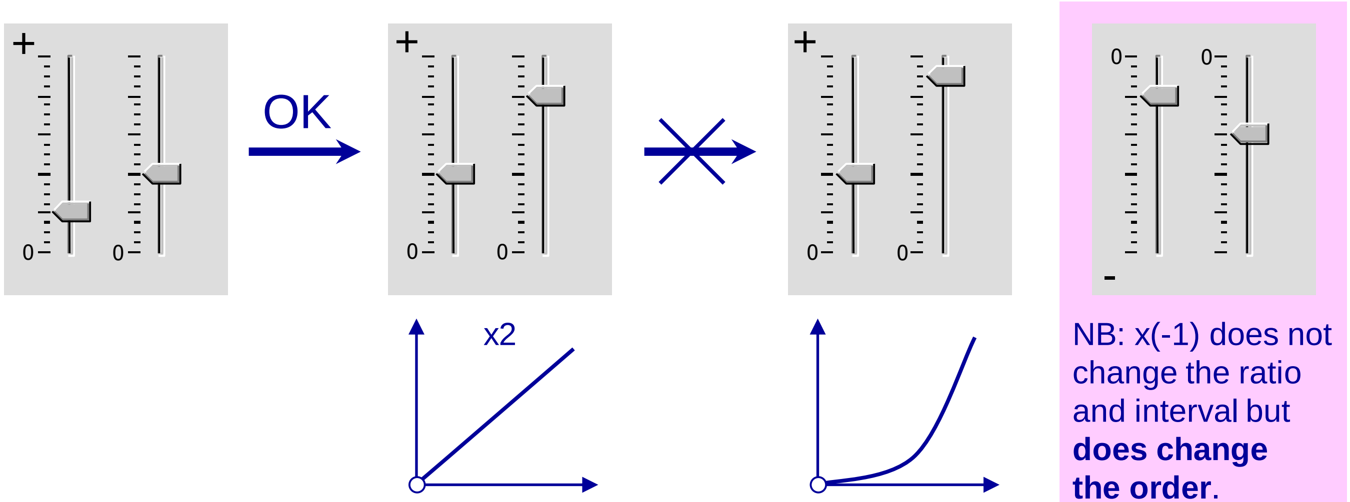


NB: x(-1) does not change the interval but **does change the order: A>C**.

4. Ratio scale

Examples: temperature (K), distance, mass, current, voltage scales, etc., where the origin or zero is absolute.

The only transformation that can be used to change the scale is the <u>multiplication by any positive real</u> number.

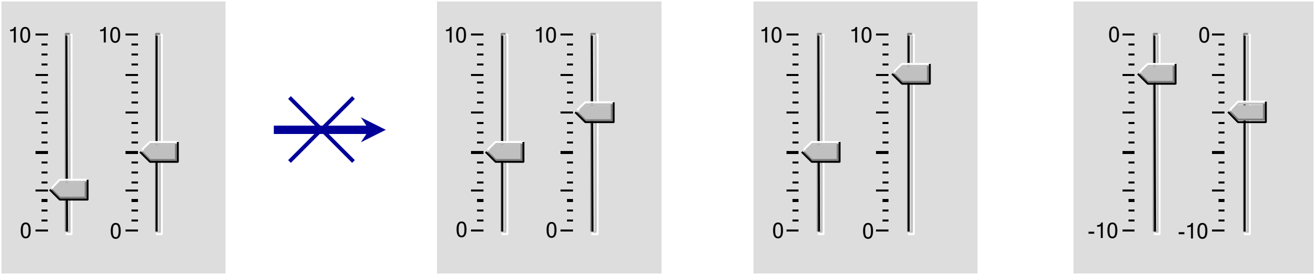


NB: x(-1) does not change the ratio and interval but **does change the order**.

5. Absolute scale

Examples:measurement of any physical quantities by comparison against an absolute unit (reference).

No transformation can be used to change the scale.



(Same interval)

(Same ratio)

(Same ratio, different order)

Not the same absolute values.

1.6. Conclusion

The concept of scale type is an important one, and Stevens’s terminology is often suitable.

We must keep in mind, however, that scale types are not fundamental attributes of the data, but rather, derive from both how the data were measured and what we conclude from the data.

To restrict our investigation only to hypotheses and calculations permitted by an a priori assignment of scale type would be far more irresponsible.

Responsible data analysis must be open to anomaly if it is to support scientific advancement.

Strain Gauge Extensometers

Nicole Stephenson

Fall 2002

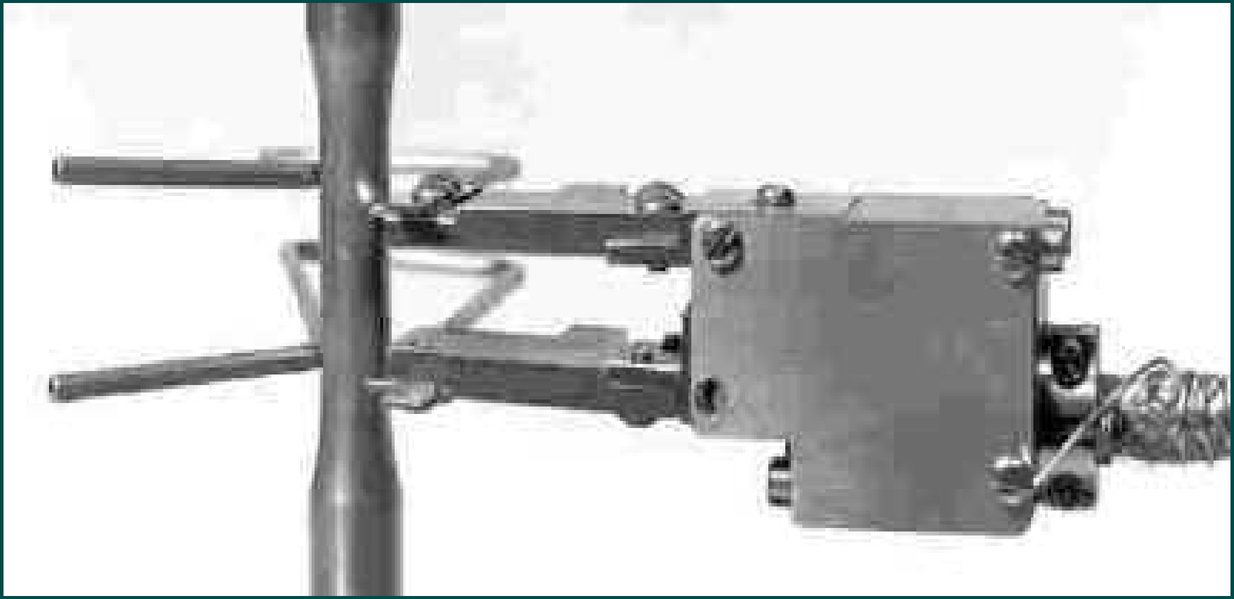
Dr. Thomas Brown

What is it?

- A device used to determine changes in linear dimensions
- Electronically measures extension of sample under load
- From load and extensometer data, stress vs. strain curve can be developed
  - Yield, tensile, ultimate strength
  - Modulus of elasticity

How does it work?

- The basic principle for a resistance-type transducer: the resistance of a wire increases with increasing strain and decreases with decreasing strain



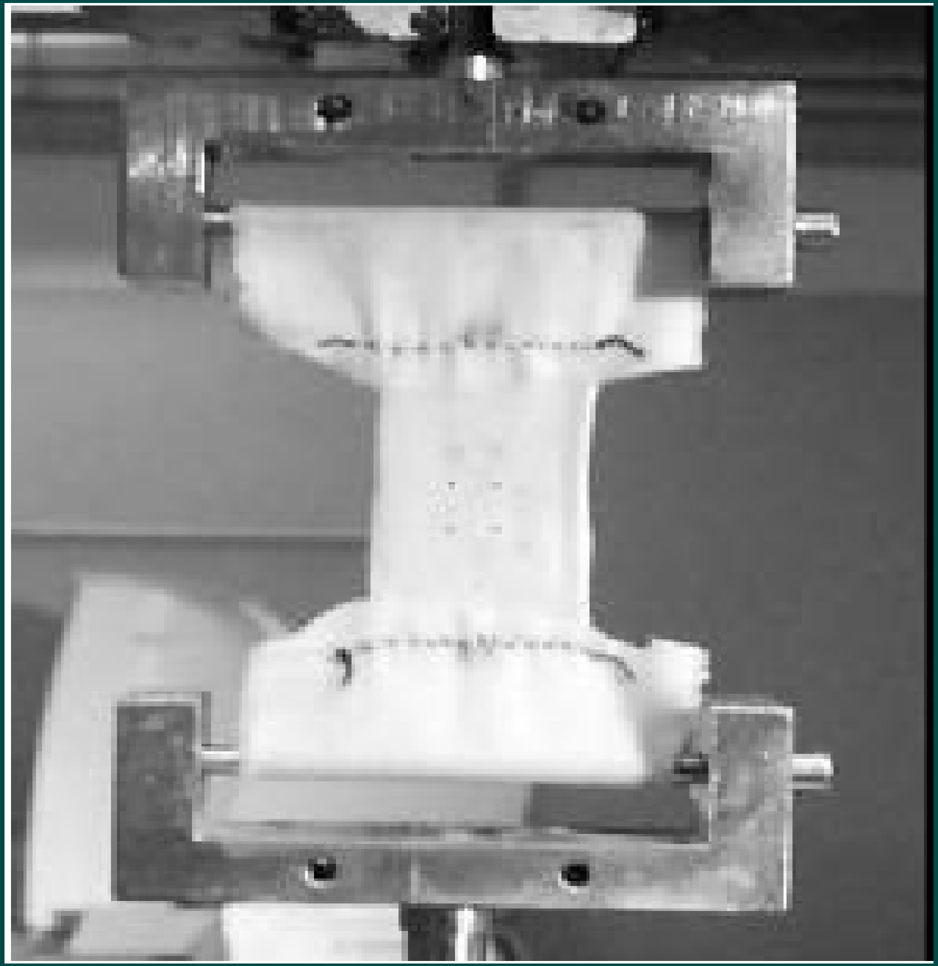
Why use an extensometer?

- Measuring crosshead displacement measures more than wanted
  - Machine deflection
  - Grip deflection
  - Possible slippage and deflection of the part outside normal reduced area
- Strain=$\Delta L/L_o$
  - No initial length without extensometer
  - Not able to accurately measure change

Use in Biomechanics

- Soft tissues: two main techniques
  - low-stiffness biomedical extensometers used for one-dimensional collagenous structures
  - optical methods based on video-extensometers and video cameras tracking target markers drawn on the specimen surface used for measuring plane states of strain on planar tissue membranes
- Hard tissues
  - Employ typical extensometers unless sample is compromised by knife edges of grips

Video Extensometers



References

- http://wwwlabs.stru.polimi.it/the%20staff/Villa/exp%20meth.pdf

  Experimental Methods in Biomechanics
- http://www.epsilontech.com/faq.htm

  FAQ, Epsilon Extensometers
- http://www.tu-darmstadt.de/fb/ms/student/fs/german/lab/w5/mse5-1.htm

  The Tensile Test, Extension Measurement Techniques

Questions?

MECH 373

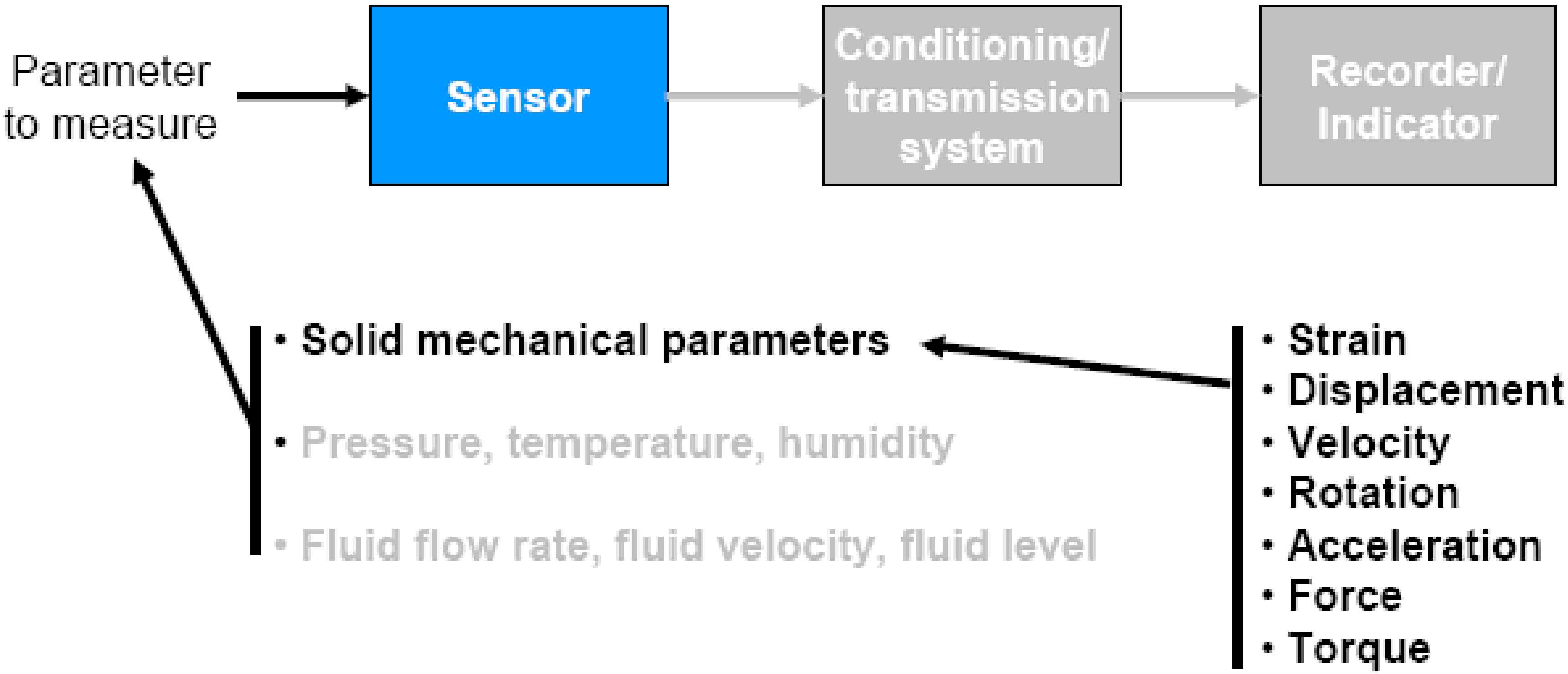
Instrumentation and Measurements

Lecture 18

Measurement of Solid-Mechanical Quantities (Chapter 8)

- **Measuring Strain**
- Measuring Displacement
- Measuring Linear Velocity
- Measuring Accepleration and Vibaration
- Measuring Force

Measurement Systems



Parameter to measure

Sensor

Conditioning/ transmission system

Recorder/ Indicator

- **Solid mechanical parameters**
- Pressure, temperature, humidity
- Fluid flow rate, fluid velocity, fluid level

- Strain
- Displacement
- Velocity
- Rotation
- Acceleration
- Force
- Torque

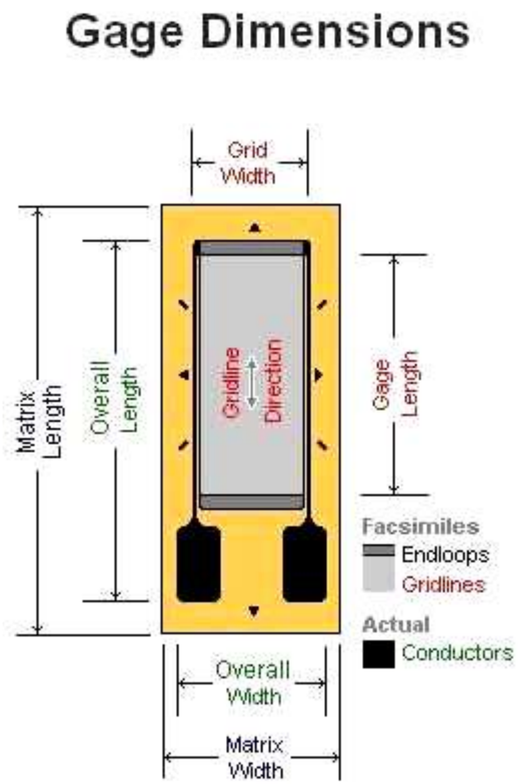
Measuring Strain (Strain Gages)

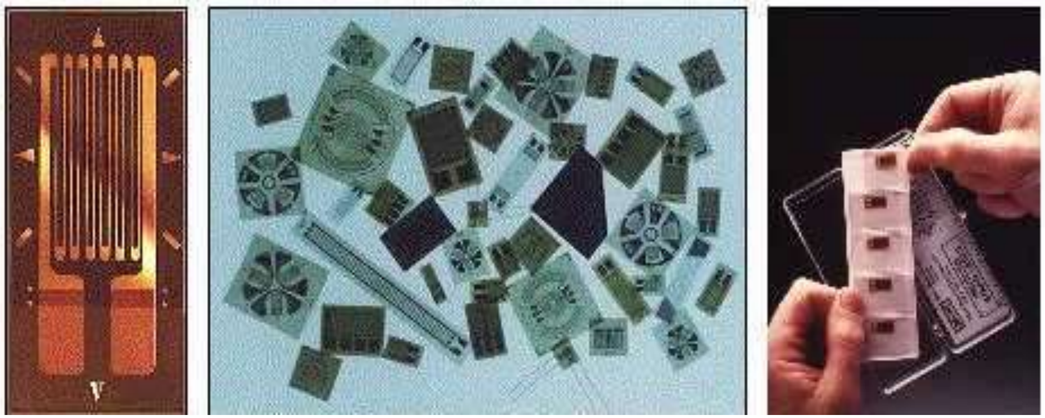
- What is Strain? Strain is the amount of deformation of a body due to an applied force. More specifically, strain is defined as the fractional change in length.
- When a force is applied to a structure, the components of the structure change slightly in their dimensions and are said to be strained.
- Devices to measure these small changes in dimensions are called *strain gages*.
- What devices can be used to measure strain?

Electrical Resistance Strain Gage

- The ideal sensor for the measurement of strain would
  - Have good spatial resolution, implying that the sensor would measure strain at a point
  - Be unaffected by changes in ambient conditions
  - Have a high-frequency response for dynamic strain measurements.
- A device that closely meets these characteristics is the *resistance strain gage*.

What is Strain Gage?





- A strain gauge, a device whose electrical resistance varies in proportion to the amount of strain in the device. The most widely used gage is the bonded metallic strain gage.

Measuring Strain (Strain Gages)

- The electrical resistance strain gage is an extremely common device used to measure strain in structures and also as a sensing element in a wide variety of transducers, including those used to measure force, acceleration and pressure.
- Electrical-resistance strain gages and associated signal conditioners are simple, inexpensive and quite reliable.
- To understand the function of a strain gage, consider the measurement of strain in a simple structure shown below.

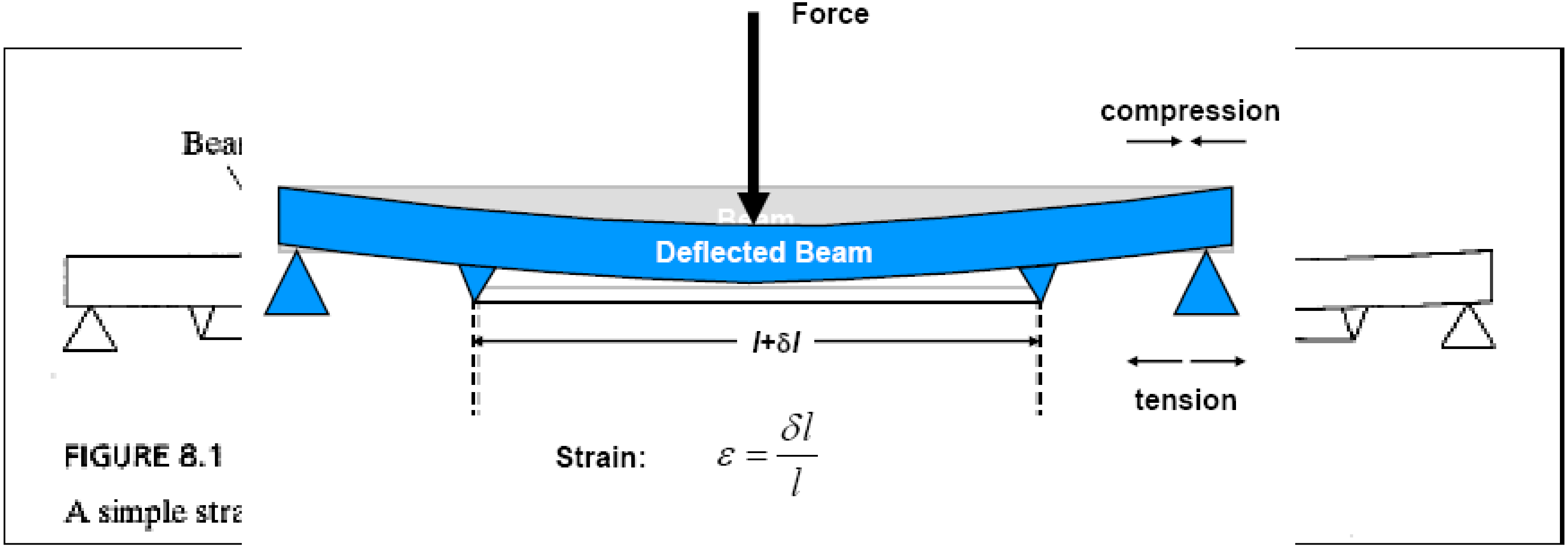


FIGURE 8.1

A simple stra

Strain: $\varepsilon = \dfrac{\delta l}{l}$

Stress: $\sigma = E\varepsilon$

Measuring Strain (Strain Gages)

- The figure shows a situation in which a supported beam is bent by applying a lateral force.

- With this type of loading, the beam will become longer on the bottom surface and shorter on the top surface.

- A wire that is attached to the beam using two standoffs functions as a simple strain gage.

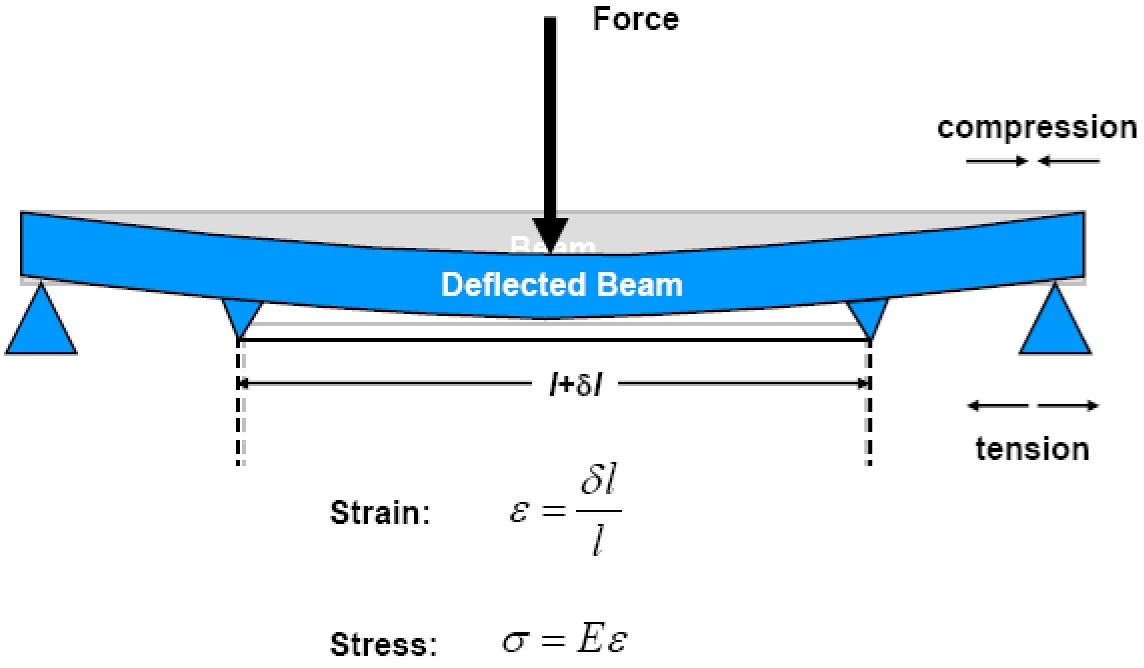
- Consider the original lengt

- When the beam is loaded, t

- The ratio δ*l*/*l* is known as t

- In the above case, the strai
in the lower surface of the be

- The stretching of the wire
the wire is a detector of strai



Measuring Strain (Strain Gages)

- Strain has units of inches per inch or millimeters per millimeter and hence it is dimensionless. In most structures the values of strain are usually very small. For example, low-strength steel will yield (take a permanent deform) at a strain about 0.0014.

- Therefore, usually the strain is expressed in units of *microstrain* (µstrain).

- Thus, 0.0014 strain = 0.0014 × 10^6 µstrain = 1400 µstrain.

- In the engineering design process, it is often necessary to determine the stresses in a structure experimentally to determine if the structure is sound.

- It is difficult to measure the stress directly, but a strain gage can be used to measure the strain, and then the stress can be determined using the Hooke's law. That is

$$\sigma = E\varepsilon$$

where, σ is the normal stress and E is the modulus of elasticity (also called Young's modulus) which is a material property.

- For a wire to work as a strain gage, the relationship between the change in resistance and the strain must be known.

Measuring Strain (Strain Gages)

- The resistance of a wire is given by

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

where, R is the resistance, ρ is the resistivity of wire which is a function of the wire material, L is the length of wire, and A is the cross-sectional area of the wire.

- Taking logarithms of both sides, separating the terms and differentiating each term, we get

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A}$$

- The above equation relates a small change in resistance to changes in resistivity, length and cross-sectional area.

- The term dL/L is the *axial strain*, ε_a.

- The term dA/A can be evaluated from the equation of the cross-sectional area $A=\pi D$^2/4.

- Taking the logarithm and differentiating the above equation we get

$$\frac{dA}{A} = 2\frac{dD}{D}$$

Measuring Strain (Strain Gages)

- The term *dD/D* is known as the *transverse strain*, ε_t.
- Solid mechanics provides the following relationship between the axial and transverse strain

$$\varepsilon_t = -v\varepsilon_a$$

where, v is known as Poisson's ratio and it is the property of material.

- The negative sign indicates that as the wire becomes longer, the transverse dimension decreases.
- Combining the above equations we get

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \varepsilon_a(1+2v)$$

- The above equation shows the relationship between the change in resistance of the wire, strain, and the change in resistivity of the wire.
- The strain gage factor, *S*, is defined as

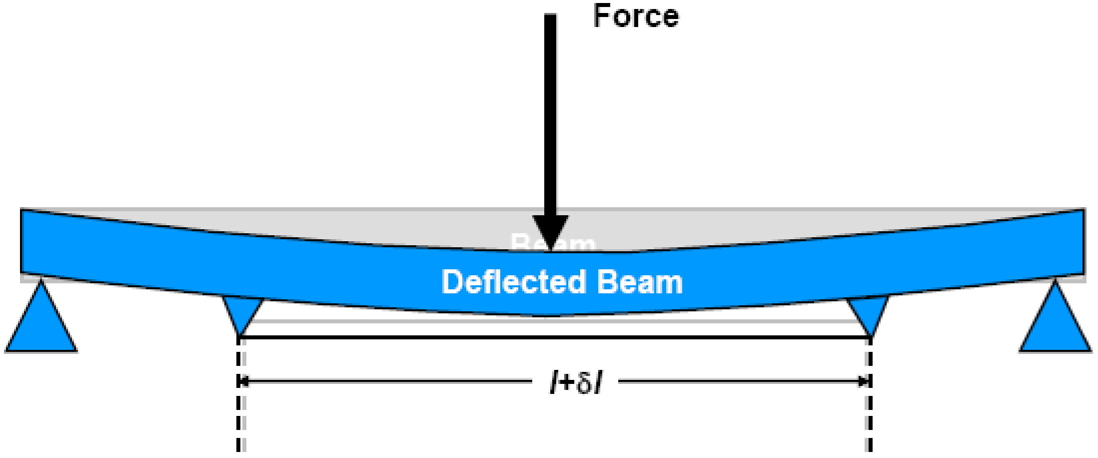
$$S = \frac{dR/R}{\varepsilon_a}$$

- Combining the above two equations we get

$$S = 1 + 2v + \frac{d\rho/\rho}{\varepsilon_a}$$

Measuring Strain (Strain Gages)

- If the temperature is held constant, the change in resistivity is proportional to the strain.
- The strain gage factor is approximately constant, although it is sensitive to the temperature change.
- In summary, we have following equations:



$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A}$$

Axial strain: $\varepsilon_a = \frac{dL}{L}$ $\quad \varepsilon_t = -\upsilon \varepsilon_a$

$$\frac{dA}{A} = 2\frac{dD}{D}$$

Transverse strain: $\varepsilon_t = \frac{dD}{D}$ $\quad \frac{dR}{R} = \frac{d\rho}{\rho} + \varepsilon_a - (-2\upsilon\varepsilon_a)$

Strain gauge factor: $S = \frac{dR/R}{\varepsilon_a}$

Strain gauge equation: $S = 1 + 2\upsilon + \frac{d\rho/\rho}{\varepsilon_a}$

Measuring Strain (Strain Gages)

- In addition to the strain gages constructed in the form of straight wires, another common type of strain gages are constructed by etching them from thin foil metal sheets that are bounded to a plastic backing, as shown below.

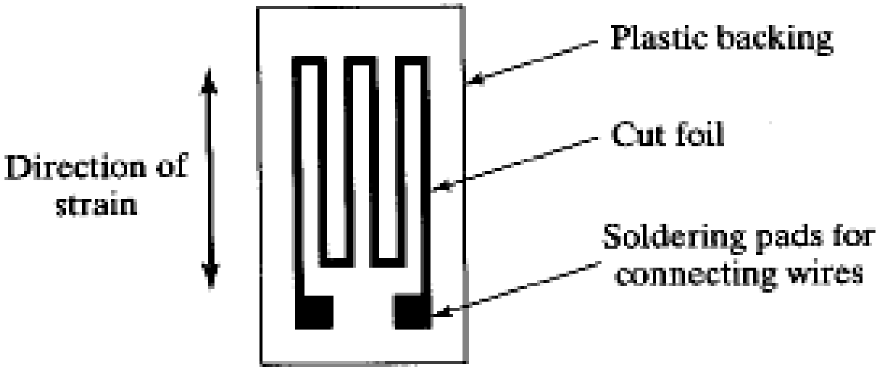
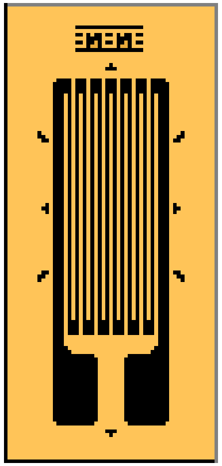


FIGURE 8.2

Foil strain gage.



- This backing is glued to the structure whose strain needs to be measured.
- The dimensions of strain gages vary. They can be as small as 200 μm.
- Strains as high as 200,000 με can be measured.
- Strain gages can also be constructed from semiconductor materials.
- The semiconductor strain gages are commonly used as sensing elements in pressure and acceleration transducers. However, they cannot measure very high strain.

Measuring Strain (Strain Gages)

- If a structure is loaded in a single direction, there exists a transverse strain but no transverse stress.
- This strain can be measured as $\varepsilon_t = -\nu\varepsilon_a$
- This effect is included when manufacturers determine strain gage factors.
- In many situations, the surface of a structure is stressed simultaneously in more than one direction, leading to the so-called *biaxial stress*.
- In biaxial stress there is a transverse strain that results from the transverse stress.
- This transverse strain affects the strain gage output and be described with a transverse gage factor, S_t, defined as

$$S_t = \frac{dR/R}{\varepsilon_t}$$

- The transverse sensitivity effects are usually neglected in the strain measurements.
- To define the strain on a surface, it is necessary to specify two orthogonal linear strains ε_x and ε_y, and a third strain called the shear strain, γ_{xy}, the change in angle between two originally orthogonal lines when the solid is strained.
- These strains can be determined by three suitably placed strain gages in an arrangement called a *strain rosette*.

Measuring Strain (Strain Gages)

- Two common arrangements of the three strain gages are:
  - Rectangular rosette
  - Equiangular rosette
- In rectangular rosette, the gages are placed at angles of 0, 45 and 90 degrees.
- In equiangular rosette, the gages are arranged at 0, 60 and 120 degrees.

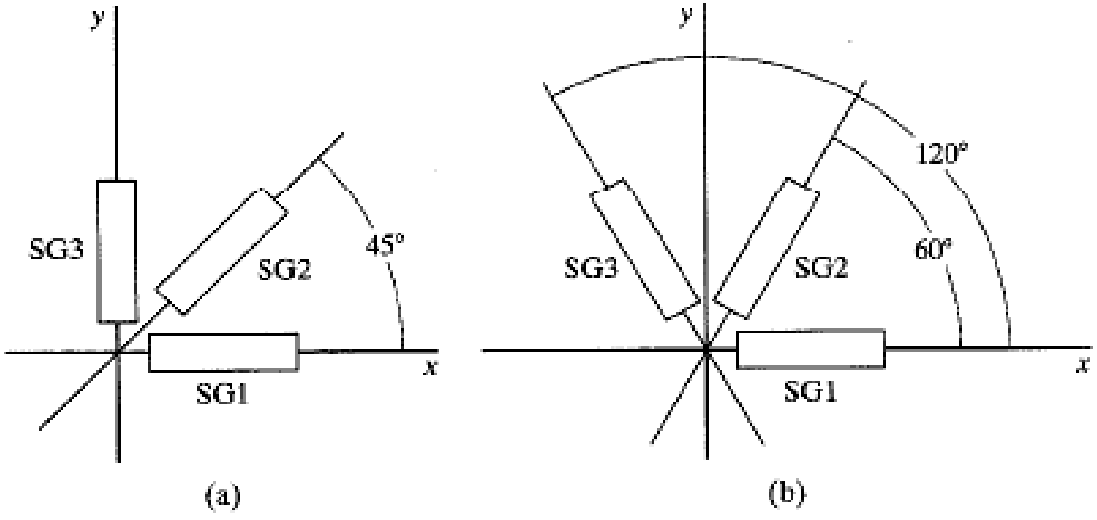


FIGURE 8.3

Orientation of strain gages in common rosettes: (a) rectangular; (b) equiangular.

Measuring Strain (Strain Gages)

- Each of these gages measure the linear strain in the direction of the axis of the gage.
- The rosette provides measurements of ε_{θ_1}, ε_{θ_2} and ε_{θ_3} . The values of ε_x, ε_y and γ_{xy} are obtained as follows.
- For rectangular rosette,

$$\varepsilon_x = \varepsilon_{0^o}$$

$$\varepsilon_y = \varepsilon_{90^o}$$

$$\gamma_{xy} = 2\varepsilon_{45^o} - \left(\varepsilon_{0^o} + \varepsilon_{90^o}\right)$$

- For equiangular rosette,

$$\varepsilon_x = \varepsilon_{0^o}$$

$$\varepsilon_y = \frac{2\varepsilon_{60^o} + 2\varepsilon_{120^o} - \varepsilon_{0^o}}{3}$$

$$\gamma_{xy} = \frac{2}{\sqrt{3}}\left(\varepsilon_{60^o} - \varepsilon_{120^0}\right)$$

Measuring Displacement

- Potentiometers are very common devices used to measure displacement. A linear potentiometer is used for linear measurements and an angular potentiometer is used for angular measurements.

- The linear potentiometer is a device in which the resistance varies as a function of the position of a slider, shown below.

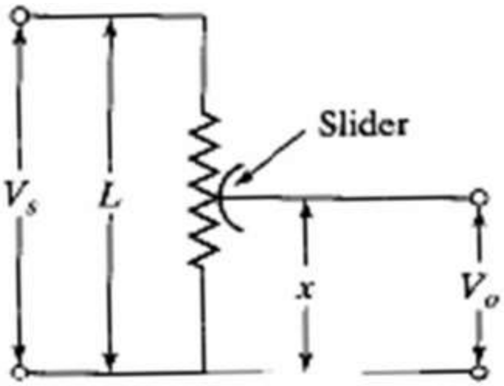


FIGURE 8.9
Linear potentiometer

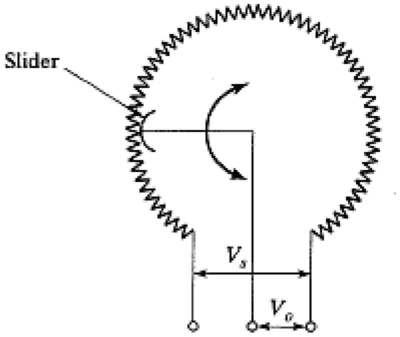


FIGURE 8.10
Angular potentiometer.

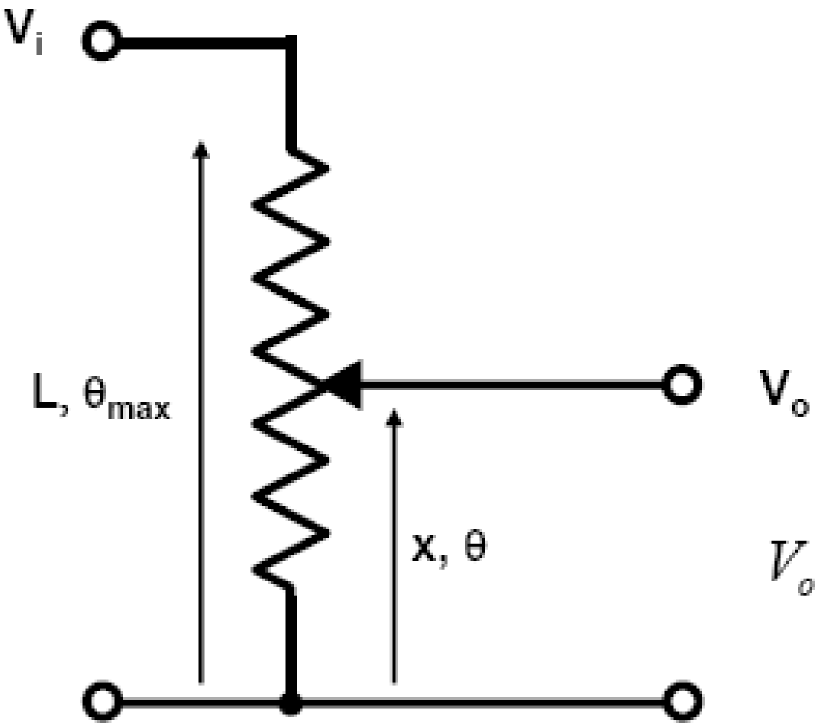
- With the supply voltage (*Vs*), the output voltage (*Vo*) will vary between zero and the supply voltage.

- For linear potentiometer, the output is a simple linear function of the slider position. That is

$$V_o = \frac{x}{L} V_s$$

Measuring Displacement

- Potentiometer



Issues:

- Noise
- Linearity
- Resolution
- Measurement range
- Lifetime
- Discrete steps

$$V_o = \frac{\theta}{\theta_{\max}} V_i$$

$$V_o = \frac{x}{L} V_i$$

- It should be noted that the device measuring *Vo* must have a high impedance to maintain a linear response and avoid loading error.

- Linear potentiometers can be used to measure displacements as small as 0.1 to 0.2 in. (2.5 to 5 mm) up to displacements of more than 1 ft.

Unit1: Electrical Resistance Strain Gauges

The strain gauges:

While there are several methods of measuring strain, the most common is with a strain gauge, a device whose electrical resistance varies in proportion to the amount of strain in the device.

The metallic strain gauge consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction (Figure 2).The cross sectional area of the grid is minimized to reduce the effect of shear strain and Poisson Strain. The grid is bonded to a thin backing, called the carrier, which is attached directly to the test specimen. Therefore, the strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in electrical resistance.

Strain gauges are used to measure the strain and to determine material stress in specimen, nature and amount of forces acting on the specimen etc. strain gauge can only perform its task properly if the strain to be measured is transferred faultlessly and free of loss.

Application of strain gauges:

- Experimental study of stress in transport vehicles.
- Experimental analysis of stress in structures and machines, apartments, building, pressure vessel, bridges, dams, towers etc.
- Experimental verification of theoretical analysis.
- Design and development of machines and structures.
- Assist failure analysis.
- As a sensing element in transducer for measurement of forces, load, pressure, displacement, torque etc

Strain Sensitivity in the Metallic Alloys

Lord Kelvin noted that the resistance of a wire increases with increasing strain and decreases with decreasing strain. The question then arises as to whether this change in resistance is due to the dimensional change in the wire under strain or to the change in resistivity of the wire with strain. It is possible to answer this question by performing a very simple analysis and comparing the results with experimental data which have been compiled on the characteristics of certain wire alloys. The analysis proceeds in the following manner:

The resistance R of a uniform conductor with a length L, cross sectional area A, and specific resistance $'\rho'$ is given by

$$R = \rho \frac{L}{A} = \frac{\rho L}{cD^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (1)$$

cD^2 is area of cross section of wire,A

Hence D is a sectional dimension and c is proportionality constant. For example, c=1 and $\frac{\pi}{4}$ for square and circular cross-section respectively.

Taking log on both side of eq (1)

$$\log R = \log \rho + \log L - \log c - 2\log D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

When the wire is strained axially, each of the variables in eq (2) may change. Differentiate eq (2)

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - 2\frac{dD}{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(a)$$

This can be written as

$$\frac{dR/R}{dL/L} = \frac{d\rho/\rho}{dL/L} + 1 - 2\frac{dD/D}{dL/L}$$

This can be written as

$$\frac{dR/R}{\in} = \frac{d\rho/\rho}{\in} + (1 + 2\vartheta)$$

$\in$ = strain in the wire

$\vartheta = \frac{\in_2}{\in_1} = -\frac{dD/D}{dL/L}$ = poisons ratio

This may be rewritten as

$$S_A = \frac{dR/R}{\in} = (1 + 2\vartheta) + \frac{d\rho/\rho}{\epsilon} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Where S_A is the sensitivity of the metallic alloy used in the conducer and is defined as the resistance change per unit of initial resistance divided by the applied strain.
Eq (3) shows that the strain sensitivity of any alloy is due to two factors, namely the change in the dimension of the conductor, as expressed by the term$(1 + 2\vartheta)$, and change in specific resistance, as represented by $\frac{(d\rho/\rho)}{\epsilon}$. Experimental results show that S_A varies from about -12.1 to 6.1 for metallic alloys. Since most metal materials have the Poisson's ratio around 0.25 to 0.35, the $(1 + 2\vartheta)$, term in the strain sensitivity factor S_A is expected to be 1.5 to 1.7.
The value of the strain sensitivity S_A will depend upon the degree of cold-working imparted to the conductor in its formation, the impurities in the alloy, and the range of strain over which the measurement of S_A is made.

The sensitivity factors of common strain gauge materials are listed in the following table.

Many of the electrical resistance strain gauges produced today are fabricated from the copper-nickel alloy know as advance. Although the sensitivity factor *S* is usually provided by the strain gauge vendors, engineers still need to choose the right gauge wire materials for their applications.

Material	Sensitivity (*S*)
Platinum (Pt 100%)	6.1
Nickel (Ni 100%)	-12.1
Silver (Ag 100%)	2.9
Copper (Cu 100%)	2.6
Isoelastic (Fe 55.5%, Ni 36% Cr 8%, Mn 0.5%) *	3.6
Constantan / Advance / Copel (Ni 45%, Cu 55%) *	2.1
Nichrome V (Ni 80%, Cr 20%) *	2.1
Karma (Ni 74%, Cr 20%, Al 3%, Fe 3%) *	2.0
Alloy 479(Pt 92%, W 8%)	4.0

- ***Constantan*** (Advance, Copel alloy) is the oldest and most widely used strain gauge materials.
  - It has a high enough electric resistivity (r = 0.49 mW·m) to achieve a proper resistance for a small gauge length.
  - It has a relatively low temperature induced strain in the temperature range of -30 to 193 ºC (-20 to 380 ºF). This material is thus considered to have self-temperature-

compensation.

- It has almost constant sensitivity across a wide range of strain.
- *Annealed Constantan* can even be used in the plastic region with strain > 5%.

But,

- The resistance of Constantan drifts continuously when the temperature rises above 65 ºC (150 ºF), which may become troublesome for strain measurements over a long period of time or in high temperature.

- ***Isoelastic*** alloy is suitable for *dynamic* strain measurement in vibration and impact.

- It has higher sensitivity (3.6 vs. 2.1 in Constantan), which improves the signal to noise ratio.
- It has higher resistance such that most Isoelastic strain gauges have resistance of 350W compared to 120 W in common Constantan strain gauges, which also increases the strain sensitivity.
- It has better fatigue properties among strain gauge materials.

But,

- Isoelastic does not have self-temperature-compensation property unlike Constantan or Karma.
- It is too sensitive to changes in temperature, so that it is not suitable for measurements which last a long period of time with temperature fluctuations.
- Sensitivity reduces from 3.1 to 2.5 when strain exceed 7,500 µ.

- ***Karma*** alloy has similar overall properties to Constantan.

- It has effective self-temperature-compensation property from -73 to 260 ºC (-100 to 500 ºF).
- It has higher cyclic strain resistance than Constantan.

But,

- It is more difficult to solder.

- Nichrome V, Armour D, and the Platinum based alloys are used for high temperature environment (> 230ºC; 450°F) or for other special purposes.

Gauge construction

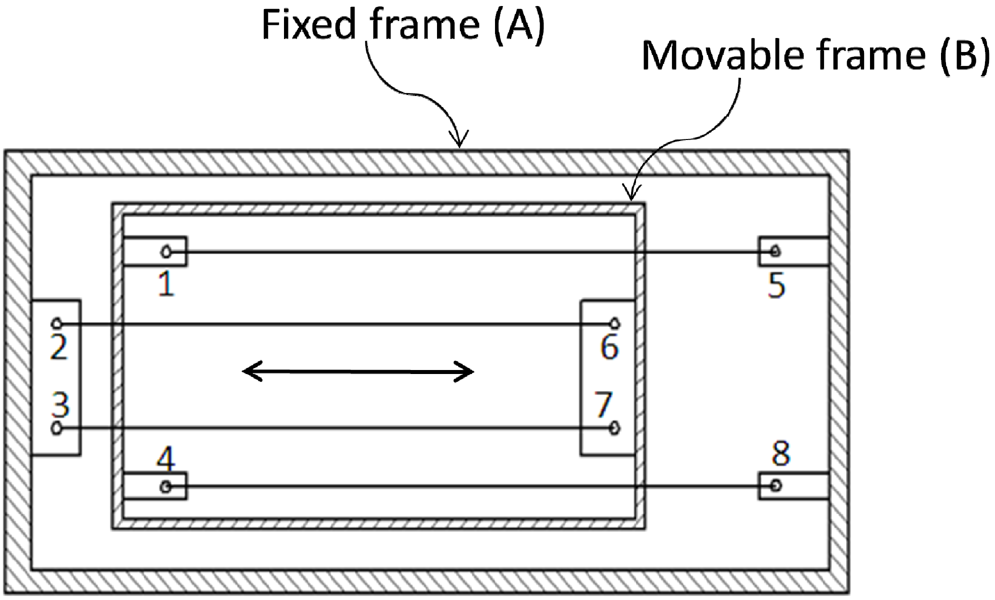
In the electrical resistance strain gauges the displacement or strain is measured as a function of the resistance change produced by the displacement in the gauging circuit. An ideal strain gauge should have the following basic characteristics:

1. The gauge should be of extremely small size so as to adequately estimate strain at a point.
2. The gauge should be of significant mass to permit the recording of dynamic strains.
3. The gauge should b easy to attach to the member being analyzed and easy to handle.
4. The strain sensitivity and accuracy of the gauge should be sufficiently high.
5. The gauge should be unaffected by temperature, vibration, humidity or other ambient conditions.
6. The calibration constant for the gauge should be stable over a wide range of temperature and time.
7. The gauge should be capable of indicating both static and dynamic strains.
8. It should be possible to read the gauge either on location or remotely.
9. The gauge should exhibit linear response to strain.
10. The gauge and the associated equipment should be available at a reasonable cost.
11. The gauge should be suitable for use as a sensing element or other transducer system.

It is theoretically possible to measure strain with, say, a single length of wire as the sensing element of the strain gauge. However, circuit requirements necessary to prevent overloading the power supply and the need to minimize gauge current place a lower limit on the gauge resistance of approximately 100Ω. For eg , with a strain gauge fabricated from wire 0.0001 in. in diameter with a resistance of 25 Ω/in. , it is clear that a 100 Ω gauge would require a single length of wire 4 in. in long. Since this gauge length is often undesirable, it is normally shortened considerably by forming a zigzag pattern with the wire at the expense of gauge width and induced cross sensitivity.

Construction details of four major classes, and the applications and advantages of each class will be discussed.

1. Unbounded Wire Strain Gauges:



The basic mechanism of unbounded stain gauge is illustrated in fig.

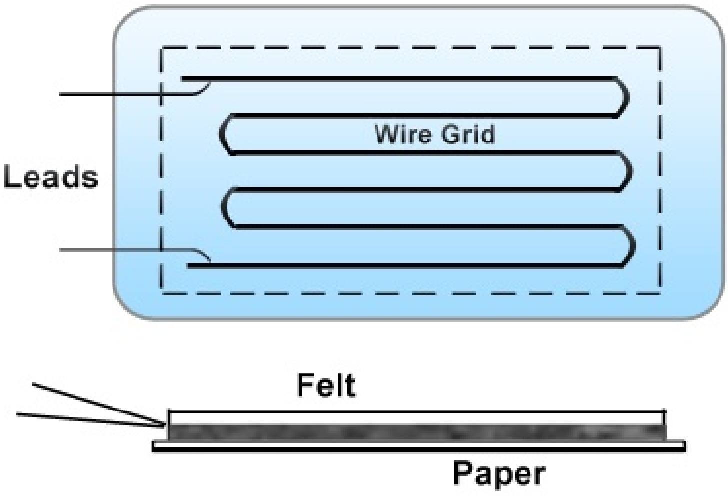
- Component parts A and B are both rigid frames; however, frames A is fixed and frame B is permitted to move in the direction indicated in the fig.
- In moving frame B, if the initial tension in wire 2-6 and 3-7 is increased, then the initial tension in wires 1-5 and 4-8 is reduced.
- These wires, which are fabricated from a strain sensitive material, represent four individual strain gauges.
- The movement of the frame B produces two positive changes in resistance and two negative changes.
- These four individual elements are connected in an appropriate fashion to a Wheatstone bridge circuit so that the resistance changes are added and the net output of the bridge is proportional to 4ΔR/R.
- Output voltages on the bridge are of the order of 40 mV full scale for an excitation voltage of 14 volts.

Applications:

a) Used in transducer application because of its excellent stability.
b) In rare occasion it is used in direct stress analysis because it is difficult to use than the bonded wire or foil strain gauge.
c) Transducers to measure acceleration, pressure, and force are commercially

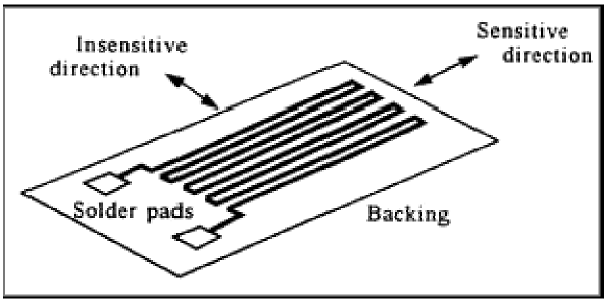
available with unbounded strain gauges employed as the sensing element.

2. Bonded wire strain gauges:



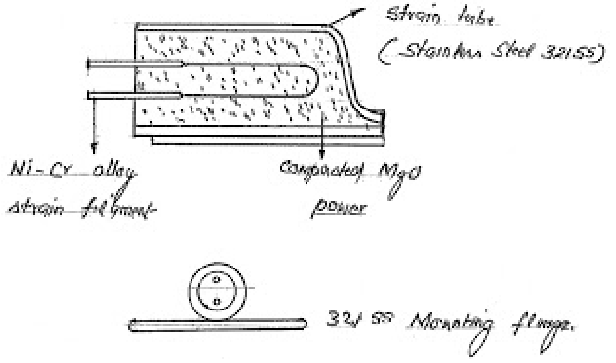
- The bonded metallic type of strain gauge consists of a strain sensitive conductor (wire) mounted on a small piece of paper or plastic backing.
- In us this gauge is cemented to the surface of the structural member to be tested.
- The wire grid may be & flat type or wrap-around.
- In the flat type after attaching the lead wires to the ends of the grids, a second piece of paper is cemented over the wire as cover.
- In the wrap-around type, the wire is wound around a cylindrical core in the form of a close wound helix. This core is then flattened & cemented between layers of paper for the purpose of protection and insulation.
- Formerly only wrap-around gauges were available, but generally flat grid gauges are preferred as they are superior to wrap-around gauge in terms of hysteresis, creep, elevated temperature, performance, stability & current carrying capacity.
- The two layer of wire and three layer of paper result in a gauge which is approximately 0.006in. thick. The backing material which carry the wire grid, protect it from damage.

3. Metal Foil Strain Gauges:



- The foil type of strain gauges has a foil grid made up of thin strain sensitive foil.
- The width of the foil is very large as compared to the thickness (microns) so that larger area of the gauge is for cementing.
- Currently the gauges are so thin (about 150μin.) that they are often referred to as metal-film gauges. It is significant but proprietary developments have been made in highly refined photo-etching process used to form the grid configurations.
- The result of these manufacturing improvements is a gauge which has better tolerances on both the gauge factor and the initial resistance.
- The metal film or foil gauges are usually mounted on a thin epoxy carrier which is approximately 0.001 in. thick and extremely flexible.
- It is mounted on to a specimen with a suitable adhesive to give a strain-measuring gauge in intimate contact with the surface of the specimen.
- The metal-film strain gauges are available in gauge lengths ranging from 1/64 to 1 in. and which range from 60 to 1,000 Ω.

4. Weld able Strain Gauges:



- Weld able strain gauges are easy to install in minutes in any environment compared to bonded type strain gauge.
- The weld able strain gauge consists of a strain sensitive element, the nickel Chromium or platinum Tungsten, housed within a small diameter stainless steel tube.
- The strain element is insulated from the tube with highly compacted ceramic insulation.
- This gauge is subsequently spot welded to structure under test and provides bonding to transfer the strain.
- The test specimen which is put into tension or compression, the stress is transmitted through the weld to mounting flange and in to strain tube. These gauges can be used for static or dynamic applications.
- The wire inside the case is reduced in diameter by an etching process; hence the minimum gauge resistance is obtained with very small-diameter high resistance wire rather than by forming a grid of larger-diameter wire.
- At present these weld able gauges are available with resistance ranging from 60 to 240 Ω and length of 9/16 to 1 5/32 in. they are suitable for use in the range from -390 to 750^0 F.

Adhesives:

The bondable strain gauges are attached to the test specimen by some form of cement or adhesives. A number of bonding cements are available which require various detailed techniques for their use. The following are the desirable characteristics of the bonding cements:

- High mechanical strength
- High creep resistance
- High dielectric strength
- Minimum temperature resistance
- Good adherence giving shear strength of 10.5 to 14N/mm^2
- Minimum moisture absorption
- Ease of application.
- Low setting time.

a) Nitro-Cellulose cement:

- Nitro-Cellulose cement is commonly used to mount paper-backed gauges.
- Since these cements contain a very large fraction of solvent (about 85%), the bonded gauge should be cured to remove all the solvents by evaporation.
- The curing time varies with the percentage of solvent, relative humidity, curing temperature and also the purpose for which the gauge is used.

- For short-time tests using thin paper gauges, curing at room temperature for several hours may sufficient. The curing time for wrap around gauges is 5 to 10 times longer than for flat-grid gauges.
- In case of long term test stability is an important requirement; a ten day room temperature cure may be required. This time can be reduced to day or two day by circulating air at about 55^{o}C over the gauge installation.
- As nitro-Cellulose cement is hydroscopic, the cured gauge should be immediately protected by a moisture resistance coating. This will ensure electrical and dimensional stability of the gauge installation.

b) Epoxy cement:

- Two types of epoxy cements-room-temperature epoxies and thermosetting epoxies-are commonly used.
- Both types have two constituents a monometer and a hardening agent. Mixing of a monomer with the hardening agent induces polymerization.
- Room temperature epoxies use amine-type hardening agent while thermosetting epoxies require anhydride type of hardening agent.
- In case of room temperature epoxy polymerization takes place at room temperature or at a temperature slightly above room temperature.
- Thermosetting epoxies need at a curing temperature in excess of 120^{o}C for several hours for complete polymerization
- Organic fillers in moderate quantities are added to improve the adhesive strength and to reduce the coefficient o expansion of the epoxy.
- A clamping pressure of 35 to 140 kPa during the curing period ensures a thin adhesive layer or bond line in case of epoxy cements.
- Epoxy cements resists moisture and chemicals and are useful for test temperatures in the range -230^{o}C to 300^{o}C.

c) Cyanoacrylate Cement:

- Cyanoacrylate cement cures rapidly at room temperature.
- It is an excellent general-purpose adhesive for laboratory and short-term field applications.
- It is compatible with most of the test materials and strain gauge backing materials.
- A firm thumb pressure for about a minute is sufficient to induce polymerization at room temperature.

- A strain gauge bonded with this adhesive can be used approximately 10 min after bonding.
- When protected with coating like microcrystalline wax or silicone rubber, the life of the strain gauge bonded with this adhesive can be extended to 1 or 2 years.
- The typical operative temperature range for this adhesive is -75^o to 65^{o}C.

d) Phenolic Adhesives:

- Phenolics are single component thermosetting adhesives requiring curing at an elevated temperature of 120^o to 175^{o}C for fairly long period.
- In most applications these adhesives have been replaced by epoxy-phenolic adhesives.
- However, phenolic adhesives are still attractive for transducer applications as they provide long-term stability under load.
- In short time tests phenolic bonded gauges can be used upto a temperature of 260^{o}C.

e) Ceramic cements:

- Ceramic cements are used for bonding high temperature strain gauges.
- One such cement consists of ceramic powders such as silica or alumina combined with a phosphoric acid.
- These powders are mixed with a solvent to form a liquid mixture. A bush is used to apply a thin layer of this liquid mixture to the test surface.
- The gauge installation is cured at 300^{o}C and used over a temperature range of -235^o to 500^{o}C.
- Flame spayed adhesives can be used over a wide temperature range of -235^o to 800^{o}C.
- They are hygroscopic and have poor insulation resistance at high temperatures.
- Gauge bonded this way function satisfactorily in vacuum and in a nuclear-radiation environment.

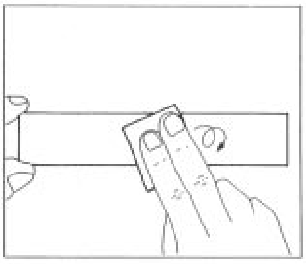
Mounting Technique:

The strain-gauge bonding method differs depending on the type of the strain gauge, the applied adhesive and operating environment. Here, for the purpose of strain measurement at normal temperatures in a room, we show how to bond a typical lead wire-equipped KFG gauge to a mild steel specimen using CC-33A quick-curing cyanoacrylate adhesive.

(1) Select strain gauge:

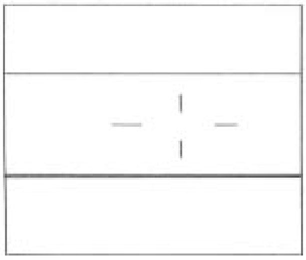
Select the strain gauge model and gauge length which meets the requirements of the measuring object and purpose.

(2) Remove dust and paint:



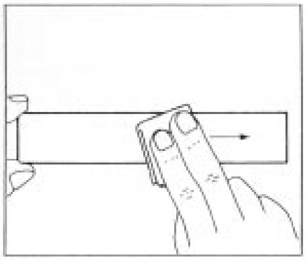
Using a sand cloth (#200 to 300), polish the strain-gauge bonding site over a wider area than the strain-gauge size. Wipe off paint, rust and plating, if any, with a grinder or sand blast before polishing.

(3) Decide bonding position:



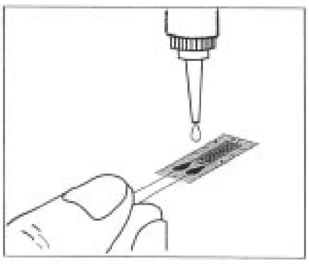
Using pencils or a marking-off pin, mark the measuring site in the strain direction. When using a marking-off pin, take care not to deeply scratch the strain-gauge bonding surface.

(4) Remove grease from bonding surface and clean:



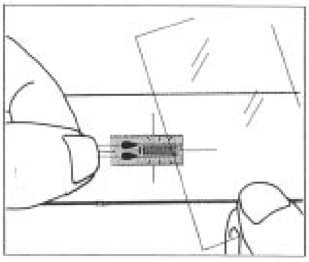
Using an industrial tissue paper (SILBON paper) dipped in acetone, clean the strain-gauge bonding site. Strongly wipe the surface in a single direction to collect dust and then remove by wiping in the same direction. A reciprocal wiping cause dust to move back and forth and does not ensure cleaning.

(5) Apply adhesive:



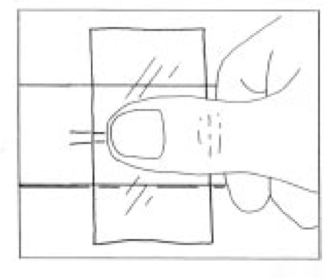
Ascertain the back and front of the strain gauge. Apply a drop of CC- 33A adhesive to the back of the strain gauge. Do not spread the adhesive. If spreading occurs, curing is adversely accelerated, thereby lowering the adhesive strength.

(6) Bond strain gauge to measuring site:



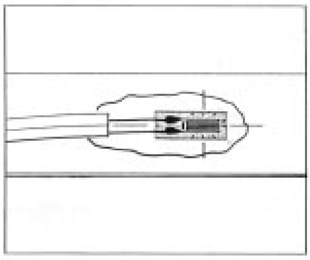
After applying a drop of the adhesive, put the strain gauge on the measuring site while lining up the center marks with the marking-off lines.

(7) Press strain gauge:



Cover the strain gauge with the accessory polyethylene sheet and press it over the sheet with a thumb. Quickly perform steps (5) to (7) as a series of actions. Once the strain gauge is placed on the bonding site, do not lift it to adjust the position. The adhesive strength will be extremely lowered.

(8) Complete bonding work:



After pressing the strain gauge with a thumb for one minute or so, remove the polyethylene sheet and make sure the strain gauge is securely bonded. The above steps complete the bonding work. However, good measurement results are available after60 minutes of complete curing of the adhesive.

Gauge Sensitivity and Gauge Factor:

The strain sensitivity of a single uniform length of a conductor was previously defined as

$$S_A = \frac{dR/R}{\in} \approx \frac{\Delta R/R}{\in} \dots\dots\dots\dots\dots..(1)$$

Here $\in$ is a uniform strain along the conductor and in the direction of the conductor. This sensitivity S_A is a function of the alloy employed to fabricate the conductor. Whenever the conductor, say a wire, is wound into a strain-gauge grid, however, certain effects take place which alter to a certain degree this value of sensitivity assigned to the gauge. The change is introduced by the end loops, which are at right angles to the straight portion of the grid. If the gauge is in a biaxial strain field, the loops will register a resistance change proportional to the cross strain.

Axial strain sensitivity:

$S_{||} = \frac{\Delta R/R}{\epsilon_{xx}}$ When $\epsilon_{yy} = 0$

In this case the gauge is directed along the x axis, and the state of strain is such that $\epsilon_{yy} = 0$

Normal strain sensitivity:

$S_{+} = \frac{\Delta R/R}{\epsilon_{yy}}$ When $\epsilon_{xx} = 0$

Here the gauge is again directed along the x axis, and the state of strain uniaxial with the strain acting normal to the axis of the gauge.

Gauge factor:

$F = S_g = \frac{\Delta R/R}{\epsilon_{xx}}$ When $\epsilon_{yy} = -0.285\,\epsilon_{xx}$

This definition gives the sensitivity provided by the manufacturer of the gauge and indicates the calibration procedure. A gauge is mounted parallel to the x axis, and the specimen is subjected to a uniaxial stressσ_{xx}. This uniaxial stress gives rise to the biaxial state of surface strain defined above. The sensitivity determined in this calibration process is called the gauge factor, which is used as the scaling factor to convert resistance change to strain. If the gauge factor is used to convert resistance change to strain in any strain field other than the one in which S_g was determined, an error will result. It is possible to correct any error resulting from the cross sensitivity of the gauge; however, the development of the correction procedure requires one further definition, namely, the cross sensitivity factor K.

Cross sensitivity factor:

$$K = \frac{S_{+}}{S_{||}} = \frac{\frac{\Delta R/R}{\epsilon_{yy}}}{\frac{\Delta R/R}{\epsilon_{xx}}}$$

It is possible to determine the cross-sensitivity factor K for a flat grid gauge from geometric consideration alone.

Parameters Influencing the Behavior of Strain Gauge:

Electrical resistance strain gauges are manufactured with a gauge factor accurate to ± 0.5% and a resistance accurate to about ± 0.2%. But during experimental analysis, several parameters can influence the behavior of the gauge and affect its accuracy. The successful application of electrical resistance strain gauges demands a thorough knowledge of all these parameters such as adhesive, strain cycles, heat dissipation, time, humidity, moisture, hydrostatic pressure, etc.

Sample preparation:

The wire or a foil type strain gauge is mounted on a specimen with an adhesive which serves the vital function of transmitting the strain from the specimen to the gauge sensing element without distortion. While employing the adhesive, it is essential that the surface of the specimen be properly prepared and absolutely clean. Any paint or oxide film on the surface of the specimen is removed by sanding. The surface is then thoroughly degreased by scrubbing it with acetone. At the same time, the bottom side of the gauge is cleaned with acetone just prior to its placement. After the gauge is installed, the adhesive must be exposed to proper combination of pressure and temperature for a suitable length of time to ensure complete cure.

The curing process is quite complicated since adhesive expands because of heat, experience a reduction in volume due to polymerization, exhibits a contraction upon cooling, and many a times indicates a posture shrinkage. Since the adhesive is sufficiently strong to control the deformation of the strain sensitive element in the gauge, any residual stress set up in the adhesive will influence the output from the strain gauge.

Adhesives:

Cellulose nitrate: it consists of 85% solvent and 15% solids; therefore an appreciable amount of solvent is to be removed by evaporation. By placing a strain gauge component in an air circulating oven at 130 F, the time required for curing is appreciably shortened and complete cure can be affected in a day or two. Once the gauge is completely dried, it must be immediately water proofed otherwise the cellulose nitrate cement will began to absorb moisture from the atmosphere and it will expand. This expansion can materially influence the gauge reading if the readout period is long.

Phonelic cement: it is cure by a combination of pressure and heat over a given interval of time. Phonelic, a combination of pheonol and formaldehyde during curing, release water as a by-product and it is necessary that this water be removed and any porosity produced as a result of the formation of water vapors must be avoided. Curing at 180 F for 12 hour at 7 to 14 kg/cm^2 pressure will be accomplishing this task.

Epoxy cement: it consists of a monometer and a hardening agent which induces polymerization. It is a thermosetting plastic and exhibits higher bond strength.

The amount of hardener added to the monometer is extremely important because the heat distortion temperatures and residual stress produced during polymerization can be materially influenced by a slight variation from the specific value. a filler material such as aluminum oxide 5% to 10% by weight is often beneficial since it improves the bond strength and reduces temperature coefficient of expansion of epoxy.

Cynoacrylate cement: it is quite unusual in that it requires neither heat nor catalyst to induce polymerization. The minute trace of water or any other weak bases on the surface of the component are sufficient to trigger the process of polymerization. The shelf life of this adhesive is very short, i.e. 2 to 3 months only. It must be stored at low temperature at 35-45^{o}F.

Ceramic cement: it consists of a blend of finely ground ceramic powder such as alumina and silica combined with phosphoric acid. This blend is mixed with a solvent such as isopropyl alcohol and an organic binder to form a liquid mixture. A precoat of ceramic cement is applied on specimen and fired so as to form a thin layer of insulation between gauge grid and specimen. A second layer of ceramic cement is than applied to bond the gauge element.

Strain cycles:

When a strain gauge is subjected to strain cycles, then for the first few cycles, the gauge sensing element is often cold worked and hysteresis and zero shift effects are evident. The cold working induces resistivity changes in the gauge alloy and due to hysteresis, the gauge output deviates from a linear relationship with the applied strain.

The hysteresis and zero shifts reduce to very normal values if the gauge is cycled five to six times before it is used to record the strain. This strain cycling stabilizes the gauge and improved the accuracy of the strain measuring system to a considerable extent.

After many thousands or millions of cycles, the gauge begins to fail in fatigue and incorrect readings are obtained. In general, foil gauge is more satisfactory than wire type gauge for fatigue applications because foil gauges withstand a large number of cycles before failure. For wire gauges, the point of failure usually is located at the joint between the heavy lead wire and the fine strain sensitive wire. To avoid this failure, gauges with duel loads are employed. Failure in the case of a foil gauge is not abrupt. Instead, a crack usually initiates in the foil near the solder terminal on the tab and slowly propagates across the width of the conductor until the circuit opens.

Cross – sensitivity:

Because a strain gauge has width as well as length, a small proportion of the resistance element lies at right angles to the major axis of the gauge, at the points where the conductor reverses direction at the ends of the gauge. So as well as responding to strain in the direction of its major axis, the gauge will also be somewhat responsive to any strain there may be at right angles to major axis.

Heat dissipation:

The temperature variation can significantly influence the output of strain gauges, particularly of those which are not temperature compensated. The temperature of the gauge is of course influenced by the ambient temperature variations and by power dissipation in the gauge in the form of heat when it is connected into a Wheatstone bridge or a potentiometer circuit. The dissipated heat depends upon voltage applied to the gauge and the gauge resistance.

P, power dissipated=$\frac{V^2}{R} = I^2R$

Where P= power in watts, W,

I= gauge current, Amperes, A,

R=gauge resistance, ohms, and

V=voltage across the gauge in volts.

There are number of factors such as gauge size, gauge configuration, material of specimen, type of adhesive, etc. which govern the heat dissipation.

Power density,$P_D = \frac{P}{A} = \frac{Power}{Area\ of\ the\ grid\ of\ the\ gage}$

Power densities which can be tolerated by a gauge are strongly related to the specimen which serves as the heat sink. For thin steel sections, power densities 0.0015 to 0.003 W/mm^2 are allowable. In other words for a strain gauge of 120 Ω resistance, 10mm gauge length, the current should be limited to 20-30mA.

Moisture and Humidity:

The gauges or the bonding adhesive may absorb water. The moisture decreases the gauge to ground resistance, degrades the strength and rigidity of the bond, and thus reduces the effectiveness of the adhesive. Moreover, the presence of water in the adhesive cause's electrolysis when current passes through the gauge and gauge filament gets ended. This can cause dimensional changes which appear as false strain values. Another effect when moisture connections forms high resistance connected in parallel with the gauge. To prevent this, gauges should be bonded in dry condition or suitable electrically insulating water repellent, such as a silicone rubber compound.

Hydrostatic pressure:

In applications like pressure vessels, the normal pressure will produce a small change in resistance of the gauge due to change in resistivity co-efficient due to pressure. The bubbles in the adhesive cannot be tolerated because the hydrostatic pressure will force the sensing element into any void beneath the gauge and erroneous resistance changes will be recorded.

Dummy gauge required for temperature compensation should not be placed in the pressure vessel but it should be mounted on a small block of material from which the pressure vessel is fabricated.

Magnetic field:

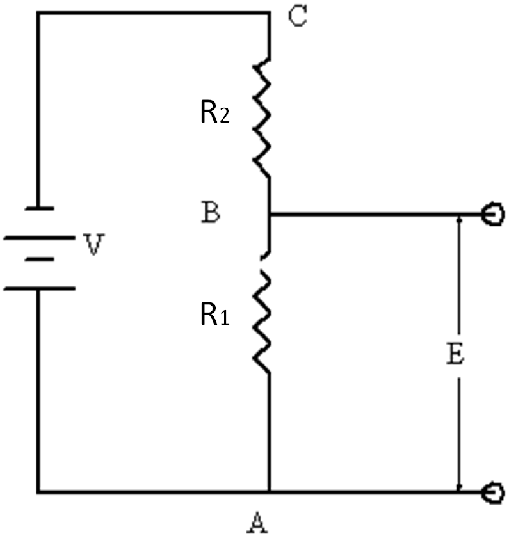
If a strain gauge is installed on or near electrical equipment producing relatively high magnetic fields then output from the gauge is affected in many ways. When the gauge is in motion it may cut flux lines and current will be generated affecting the gauge output. Isoelastic alloy is magnetostrictive, i.e. the dimensions of the alloy change in relation to the strength of the magnetic field. If a gauge fabricated from this alloy is employed in proximity to magnetic field, significant errors can result.

Time:

Sometimes the readout period of output from a strain gauge is very long, i.e. several months or even years, and the specimens cannot be unloaded to determine the error due to zero drift. During this long readout period, all the factors which can influence the behavior of the strain gauge get an opportunity to do so and the error developed due to each of the factors can be considerable.

Potentiometer circuit:

The potentiometer circuit is well suited for dynamic strain measurements. An attractive feature of this circuit is its extreme simplicity. The increment of the open-circuit voltage ΔE of the potentiometer circuit can be derived as follows:



When the resistances in the circuit are R_1 and R_2 the open-circuit voltage E across AB is

$$E = V \cdot \frac{R_1}{R_1+R_2} = V \cdot \frac{1}{1+m} \ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where m=R_2/R_1 and V is the excitation voltage. If resistance R_1 and R_2 change by incremental amounts ΔR_1 and ΔR_2 respectively,

$$E+\Delta E= V \cdot \frac{R_1+\Delta R_1}{R_1+\Delta R_1+R_2+\Delta R_2} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

From (1) - (2)

$$\Delta E= V \cdot \left(\frac{R_1+\Delta R_1}{R_1+\Delta R_1+R_2+\Delta R_2} - \frac{R_1}{R_1+R_2}\right) \ldots\ldots\ldots\ldots (a)$$

On simplification

$$\Delta E= \frac{\frac{m}{(1+m)^2}\left(\frac{\Delta R_1}{R_1}-\frac{\Delta R_2}{R_2}\right)}{1+\frac{1}{1+m}\left[\frac{\Delta R_1}{R_1}+m\frac{\Delta R_2}{R_2}\right]} \cdot V \ldots\ldots\ldots\ldots\ldots.. (3)$$

or

$$\Delta E= V \frac{m}{(1+m)^2}\left(\frac{\Delta R_1}{R_1}-\frac{\Delta R_2}{R_2}\right)(1-\eta) \ldots\ldots.. (4)$$

Where nonlinear term η is

$$\eta = 1 - \frac{1}{1+\frac{1}{1+m}\left[\frac{\Delta R_1}{R_1}+m\frac{\Delta R_2}{R_2}\right]} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The error due to nonlinearity of the circuit can be estimated with R_1 as the resistance due to a strain gauge, R_2 as a resistor of fixed resistance and ΔR_1 as the change in the resistance of the gauge due to a strain$\in$,

$$\eta = 1 - \frac{1}{1+\left[\frac{\Delta R_1}{R_1} \cdot \frac{1}{1+m}\right]} \text{ ….. (6)}$$

$$\eta = 1 - \frac{1}{1+\left[F\in\frac{1}{1+m}\right]} \text{………….. (7)}$$

It is seen that the nonlinear term is dependent on the magnitude of strain$\in$, gauge factor F and the ratio m=R_2/R_1. Hence in most strain measurements, the nonlinearity term η can be neglected and ΔE can be determined from

$$\Delta E = V\frac{m}{(1+m)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2}\right) \text{…….. (8)}$$

However, if high accuracy in strain measurement is required or large strains are to be measured, the output signal determined through eq (8) can be corrected for the error due to nonlinearity.

The output signal per unit strain or the circuit sensitivity S_v of the potentiometer circuit is given by

$$S_v = \frac{\Delta E}{\in} = \frac{V}{\in}\frac{m}{(1+m)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2}\right) \text{…… (9)}$$

With an active strain gauge R_1 and fixed-ballast resistorR_2,

$$S_v = \frac{V}{\in} \cdot \frac{m}{(1+m)^2} \cdot \left(\frac{\Delta R_1}{R_1}\right) = F \cdot V \cdot \frac{m}{(1+m)^2} \text{……… (10)}$$

Thus the circuit sensitivity of the potentiometer circuit is dependent on the voltage V and ratio m=R_2/R_1. The sensitivity S_v is limited by the maximum power P_g that can dissipated by the gauge without unfavorable effects on its performance. As power dissipated in the gauge is equal to I^2R_g.By Ohm's law relationship between V and I is given by

$$V = I_gR_g(1+m) \text{…….. (11)}$$

Substituting this value of V in eq 10

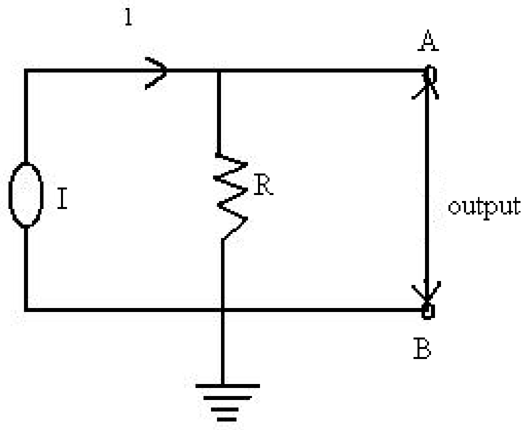
$$S_v = F \cdot \sqrt{P_gR_g} \cdot \frac{m}{(1+m)} \text{………………. (12)}$$

Thus as in the case of the Wheatstone bridge circuit, the circuit sensitivity of the potentiometer circuit is dependent on $m/(1+m)$ and $F \cdot \sqrt{P_gR_g}$. The term $m/(1+m)$ is depend on the design of the circuit or on the ratio R_2/R_1 .the term $F \cdot \sqrt{P_gR_g}$ is entirely depend on the characteristic of the strain gauge it may be noted that the circuit sensitivity, S_v in practice is quite low; it is often of the order 5 to 10µV per micro strain.

Constant Current Potentiometer Circuits:

The potentiometer circuit described in the previous sections has a constant voltage source. In such circuits the error due to nonlinear effects is significant if the change in the resistance $\Delta R/R$ is large. As semiconductor gauges have a very large gauge factor, about 50 to 70 times that of metallic strain gauges, the change in their resistance $\Delta R/R$ is large even at relative low strain levels. Hence constant voltage potentiometer circuit is not well-suited for use with semiconductor gauges. Special constant current circuits have been developed for use with semiconductor gauges.

(a) Constant current potentiometer circuit:



A constant current potentiometer circuit is shown in fig above. Hence the current supplied by the source remains constant while the resistance R changes from R to R+ΔR.the open-circuit voltage across AB is

$$E = I(R)\ldots\ldots(1)$$

When resistance R changes to R+ΔR, the output voltage is

$$E + \Delta E = I(R + \Delta R)\ldots\ldots\ldots..(2)$$

Hence the change in output voltage ΔE corresponding to the change in resistance ΔR is, from eq 1 and 2

$\Delta E = I \cdot \Delta R = I \cdot \frac{\Delta R}{R} \cdot R$…………..(3)

If $R = R_g$ is the resistance of a strain gauge with gauge factor F, and ΔR_g is the change in resistance corresponding to strain ε,

$\Delta E = I_g R_g F$ ε…………(4)

It is seen from eq 3 and 4 that the relationship between the output voltage ΔE and the change in resistance ΔR_g or strain ε is linear. The circuit sensitivity S_v is

$S_v = I_g R_g F$….. (5)

By increasing the gauge current I_g to the maximum value dictated by power-dissipation considerations, the circuit sensitivity can be maximized. Thus

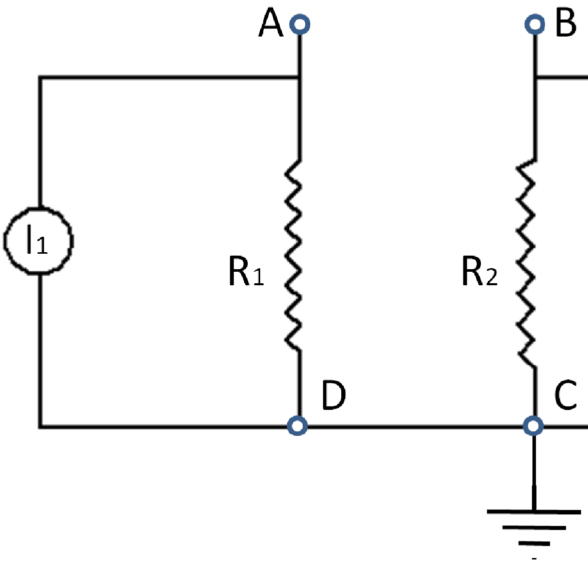
$S_v = I_g R_g F = \sqrt{P_g R_g} \cdot F$…………(6)

Where the power dissipation in the strain gauge $P = {I_g}^2 R_g$. Thus by proper selection of the strain gauge, i.e. proper choice of gauge with appropriate P, F and R_g, the desired circuit sensitivity can be achieved.

As in a constant –voltage potentiometer circuit, an R-C filter is required to eliminate the static component E in the output signal$\mathrm{E} + \Delta E$. Thus the simple constant current potentiometer circuit is only suitable for dynamic strain measurements.

However through the use of a double-constant-current potentiometer circuit, both static and dynamic strain can be measured. In such a circuit temperature compensation can be effected through the use of an additional dummy/ active gauge.

(b)**Double constant current potentiometer circuit:**



In a double-constant-current potentiometer circuit two constant-current genetrators are used as shown in fig . the terminals C and D of the circuit are earthed. The output voltage is mesured across points A and B. with currents I_1 and I_2 passing through the resistance R_1 and R_2 respectively, the potentials at points A and B are

$V_A = I_1R_1$ *and* $V_B = I_2R_2$……………. (1)

The output voltage across AB is then

$E = V_A - V_B = I_1R_1 - I_2R_2$………………… (2)

If the circuit is balanced initially, i.e. E=0, then

$I_1R_1 - I_2R_2 = 0$ *or* $I_1R_1 = I_2R_2$ …………….. (3)

Let the resistances R_1 and R_2 change by ΔR_1 and ΔR_2 respectively. The output voltage across AB is given by

$E + \Delta E = I_1(R_1 + \Delta R_1) - I_2(R_2 + \Delta R_2)$ ……. (4)

In an initially balaced circuit, E=0 and $I_1R_1 = I_2R_2$. Substituteing these in eq.(4)

$$\Delta E = I_1\Delta R_1 - I_2\Delta R_2 = I_1R_1\frac{\Delta R_1}{R_1} - I_2R_2\frac{\Delta R_2}{R_2}$$

$$\Delta E = I_1R_1\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2}\right) \text{……..(5)}$$

A study of eq 5 shows that the output voltage ΔE varies linearly with changes ΔR_1 and ΔR_2 of resistance R_1 and R_2 respectively, i.e., $R_1 = R_2 = R_g$. The output voltage ΔE will be given by

$$\Delta E = I_gR_g\left(\frac{\Delta R_1}{R_1}\right) = I_gR_gF\,\epsilon \text{……..(6)}$$

The circuit sensitivity with gauge current set equal to the limiting value corresspronding to the strain gauge used is

$S_v = \Delta E/\in = I_g R_g F = \sqrt{P_g R_g} \cdot F$……..(7)

Where the power dissipation in the strain gauge is $P = {I_g}^2 R_g$. Thus the circuit sensitivity with one active gauge in the double-constant-current potentiometer circuit is the same as for a constant –current potentiometer circuit.

When the both the gauges placed in positions of resistance R_1 and R_2 are active and the strains in these gagues are equal but of opposite sign, the output voltage ΔE is from eq (5)

$\Delta E = 2 I_g R_g \frac{\Delta R_1}{R_1} = 2\sqrt{P_g R_g} \cdot F \in$…………(8)

The corresponding circuit sensitivity is

$S_v = 2 I_g R_g F = 2\sqrt{P_g R_g} \cdot F$…….(9)

Thus when both gauges are active, the circuit sensitivity is doubled.

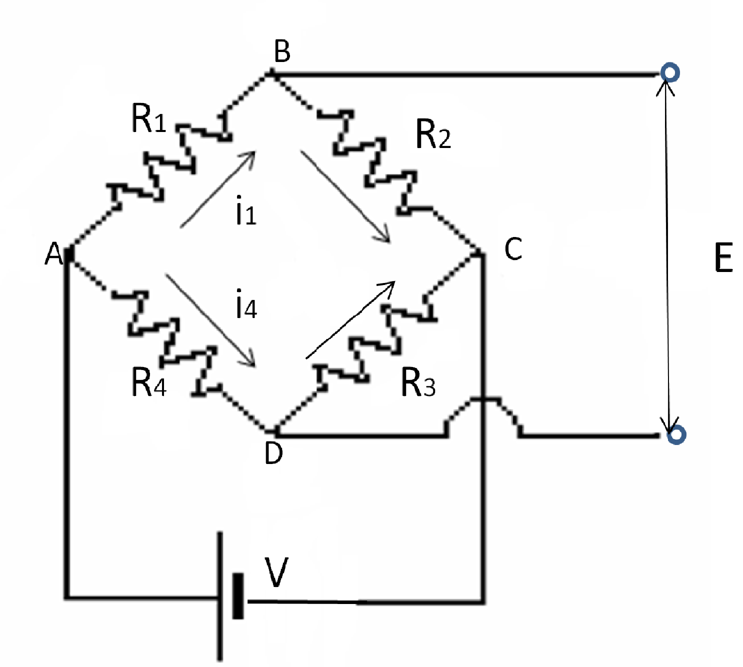
The main feature of the double constant current potentiometer circuit are:

I. It is well-suited for use with semicondutor gauges as the output voltage ΔE varies linearly with the resistance change $\Delta R/R$.
II. It is suitable for measurement of both static and dynamic strains.
III. Temprature compensation can be achived through the use of additional dummy/ active gauges.
IV. The circuit is suittable for use with transducers using multiple gagues.
V. As in conventional potentiometer circuit the circuit can be grounded, a relatively high signal-to-noise ratio can be achived.
VI. The constant current source should be of high quality.this reqirement increases the cost of this rather simple circuit.

Wheatstone bridge:

A dc wheatstone bridge consisting of four resistance arms with a battery and a meter is shown in fig below. In this bridge the resistance shown in each of the four arms of the bridge can represent a strain gauge. A voltage V is applied to the bridge.some mesureing instruments such as galvonometer is used to measure the output of the bridge.

The reqirements for balance, i.e. zero potential difference E between points B and D can be determined as follows:



The voltage drop V_{AB} across R_1 is

$$V_{AB} = i_1 R_1 = \frac{V}{R_1+R_2} \cdot R_1 \ldots\ldots\ldots\ldots\ldots\ldots(a)$$

Similarly, the voltage drop V_{AB} across R_4 is

$$V_{AD} = i_4 R_4 = \frac{V}{R_3+R_4} \cdot R_4 \ldots\ldots\ldots\ldots\ldots\ldots(b)$$

The potential differnce between B and D, V_{BD}, is

$$V_{BD} = V_{AB} - V_{AD} = E \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(c)$$

On substituteing of eq (a) and (b) in (c), we get

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

$$E = V\left(\frac{R_1R_3 - R_2R_4}{(R_1+R_2)(R_3+R_4)}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The condetion for balance is that the voltage E should be zero, i.e. the numerator in eq 1 should be zero

$$R_1R_3 = R_2R_4 \ldots\ldots\ldots(2)$$

$$\frac{R_1}{R_2} = \frac{R_4}{R_3} \ldots\ldots(2a)$$

Or

$\frac{R_1}{R_4} = \frac{R_2}{R_3}$……..(2b)

Eq (2a) and (2b) gives the condetion for the wheatstone bridge to balance-the ratio of resistance of any two adjacent arms of the bridge must be equal to the ratio of the resistance of the remaining two arms taken in the same order.

Then change the resistance R_1 by an amount ΔR_1. As the bridge willl then be unbalanced, a voltage ΔE will be prodused between B and D which can be measured with a suitable meter. An expression for ΔE is derived as follows:

As the bridge is initially balanced, from eq.2b

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

when the bridge is unbalanced due to R_1 changing from R_1 to $R_1 + \Delta R_1$, the voltage ΔE across B and D is form eq 1

$\Delta E = V\left(\frac{(R_1+\Delta R_1)R_3 - R_2R_4}{(R_1+\Delta R_1+R_2)(R_3+R_4)}\right)$ …..(3a)

Divideing both numrator and denominator on the R.H.S. of Eq. (3a) by R_1R_3 and noting that $R_1R_3 = R_2R_4$, we get

$$\Delta E = V \cdot \frac{\left(1+\frac{\Delta R_1}{R_1}\right) - \frac{R_2R_4}{R_1R_3}}{\left(1+\frac{\Delta R_1}{R_1}+\frac{R_2}{R_1}\right)\left(1+\frac{R_4}{R_3}\right)}$$

$\Delta E = V \cdot \frac{\frac{\Delta R_1}{R_1}}{\left(1+\frac{\Delta R_1}{R_1}+\frac{R_2}{R_1}\right)\left(1+\frac{R_4}{R_3}\right)}$ ……..(3b)

Substituteing in Eq(3b) $R_2/R_1 = R_3/R_4 = m$ and simplifying the denominator on the R.H.S of Eq.(3b), we get

$\Delta E = V \cdot \frac{\frac{\Delta R_1}{R_1}}{\left(1+\frac{\Delta R_1/R_1}{(1+m)}\right)} \frac{m}{(1+m)^2}$……………..(3c)

$\Delta E = \frac{m}{(1+m)^2} V \cdot \frac{\Delta R_1}{R_1}(1-\eta)$….(3)

Where

$(1-\eta) = \frac{1}{1+\left(\frac{1}{1+m}\right)\frac{\Delta R_1}{R_1}}$…………..(3d)

$(1-\eta)$ is the nonlinearity factor in the expression for ΔE.

A general expression for ΔE can be derived in a similar manner for the case where all the four resistances R_1, R_2, R_3, R_4 change by incremental amounts $\Delta R_1, \Delta R_2, \Delta R_3, \Delta R_4$ respectively. This expression is given below

$$\Delta E = \frac{m}{(1+m)^2} V \cdot \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)(1-\eta) \ldots\ldots\ldots\ldots\ldots..(4)$$

Where

$$(1-\eta) = \frac{1}{1+\left(\frac{1}{1+m}\right)\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_4}{R_4} + m\left(\frac{\Delta R_3}{R_3} + \frac{\Delta R_2}{R_2}\right)\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4a)$$

It is seen from eq 4 and also from eq 3 that the relationship between the output ΔE and change in resistance $\Delta R_1/R_1$, $\Delta R_2/R_2$ etc. is nonlinear.the nonlinear term η has to be neglected in order to obtain linear relations for one and four active gauges as follows.

$$\Delta E_1 = \frac{m}{(1+m)^2} V \cdot \frac{\Delta R_1}{R_1} \ldots\ldots(5a)$$

$$\Delta E_2 = \frac{m}{(1+m)^2} V \cdot \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) \ldots\ldots(5)$$

The sensitivity of the wheat stone bridge may be defined as the out of balance voltage, ΔE produced by unit strain.from eq 5, the brige sensitivity S_v is

$$S_v = \frac{m}{(1+m)^2} \frac{V}{\epsilon} \cdot \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) \ldots\ldots\ldots\ldots..(6)$$

in multiple gauge circuit with n strain gauges (n can be 1,2,3 or 4), the strain gauge are usually so connected that their outputs add up. Hence one can write

$$\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) = k \frac{\Delta R_1}{R_1} \ldots.(6a)$$

Where k is termed as the bridge factor. & substituteing eq 5 in eq 6a, we get

$$\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) = kF\epsilon \ldots.(6b)$$

Substituteing eq 6b in 6 gives

$$S_v = \frac{m}{(1+m)^2} \cdot V \cdot k \cdot F \ldots.(8)$$

it may be noted that this eq is applicable in case where the bridge voltage V is fixed and is independent of the gauge current. It is also seen that the bridge sensitivity is dependent on:

(1) The magnitude of the bridge voltage, V,
(2) The gauge factor, F,
(3) The bridge factor, k or the number of active arms employed, and
(4) The ratio of the resistances, m or R_2/R_1.

Fundamentals of Photoelasticity

- Some Useful Definitions
- How Stress Is Calculated
- Principles of Photoelasticity
- Stress Measurement Techniques

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Some Useful Definitions

- Residual Stress
- Polarized Light
- Index of Refraction
- Photoelasticity
- Birefringence
- Stress-Optical Constant
- Retardation

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Residual Stress

Residual stress is an intrinsic tension or compression which exists in a material without an external load being applied. In glass, so-called permanent residual stress is induced in the primary manufacturing process. It is relieved through annealing or subsequently added in secondary thermal processing operations to impart desired mechanical characteristics.

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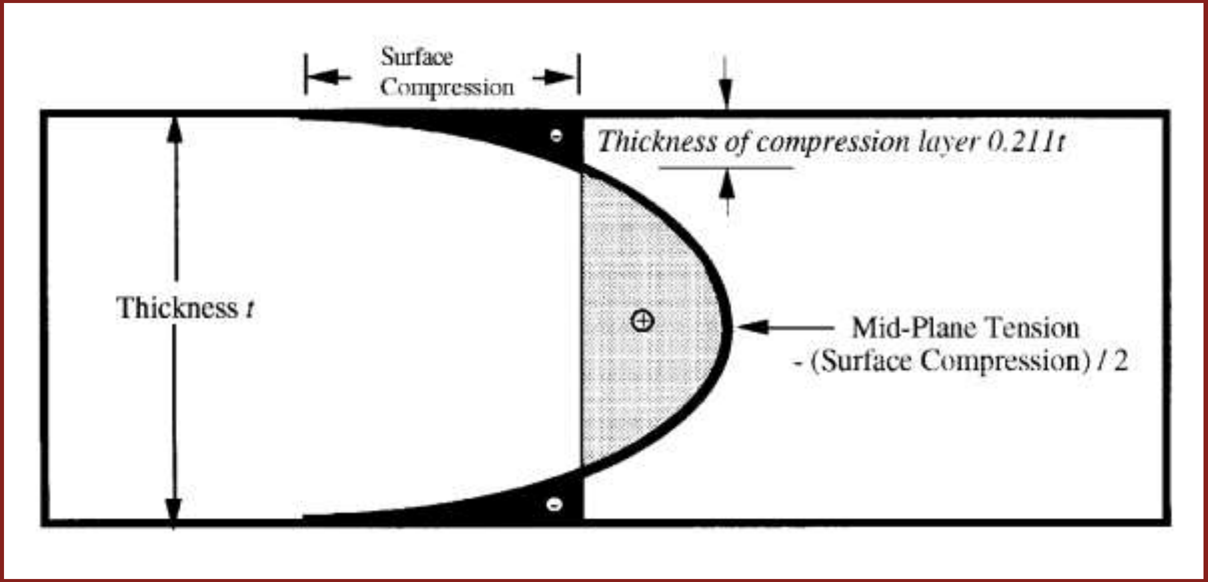
Residual Stress

When there is an equilibrium between the tensile and compressive stresses, the glass is said to be stable. An imbalance in residual stresses can cause unexpected weakness or spontaneous breakage.



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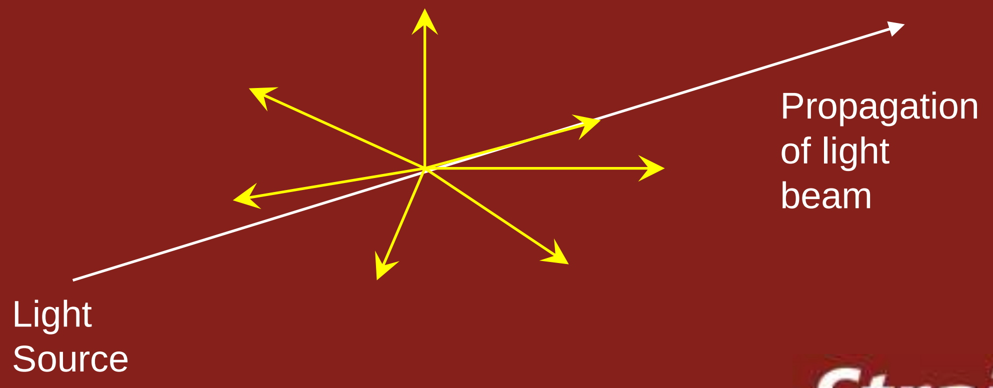
Polarized Light

- Light moves through transparent materials in the form of waves. The frequency of the waveform varies with the type of light. The standard wavelength for white light through glass is 565 nanometers (10^{-9} meters).

- These waves are omnidirectional and “vibrate” out at a perpendicular angle from the direction (propagation) of the light beam.



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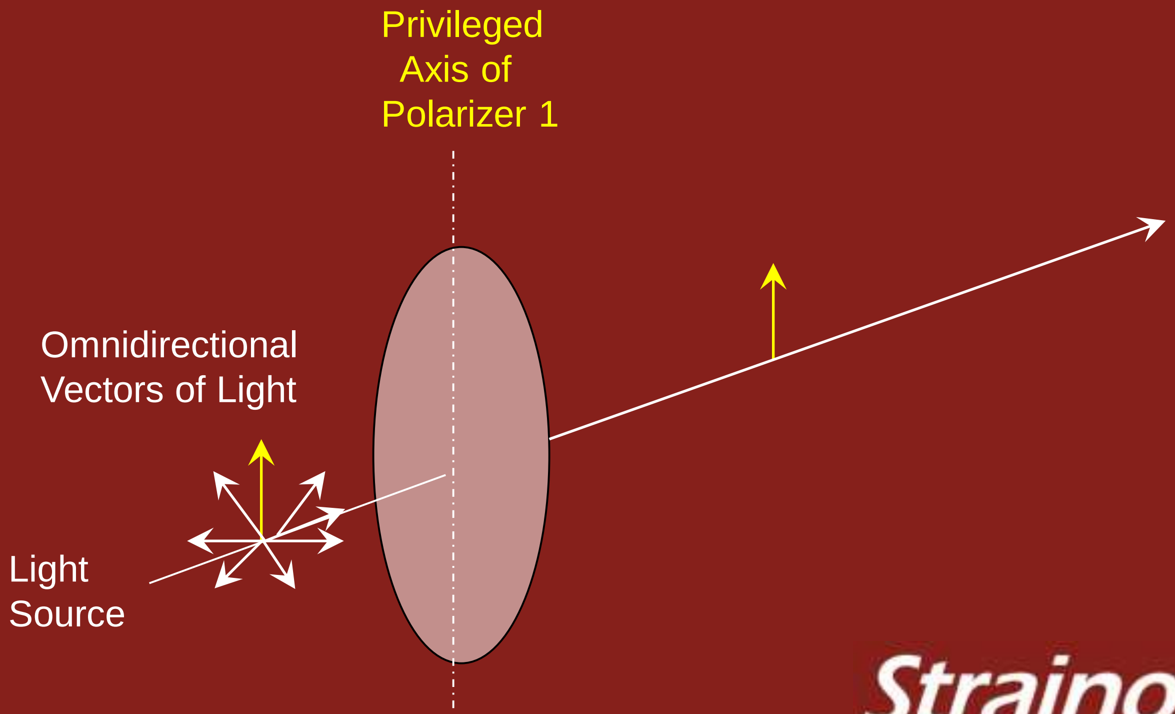
Polarized Light

When light passes through a polarizing lens, all components of the light wave are blocked except for the components of the light wave in the plane of vibration allowed to pass by the polarizing filter.



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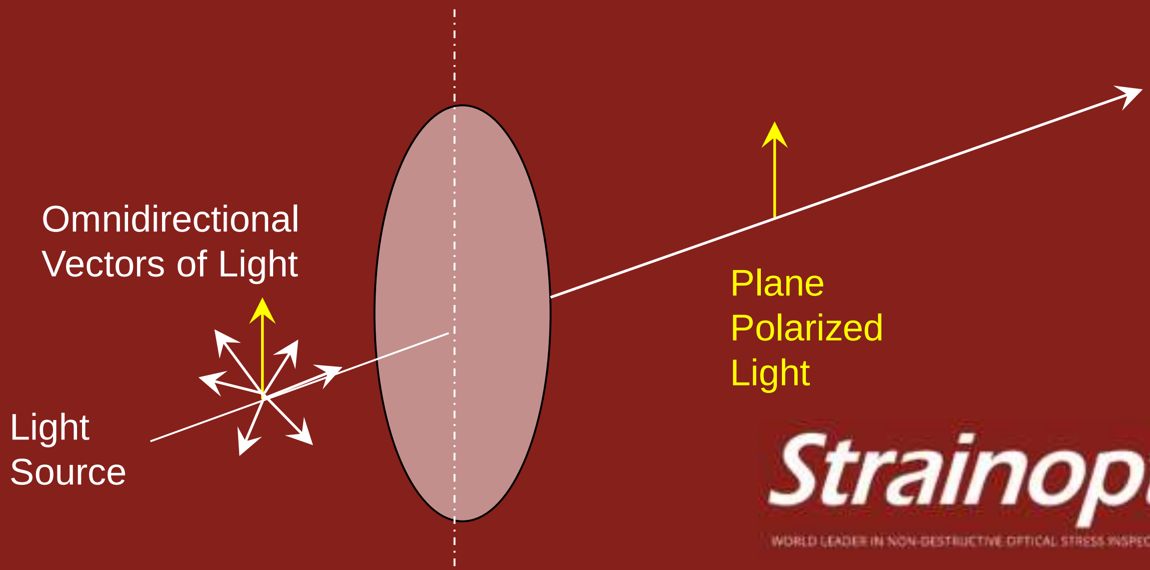
Polarized Light

In “plane” or linear polarization, only the components of the light vector parallel to the privileged axis of the polarizer pass through. Light may also be subject to “circular” and “elliptical” polarization methods, which involve adding devices to the light path which alter its characteristics.



Privileged
Axis of
Polarizer 1

Omnidirectional
Vectors of Light

Light
Source

Plane
Polarized
Light

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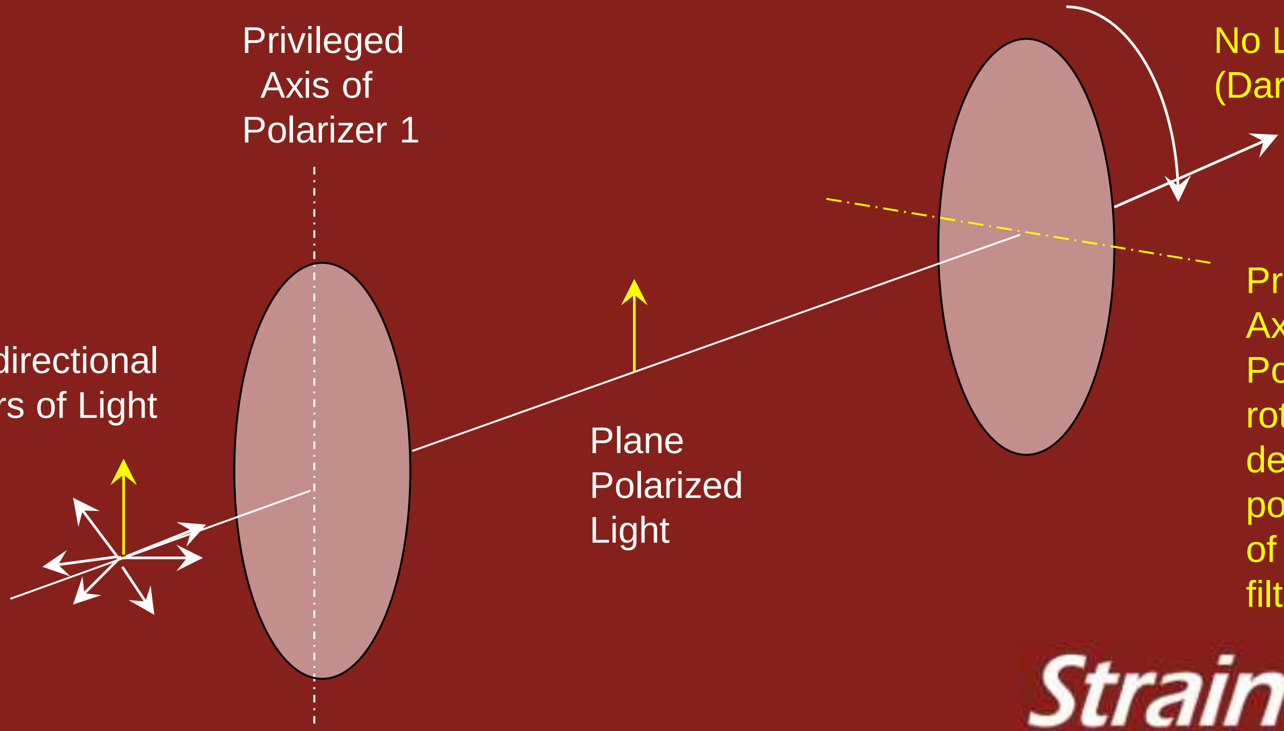
Polarized Light

If another polarizing filter is placed in the path of the polarized light beam, and rotated 90° (perpendicular) to the polarizing axis of the first filter, all light will be blocked.



Privileged Axis of Polarizer 1

No Light (Dark Field)

Privileged Axis of Polarizer 2 rotated 90 degrees to the polarizing axis of the first filter.

Omnidirectional Vectors of Light

Plane Polarized Light

Light Source

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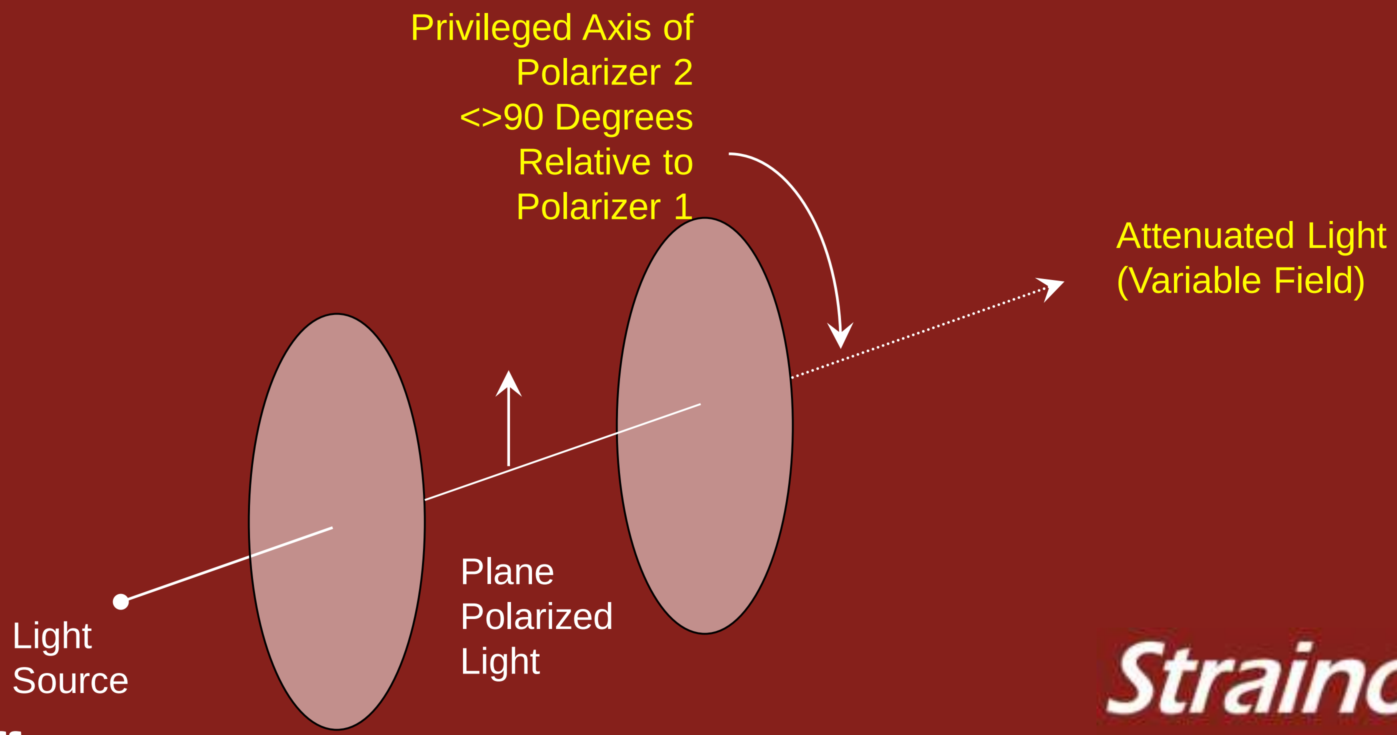
Polarized Light

If the second polarizing filter is rotated to an angle less than or greater than 90° relative to the first polarizing lens, only the components of the light wave vibrating in that plane will pass through the filter.



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Index of Refraction

A material's index of refraction is defined as the speed of light through a vacuum 3 x 10^8 meters/sec divided by the speed of light through the material.

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Photoelasticity

The property exhibited by some transparent solids, whereby they become doubly refractive, or “birefringent,” when subjected to stress.

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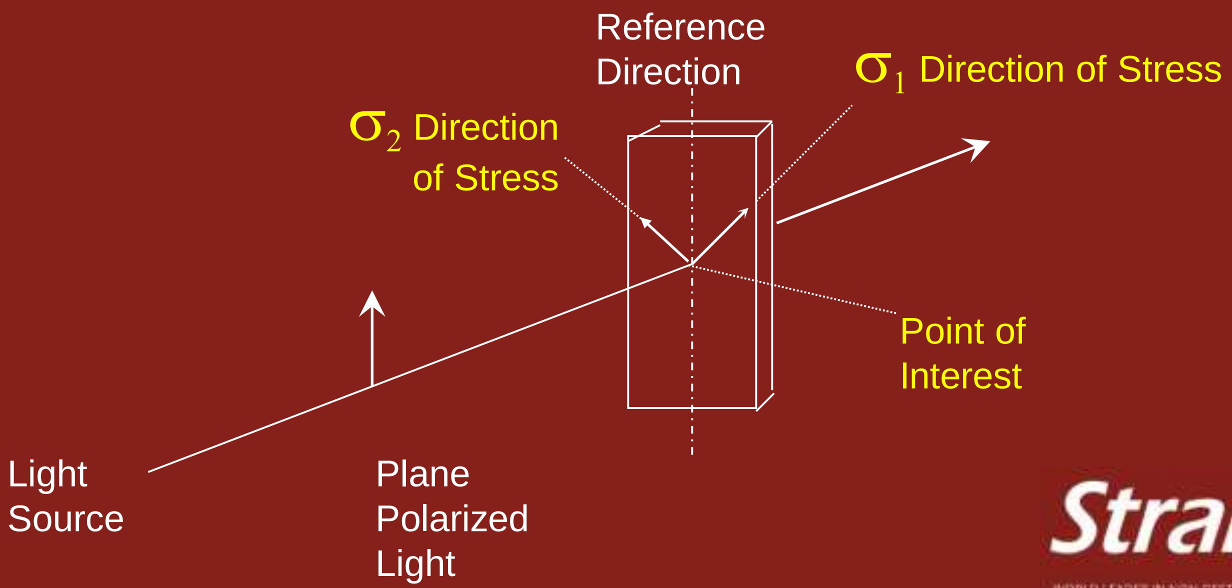
Birefringence

When polarized light passes through a stressed material, the light separates into two wavefronts traveling at different velocities, each oriented parallel to a direction of principal stress (σ_1, σ_2) in the material, but perpendicular to each other.



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Birefringence

Birefringence results in the stressed material having two different indices of refraction
(n_1, n_2).

In most materials, the index of refraction remains constant; however, in glass and plastics, the index value varies as a function of the stress applied. This gave rise to the Stress-Optic, or “Brewster’s” Law .

The Stress-Optic (Brewster's) Law

$$(n_1 - n_2) = C_B (\sigma_1 - \sigma_2)$$

WHERE

n_1, n_2 = Indices of refraction

C_B = Stress-optical constant,
in Brewsters

σ_1, σ_2 = Principal stresses

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The Stress-Optic Law

This law established that birefringence is directly proportional to the difference of principal stresses, which is equal to the difference between the two indices of refraction, n_1-n_2, exhibited by a stressed material.

Therefore, birefringence can be calculated by determining Δn.

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Retardation

The phase difference between the two light vectors traveling through the material at different velocities (fast, slow) is known as retardation, commonly represented by the symbol delta, δ.

The retardation value divided by a material’s thickness is proportional to the difference between the two indices of refraction, i.e.,

$$\delta / t = \Delta n$$

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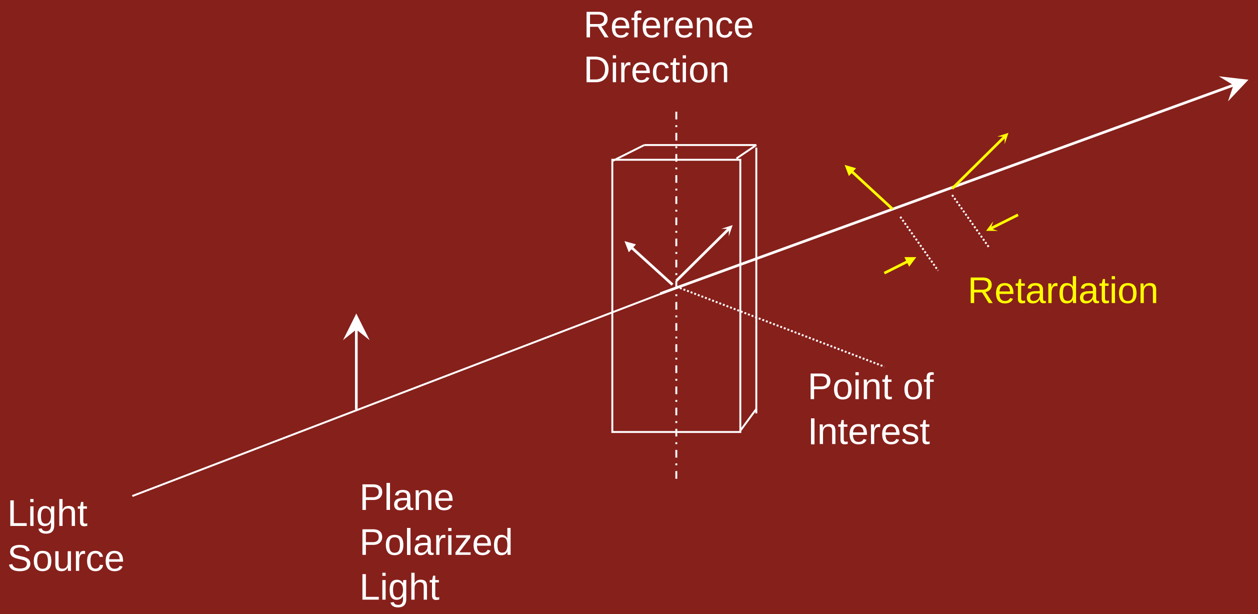
Retardation of Polarized Light Through a Stressed Material



Reference
Direction

Retardation

Point of
Interest

Light
Source

Plane
Polarized
Light

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How Stress Is Calculated

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The Stress Equation

$$\text{Stress} = \frac{\text{Retardation}}{\text{Thickness} * \text{Stress-Optical Constant}}$$

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The Stress Equation

$$\sigma = \delta / tC_B$$

WHERE

σ = Stress (in MPa*)

δ = Retardation (in nanometers)

t = Thickness

C_B = Stress-optical constant (in Brewsters)

*(1 MPa = 145 psi)

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Principles of Photoelasticity

Instruments designed to observe objects under polarized light are called *polariscopes or strain viewers*. The first, or fixed, polarizing filter is known as the "polarizer." The second, or rotating, polarizing filter is known as the "analyzer." If the analyzer has a calibrated scale that can be used for making quantitative measurements, it is called a *polarimeter*.

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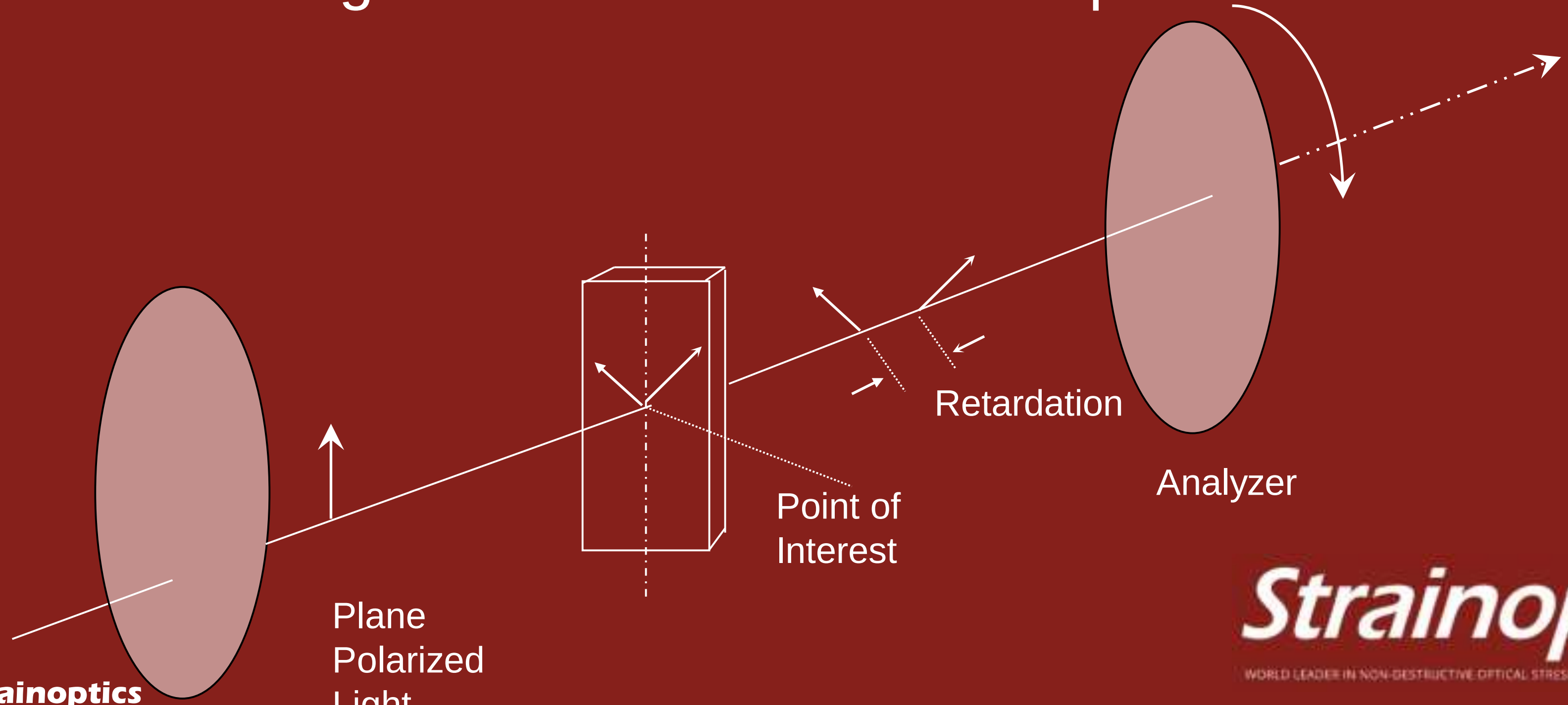
Principles of Photoelasticity

By rotating the second polarizing filter (*analyzer*), the user can control the amount (intensity) of light allowed to pass through. The components of the two light waves that do pass through at any given angle of analyzer rotation interfere with each other, resulting in a characteristic color spectrum.



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Principles of Photoelasticity

The intensity of colors displayed when a stressed transparent or translucent material is viewed under polarized light is modulated by the retardation.

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Principles of Photoelasticity

Each integer multiple of the standard wavelength of light (λ = 565 nm for glass; 570 nm for plastics) is called a *fringe (N)*.

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Principles of Photoelasticity

The intensity of the colors diminishes as the retardation or fringe order increases.

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Principles of Photoelasticity

The photoelastic color sequence (showing increasing stress) is:

Black (zero)

Yellow
Red

Blue-Green
Yellow
Red

Green
Yellow
Red

Green

Yellow

Red

Zero Order

First Order

Second Order

Third Order

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Principles of Photoelasticity

These color patterns, visible when using polarized light, can be used to observe and make a qualitative evaluation of stress in an object. This method is very subjective and requires experience and training.

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Principles of Photoelasticity

A quantitative measurement of residual stress can be obtained using a polarimeter, an instrument that measures retardation, which is proportional to stress.

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Principles of Photoelasticity

Plane Polarization
and
Circular Polarization

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Principles of Photoelasticity

To determine the direction of principal stresses in a sample, a plane polarization technique is typically used. To do this using plane-polarized light, it is important to first orient the sample such that the point of interest (POI) exhibits minimum light intensity.

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Principles of Photoelasticity

In this orientation, a direction of principal stress at the point of interest (either x or y) will be parallel to the axes of the analyzer and polarizer.

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Principles of Photoelasticity

Rotating the sample 45 degrees places the sample in the proper position for measuring retardation.

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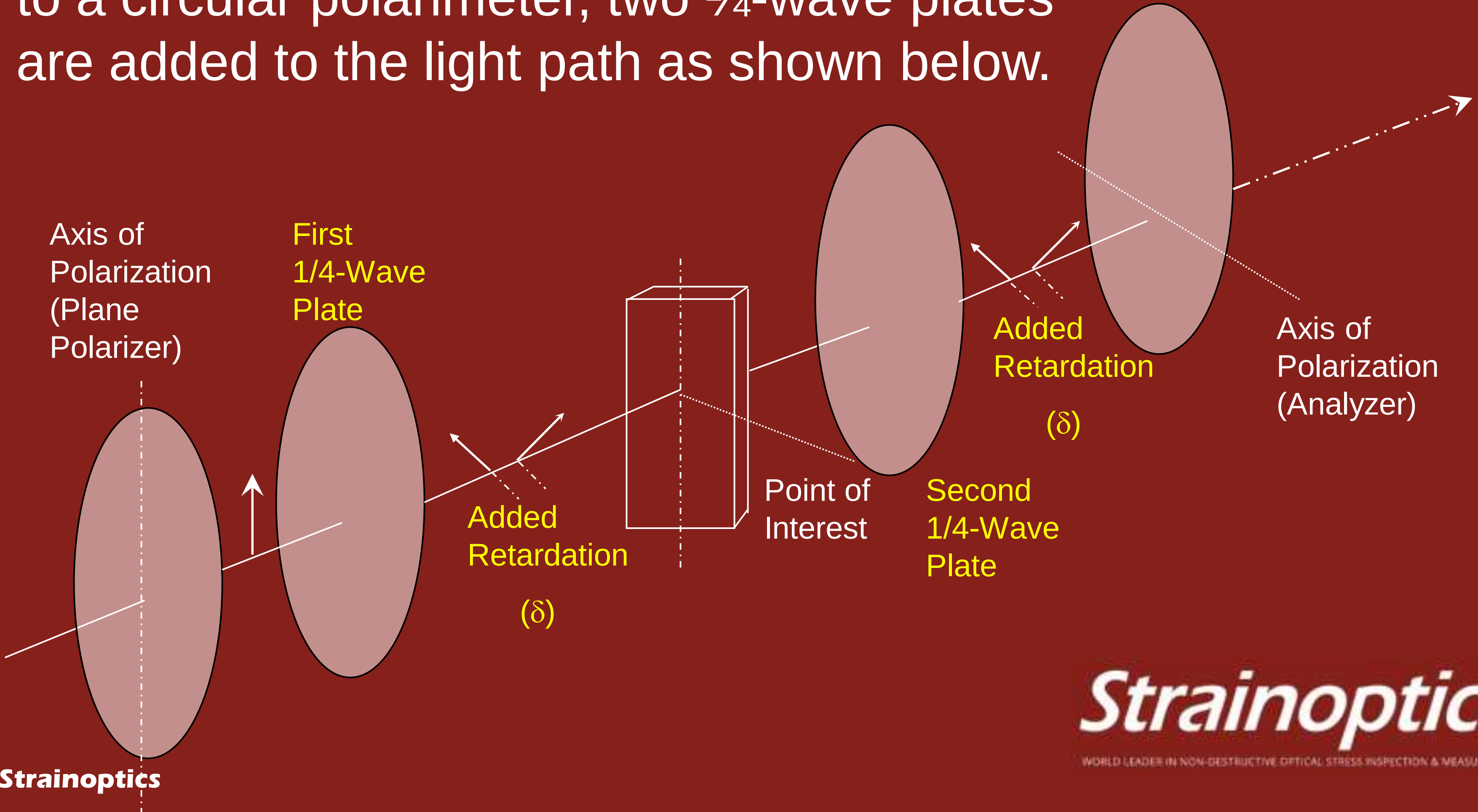
Principles of Photoelasticity

Using circularly polarized light, the measurement is independent of the direction of the principal stresses at the point of interest. To change a plane polarimeter to a circular polarimeter, two ¼-wave plates are added to the light path as shown below.



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Principles of Photoelasticity

The relation used for calculating the retardation of polarized light transmitted through a stressed material is:

$$\delta = C_B t \, (\sigma_x - \sigma_y)$$

WHERE

δ = Retardation (in nanometers)

C_B = Brewster Constant

t = Material Thickness

$\sigma_{x,y}$ = Principal Stresses

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Measuring Techniques

Observation of Color Pattern Method

Compensator Method

Analyzer Rotation Method

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Observation of Color Pattern Method

Strain Viewer/
Polariscope

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Observation of Color Pattern Method

White light produces a complete spectrum of light. This includes the visible spectrum of 400 nm to 700 nm.

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Observation of Color Pattern Method

The intensity of the light is modulated by the retardation exhibited by the sample.

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Observation of Color Pattern Method

- Results are highly subjective to interpretation
- Can only be used for qualitative measurements

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Compensator Method

Compensator

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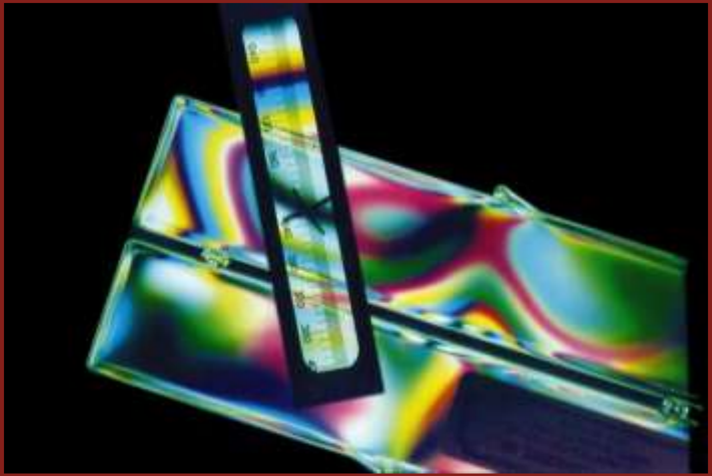
Compensator Method



- Simplest method of measuring retardation
- Compensator (wedge) is a calibrated, handheld device that optically adds a retardation of equal, but opposite sign to the sample.
- The net result is a light intensity of zero, which is easily recognized visually as black in the color pattern.

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Compensator Method

There are two types of compensators in common usage:

- Babinet or “Wedge” compensator (scale readout)
- Babinet-Soleil or “Double-Wedge” compensator (digital readout)

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Analyzer Rotation Method


Analyzer

Polarimeter (with microscope option)

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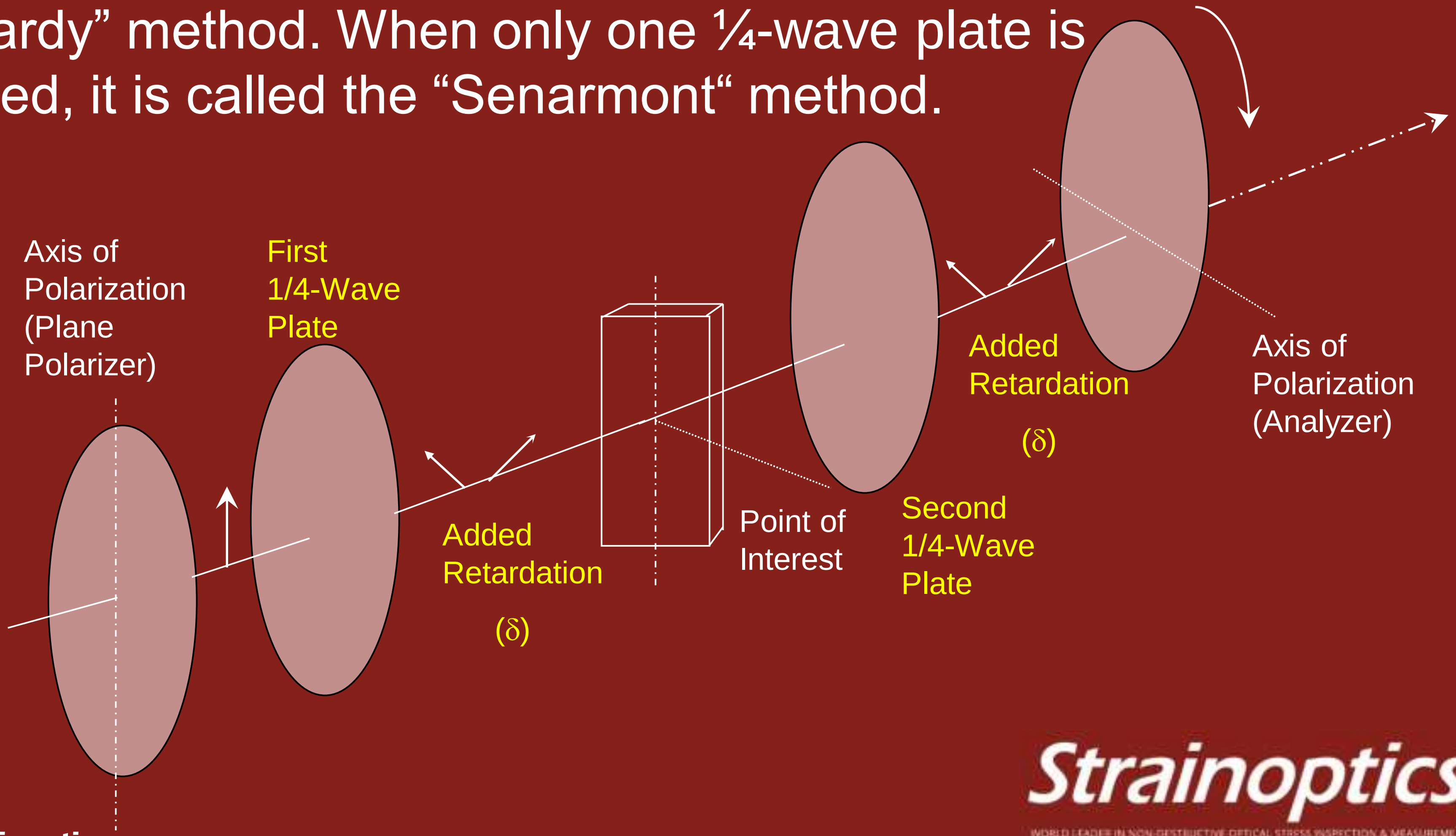
Analyzer Rotation Method

The Analyzer Rotation Method uses a circular polarimeter setup as shown below. This is called the ”Tardy” method. When only one ¼-wave plate is used, it is called the “Senarmont“ method.



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Analyzer Rotation Method

- The analyzer rotation method is generally used to measure fractional levels of retardation (<570 nm).
- The sample is first positioned parallel to the reference axis of the polarizer and analyzer.
- The analyzer is rotated until a minimum light intensity is observed.
- The sample is then rotated 45 degrees from the reference axis.

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Analyzer Rotation Method

Retardation is calculated from the fractional fringe order that is read directly from the dial.

509 nm =
0.9 x 565

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Analyzer Rotation Method

This measurement (509 nm of retardation) is then converted to stress using the equation below or referring to a conversion chart.

$$\sigma = \delta/tC_B$$

WHERE

σ = Stress (in MPa)

δ = Retardation (in nanometers)

t = Thickness

C_B = Brewster Constant

(1 MPa = 145 psi)

©Strainoptics

Analyzer Rotation Method

Example:

Retardation (δ) = 509 nm

Thickness (t) = 6 mm

$C_B = 2.54$

$$\sigma = \delta / tC_B = 509/(6.0 \times 2.54)$$

$$\sigma = 509/15.24$$

σ = 33.4 MPa or 4843 psi

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REVA UNIVERSITY

A Unit of DivyaSree

Presentation on
mechanism of formation of moire fringes

Under the guidance of Dr.Manjunatha L H

Prepared by:

BEERAPPA
R14MMD02

CONTENTS

INTRODUCTION

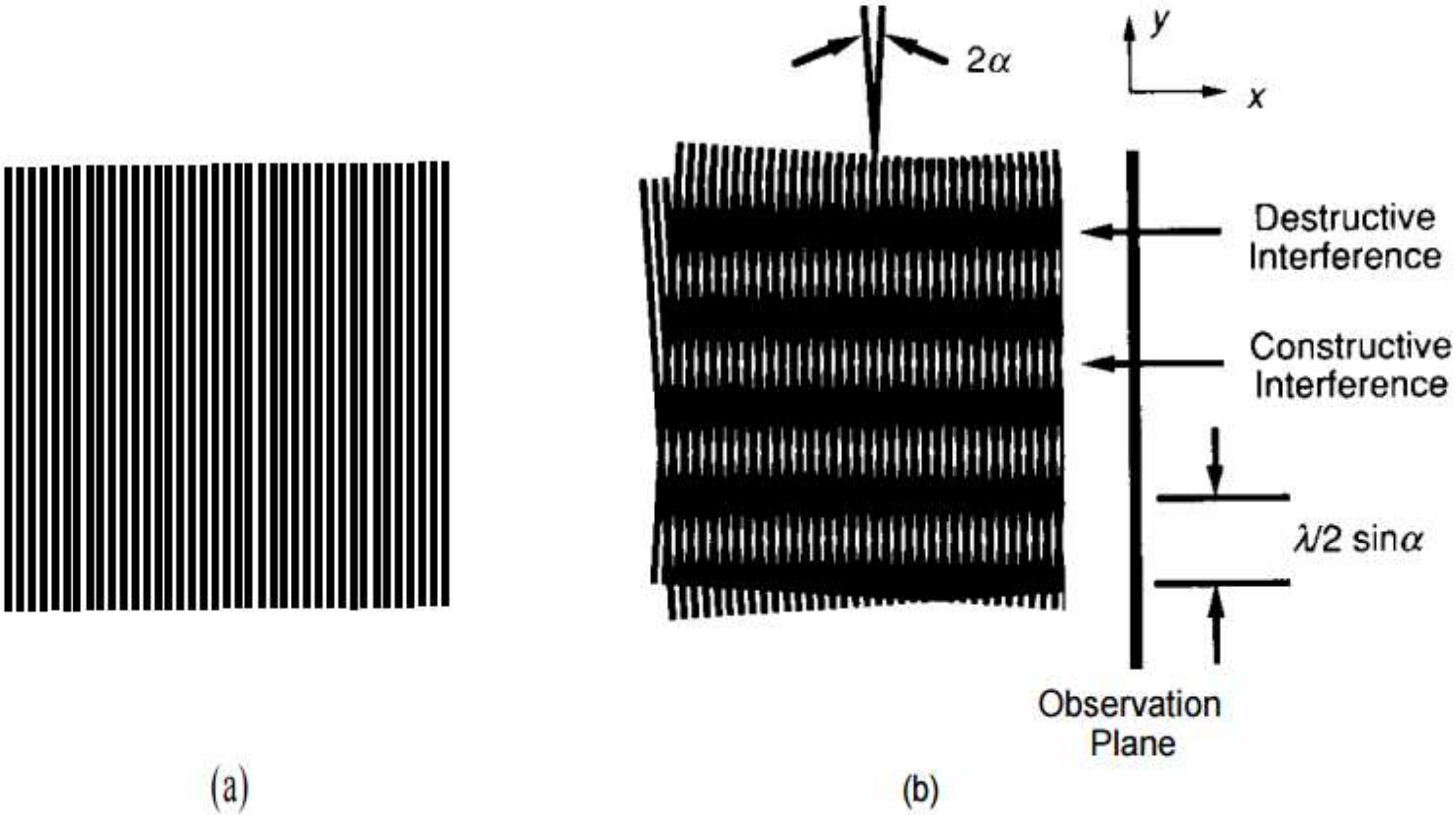
- The term “moiré” is not the name of a person; in fact, it is a French word referring to “an irregular wavy finish usually produced on a fabric by pressing between engraved rollers”.
- In optics it refers to a beat pattern produced between two gratings of approximately equal spacing.
- It can be seen in everyday things such as the overlapping of two window screens, the rescreening of a half-tone picture, or with a striped shirt seen on television.
- The use of moiré for reduced sensitivity testing was introduced by Lord Rayleigh in 1874.

Moire techniques

- Moiré can be obtained by the principle of pattern formation of in-plane and out-of plane moirés.
- In plane moire: measurement of in planed de formation and strains.
- Out-of-plane moiré: measurement of out-of plane and deformations (Contouring).

WHAT IS MOIRÉ?

- Moiré patterns are extremely useful to help understand basic interferometry and interferometric test results.
- Figure .1 shows the moiré pattern (or beat pattern) produced by two identical straight-line gratings rotated by a small angle relative to each other.
- A dark fringe is produced where the dark lines are out of step one-half period, and a bright fringe is produced where the dark lines for one grating fall on top of the corresponding dark lines for the second grating.
- If the angle between the two gratings is increased, the separation between the bright and dark fringes decreases.
- If the gratings are not identical straight-line gratings, the moiré pattern (bright and dark fringes) will not be straight equi-spaced fringes.



(a)

(b)

Fig .1.(a) Straight-line grating. (b) Moiré between two straight-line gratings of the same pitch at an angle a with respect to one another.

- The following analysis shows how to calculate the moire pattern for arbitrary gratings. Let the intensity transmission function for two gratings f1 (x, y) and f2 (x, y) be given by

$$f_1(x, y) = a_1 + \sum_{n=1}^{\infty} b_{1n} \cos\,[n\phi_1(x, y)],$$

$$f_2(x, y) = a_2 + \sum_{m=1}^{\infty} b_{2m} \cos\,[m\phi_2(x, y)],$$

- where f (x, y) is the function describing the basic shape of the grating lines. For the fundamental frequency, f (x, y) is equal to an integer times 2 ∏ at the center of each bright line and is equal to an integer plus one-half times 2 ∏ at the center of each dark line. The b coefficients determine the profile of the grating lines (i.e., square wave, triangular, sinusoidal, etc.) For a sinusoidal line profile, is the only nonzero term.

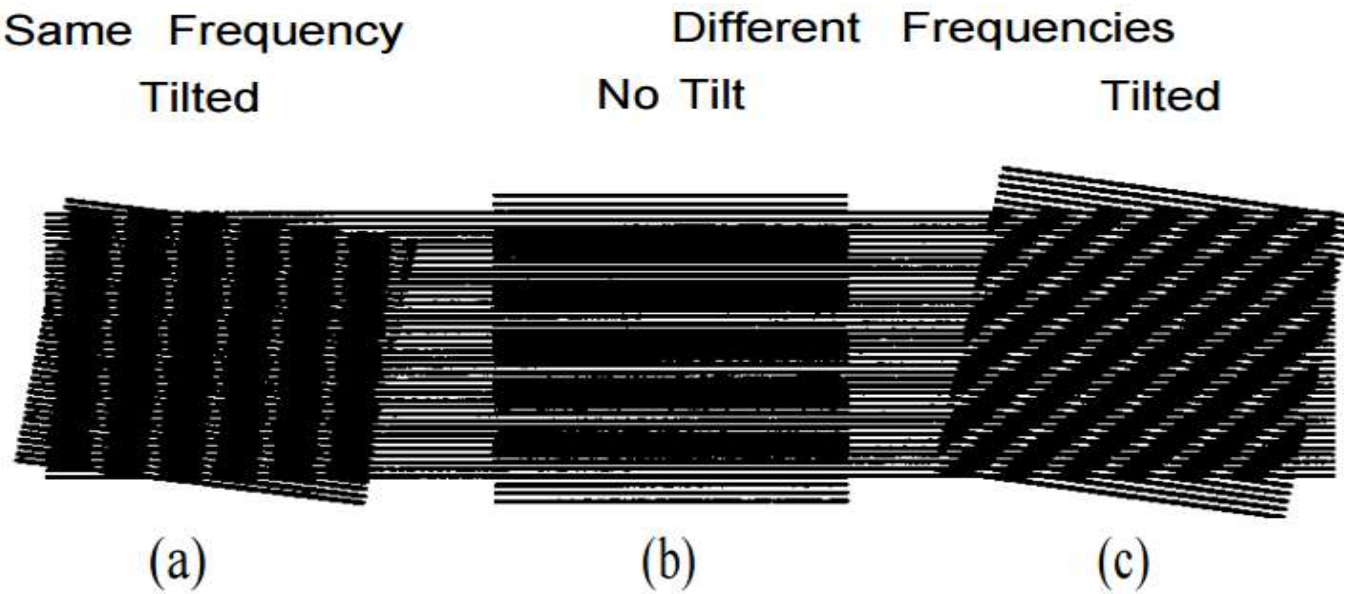


Fig 2.Moiré patterns caused by two straight-line gratings with (a) the same pitch tilted with respect to one another, (b) different frequencies and no tilt, and (c) different frequencies tilted with respect to one another.

- These fringes are equally spaced, vertical lines parallel to the y axis. For the more general case where the two gratings have different line spacings and the angle between the gratings is nonzero, the equation for the moiré fringes will now be

$$M\bar{\lambda} = \frac{\bar{\lambda}}{\lambda_{\text{beat}}} x \cos \alpha + 2y \sin \alpha .$$

MOIRÉ AND INTERFEROGRAMS

- Interferograms shows the difference in the aberrations of the two interferograms.
- For example, Fig. 3 shows the moiré produced by superimposing two computer-generated interferograms.
- One interferogram has 50 waves of tilt across the radius (Fig. 3a), while the second interferogram has 50 waves of tilt plus 4 waves of defocus (Fig. 3b).
- If the interferograms are aligned such that the tilt direction is the same for both interferograms , the tilt will cancel and only the 4 waves of defocus remain (Fig. 3c).

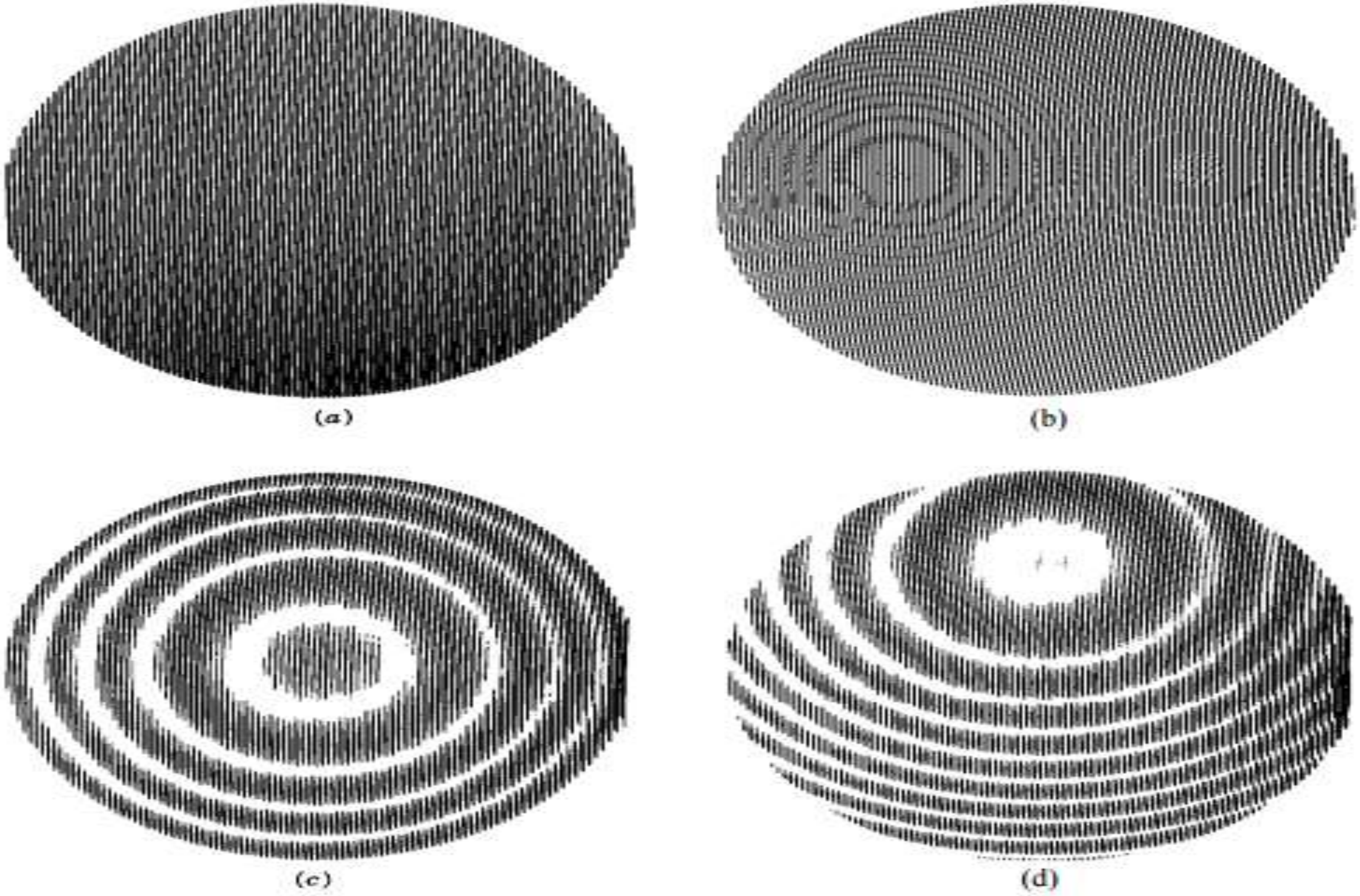


Fig 3. Moiré between two interferograms. (a) Interferogram having 50 waves tilt. (6) Interferogram having 50 waves tilt plus 4 waves of defocus. (c) Superposition of (a) and (b) with no tilt between patterns. (d) Slight tilt between patterns.

- In Fig. 3d, the two in ferograms are rotated slightly with respect to each other so that the tilt will quite cancel. These results can be described mathematically by looking at two grating functions:

$$\phi_1(x, y) = 2\pi(50\rho \cos \phi + 4\rho^2)$$

- and

$$\phi_2(x, y) = 2\pi[50\rho \cos (\phi + \alpha)].$$

- A bright fringe is obtained when

$$50\rho[\cos \phi - \cos (\phi + \alpha)] + 4\rho^2 = M.$$

APPLICATIONS

- These techniques can all be used for displacement measurement or stress analysis as well as for contouring objects.

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Thank You!

Introduction to Nondestructive Testing

Prepared by the Collaboration for NDT Education.
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Outline

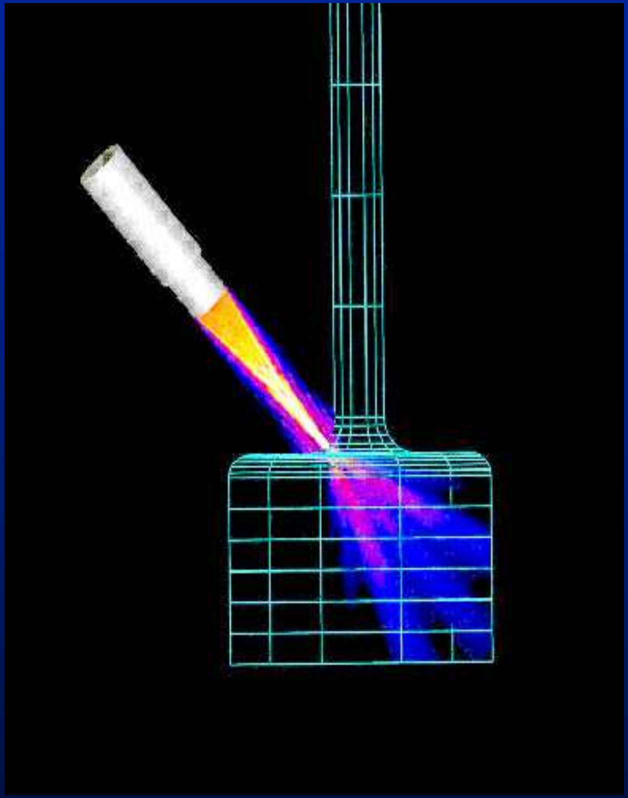
- Introduction to NDT
- Overview of Six Most Common NDT Methods
- Selected Applications

Definition of NDT

The use of noninvasive techniques to determine the integrity of a material, component or structure

or

quantitatively measure some characteristic of an object.



i.e. Inspect or measure without doing harm.

Methods of NDT

Visual

Microwave

Thermography

Tap Testing

Magnetic Particle

X-ray

Acoustic Microscopy

Acoustic Emission

Magnetic Measurements

Liquid Penetrant

Ultrasonic

Replication

Laser Interferometry

Eddy Current

Flux Leakage

What are Some Uses of NDE Methods?

Fluorescent penetrant indication

- Flaw Detection and Evaluation
- Leak Detection
- Location Determination
- Dimensional Measurements
- Structure and Microstructure Characterization
- Estimation of Mechanical and Physical Properties
- Stress (Strain) and Dynamic Response Measurements
- Material Sorting and Chemical Composition Determination

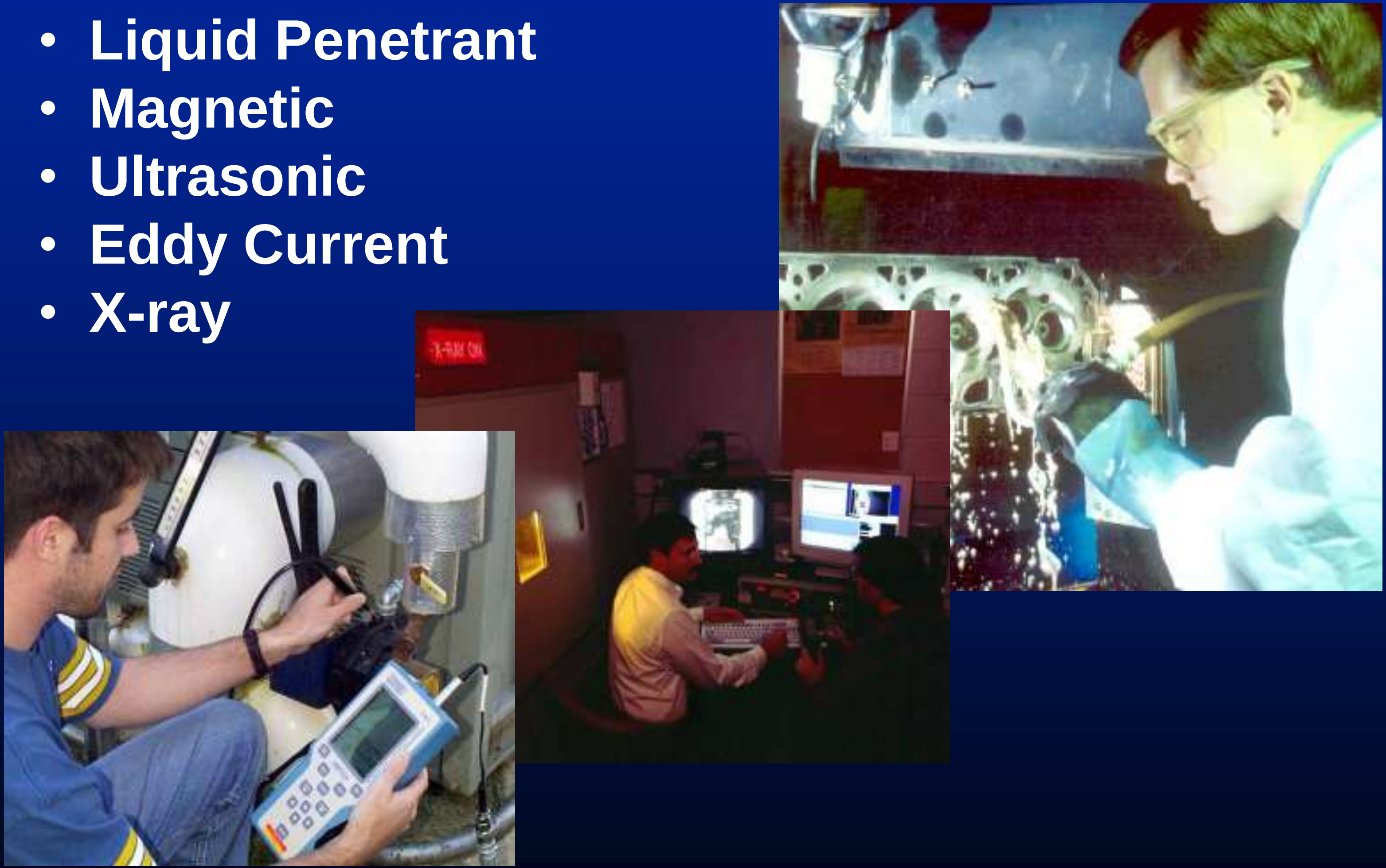
When are NDE Methods Used?

There are NDE application at almost any stage in the production or life cycle of a component.

- To assist in product development
- To screen or sort incoming materials
- To monitor, improve or control manufacturing processes
- To verify proper processing such as heat treating
- To verify proper assembly
- To inspect for in-service damage

Six Most Common NDT Methods

- Visual
- Liquid Penetrant
- Magnetic
- Ultrasonic
- Eddy Current
- X-ray



Visual Inspection

Most basic and common inspection method.

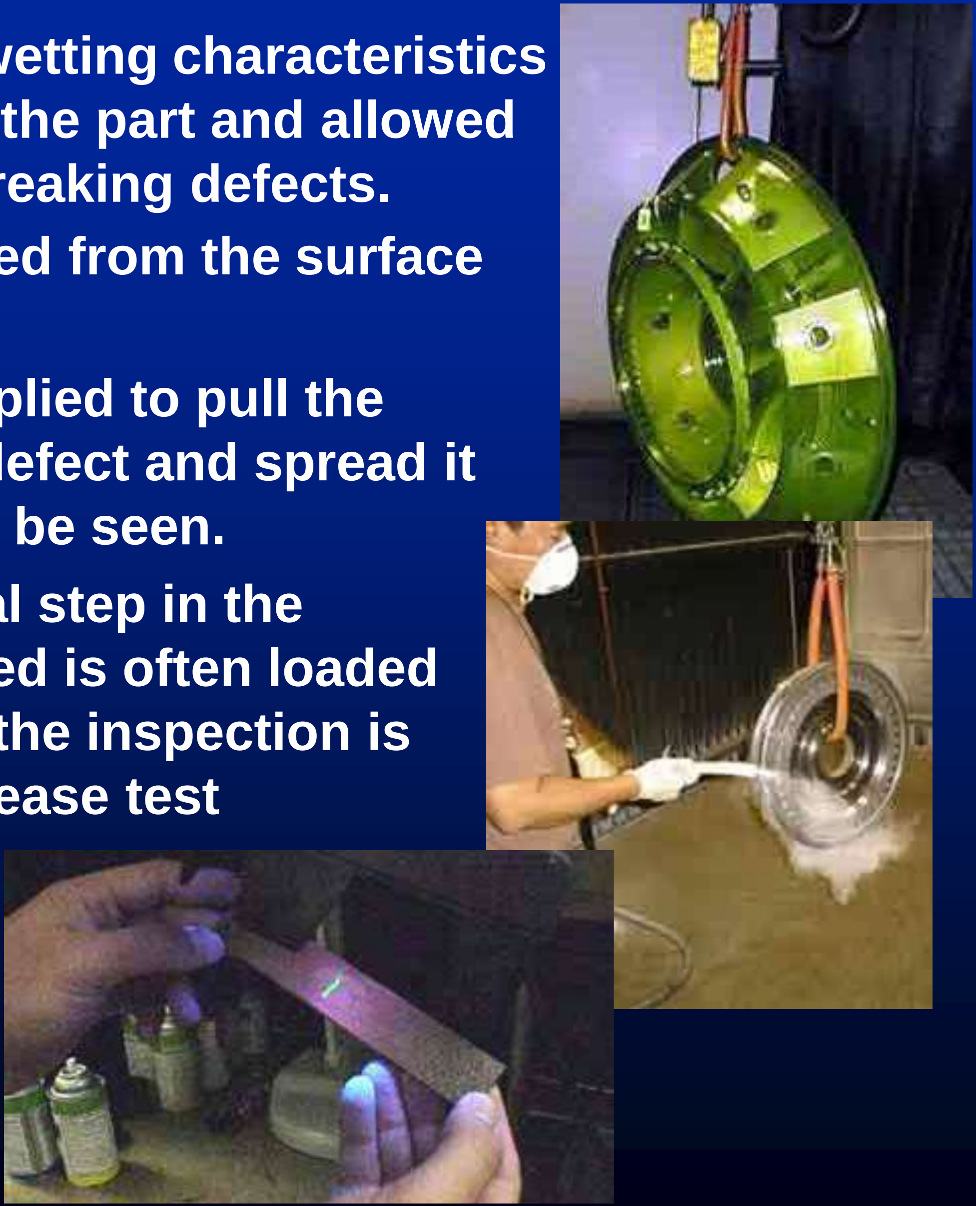
Tools include fiberscopes, borescopes, magnifying glasses and mirrors.

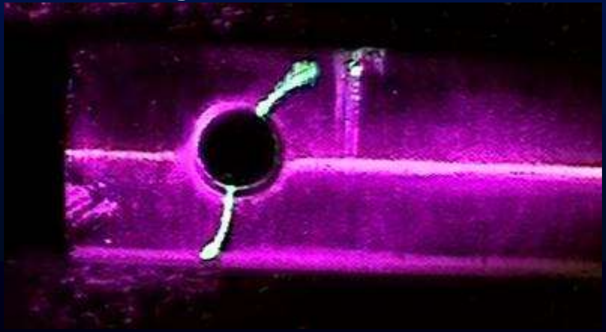
Portable video inspection unit with zoom allows inspection of large tanks and vessels, railroad tank cars, sewer lines.

Robotic crawlers permit observation in hazardous or tight areas, such as air ducts, reactors, pipelines.

Liquid Penetrant Inspection

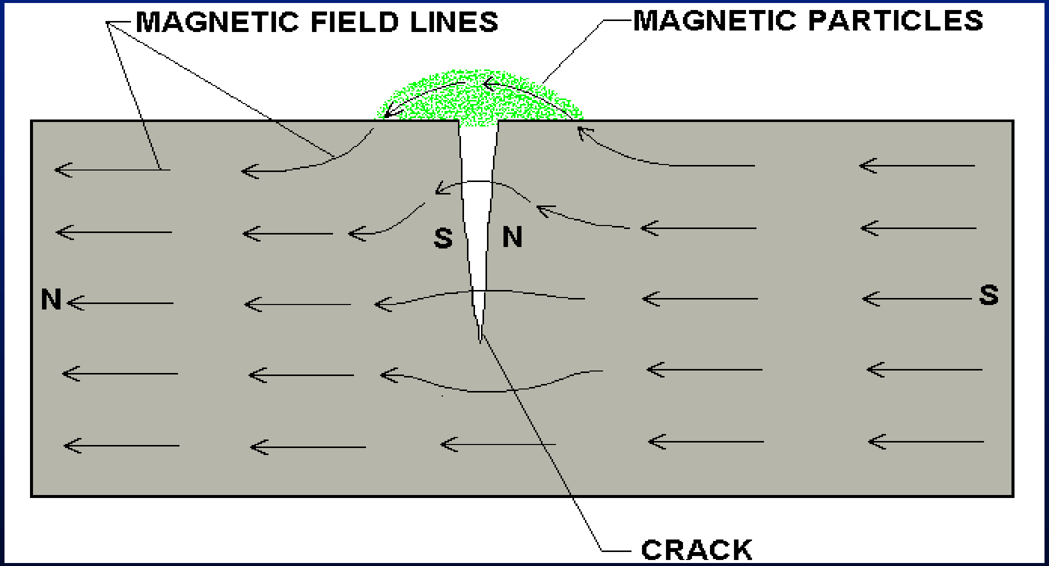
- A liquid with high surface wetting characteristics is applied to the surface of the part and allowed time to seep into surface breaking defects.
- The excess liquid is removed from the surface of the part.
- A developer (powder) is applied to pull the trapped penetrant out the defect and spread it on the surface where it can be seen.
- Visual inspection is the final step in the process. The penetrant used is often loaded with a fluorescent dye and the inspection is done under UV light to increase test sensitivity.



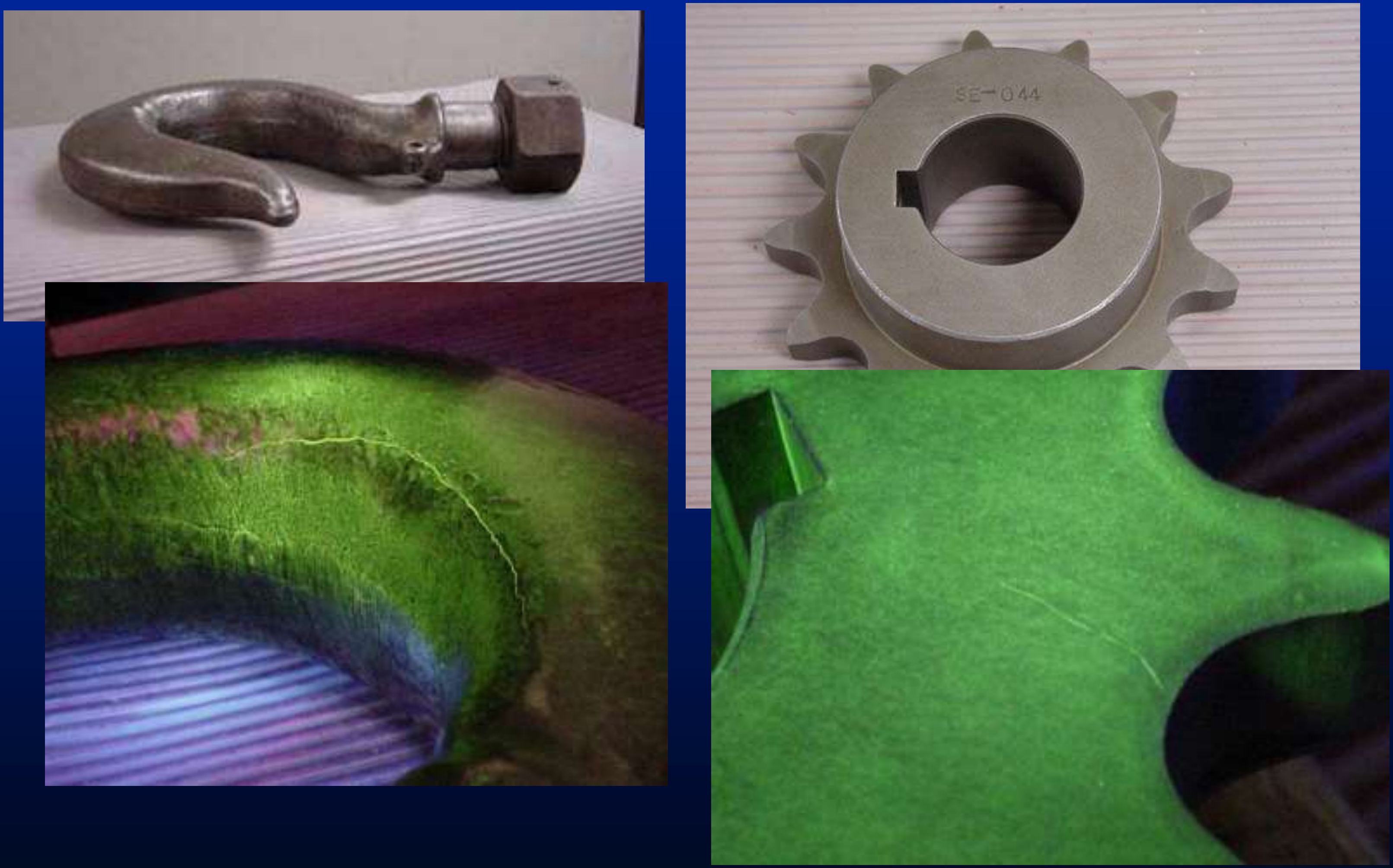


Magnetic Particle Inspection

The part is magnetized. Finely milled iron particles coated with a dye pigment are then applied to the specimen. These particles are attracted to magnetic flux leakage fields and will cluster to form an indication directly over the discontinuity. This indication can be visually detected under proper lighting conditions.

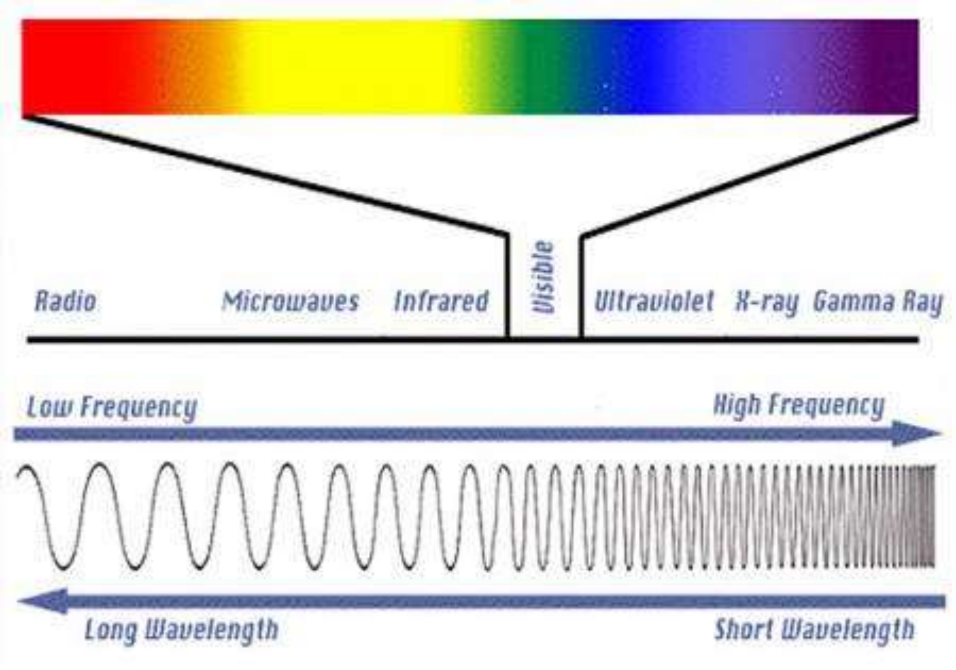


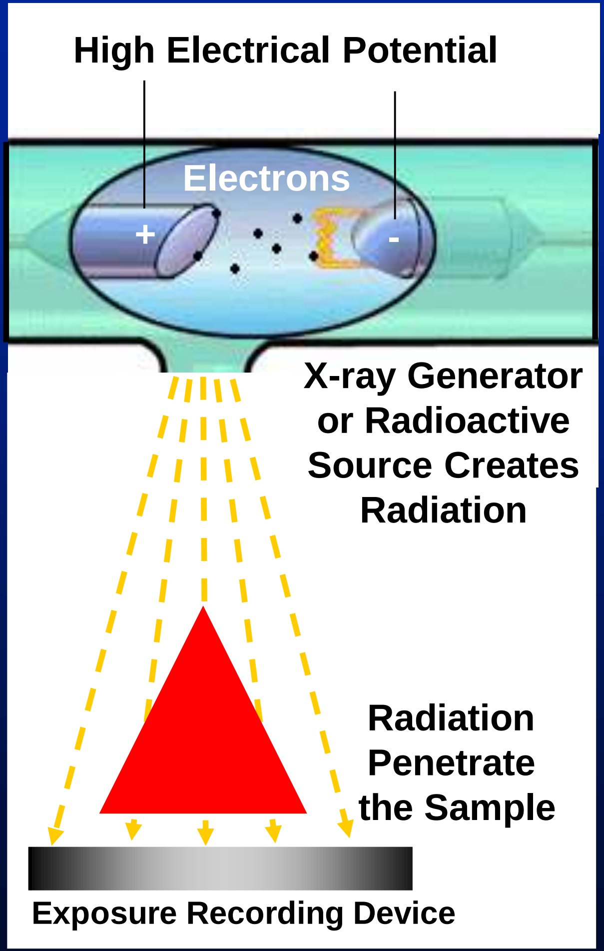
Magnetic Particle Crack Indications



Radiography

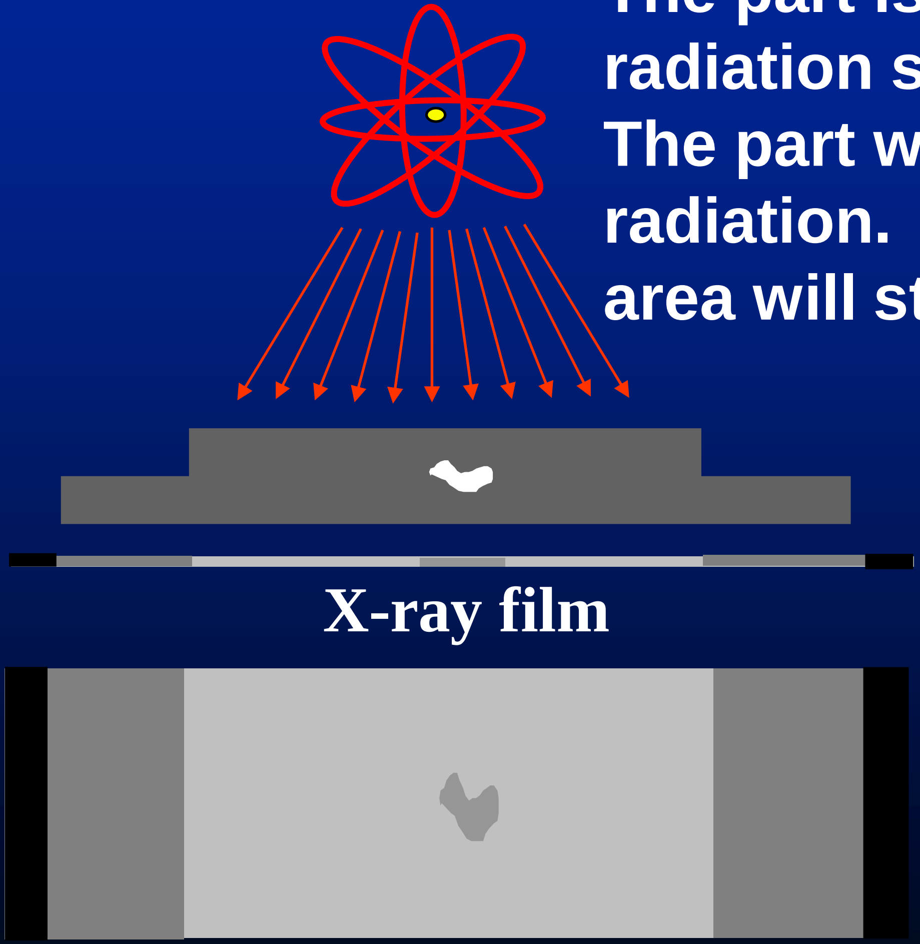
The radiation used in radiography testing is a higher energy (shorter wavelength) version of the electromagnetic waves that we see as visible light. The radiation can come from an X-ray generator or a radioactive source.





Film Radiography

The part is placed between the radiation source and a piece of film. The part will stop some of the radiation. Thicker and more dense area will stop more of the radiation.



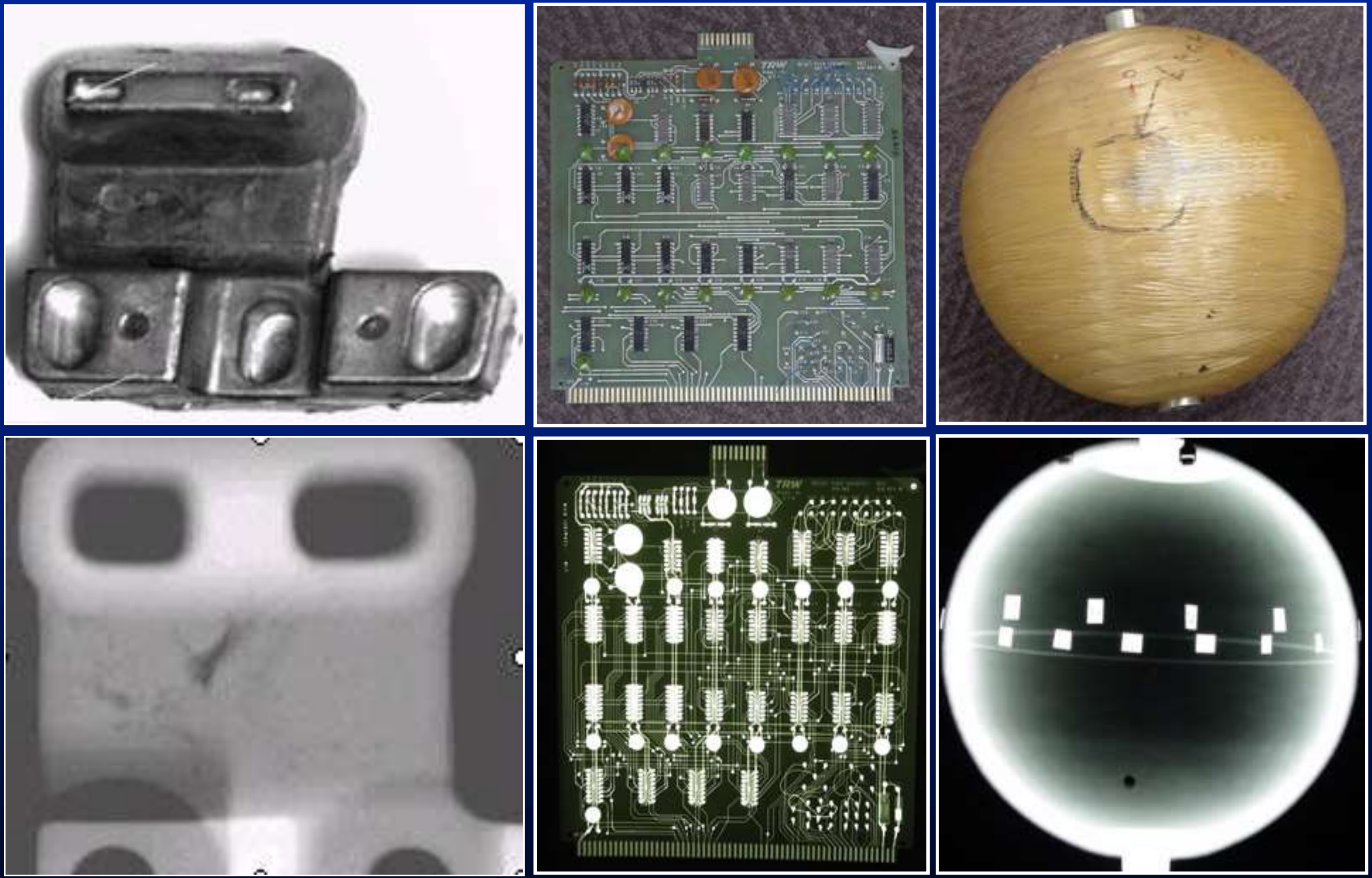
Top view of developed film

The film darkness (density) will vary with the amount of radiation reaching the film through the test object.

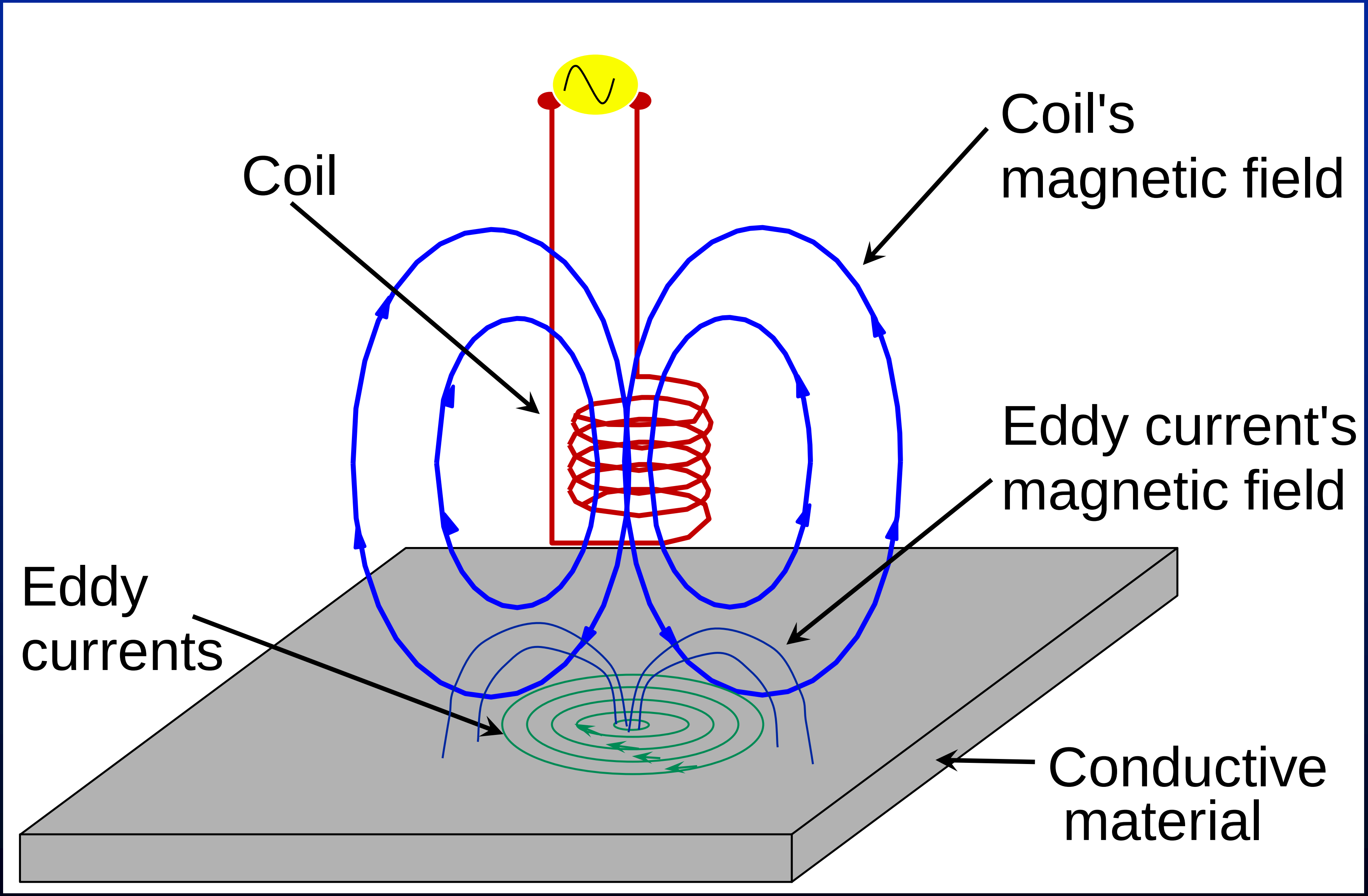
⬜ = less exposure

▨ = more exposure

Radiographic Images



Eddy Current Testing



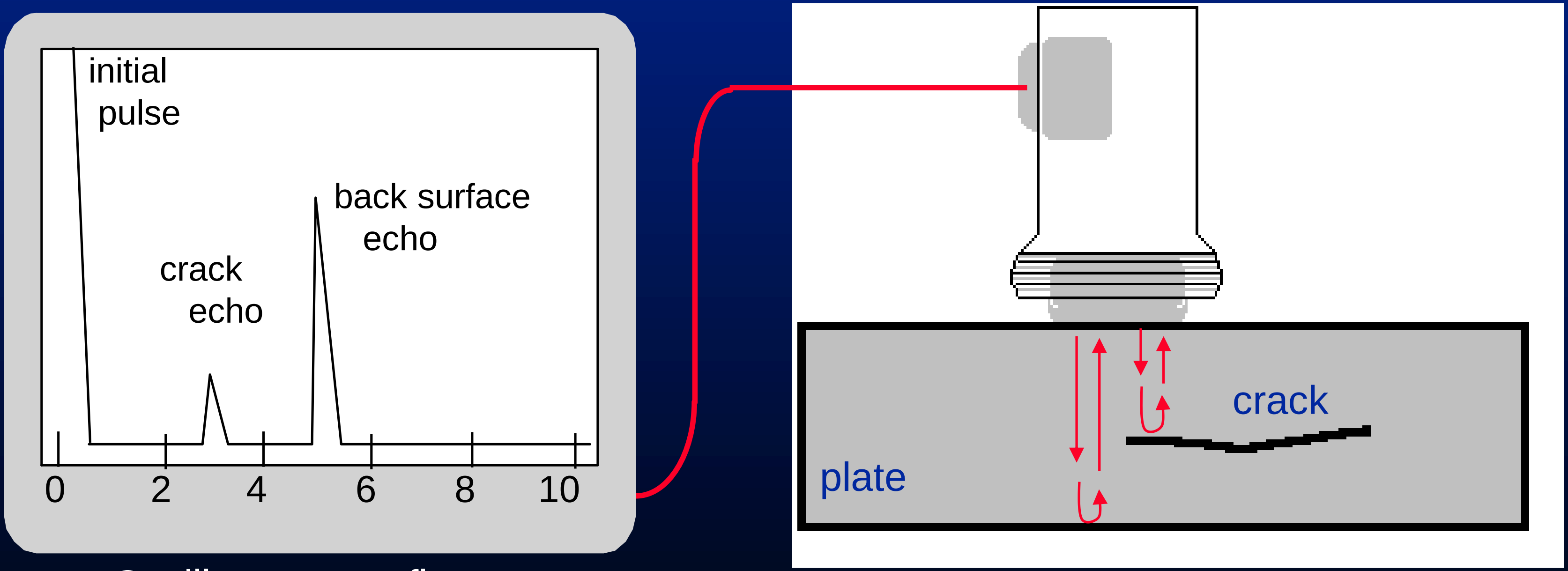
Eddy Current Testing

Eddy current testing is particularly well suited for detecting surface cracks but can also be used to make electrical conductivity and coating thickness measurements. Here a small surface probe is scanned over the part surface in an attempt to detect a crack.

Ultrasonic Inspection (Pulse-Echo)

High frequency sound waves are introduced into a material and they are reflected back from surfaces or flaws.

Reflected sound energy is displayed versus time, and inspector can visualize a cross section of the specimen showing the depth of features that reflect sound.

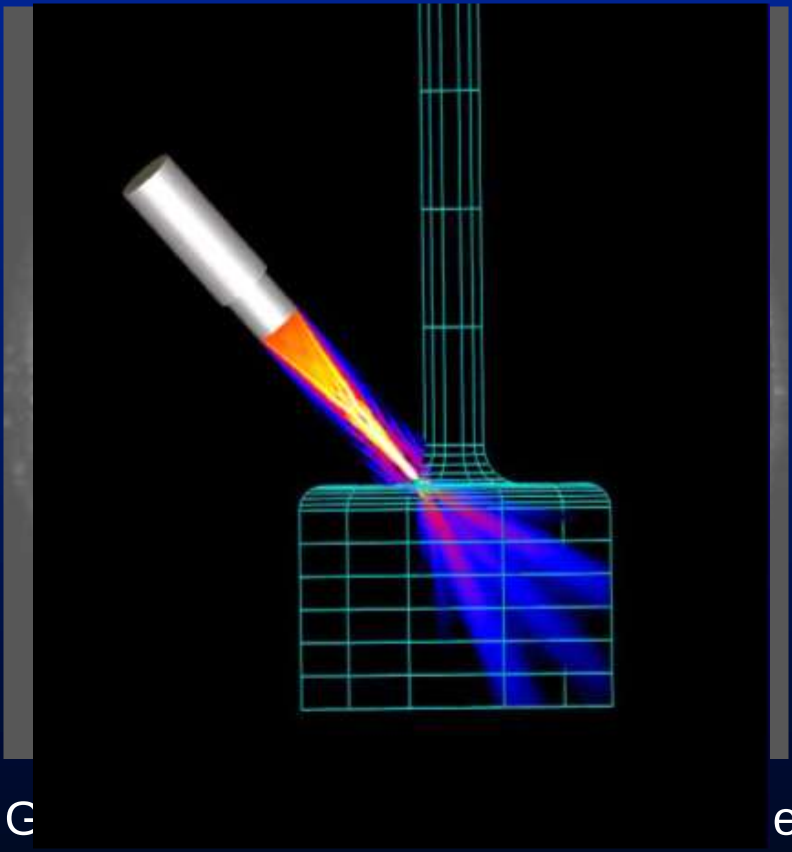


Oscilloscope, or flaw detector screen

Ultrasonic Imaging

High resolution images can be produced by plotting signal strength or time-of-flight using a computer-controlled scanning system.

Gray scale image produced using the sound reflected from the front surface of the coin



G e
sound reflected from the back surface of the coin (inspected from “heads” side)

Common Application of NDT

- Inspection of Raw Products
- Inspection Following Secondary Processing
- In-Services Damage Inspection

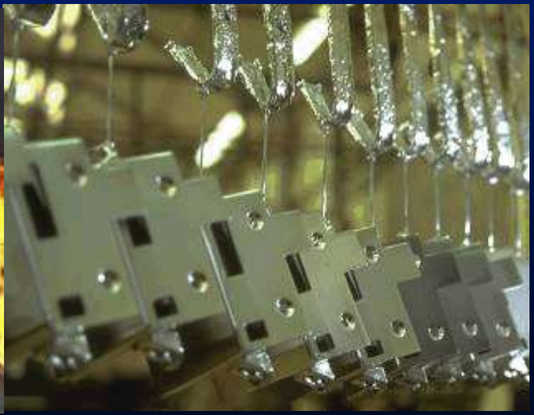
Inspection of Raw Products

- Forgings,
- Castings,
- Extrusions,
- etc.

Inspection Following Secondary Processing

- Machining
- Welding
- Grinding
- Heat treating
- Plating
- etc.

Photo courtesy of New Brunswick Community College

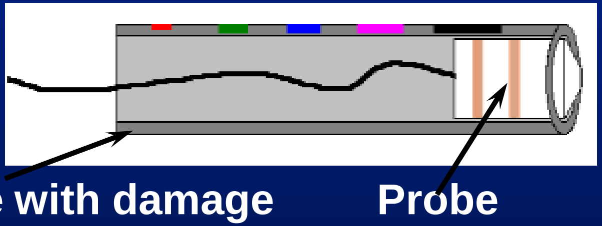


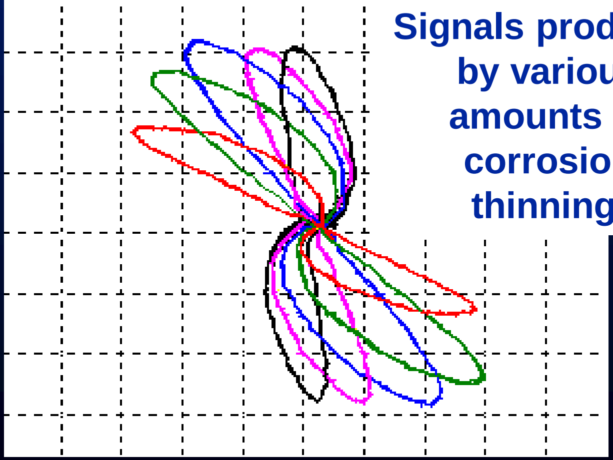
Inspection For In-Service Damage

- Cracking
- Corrosion
- Erosion/Wear
- Heat Damage
- etc.

Power Plant Inspection

Periodically, power plants are shutdown for inspection. Inspectors feed eddy current probes into heat exchanger tubes to check for corrosion damage.





Signals produced by various amounts of corrosion thinning.

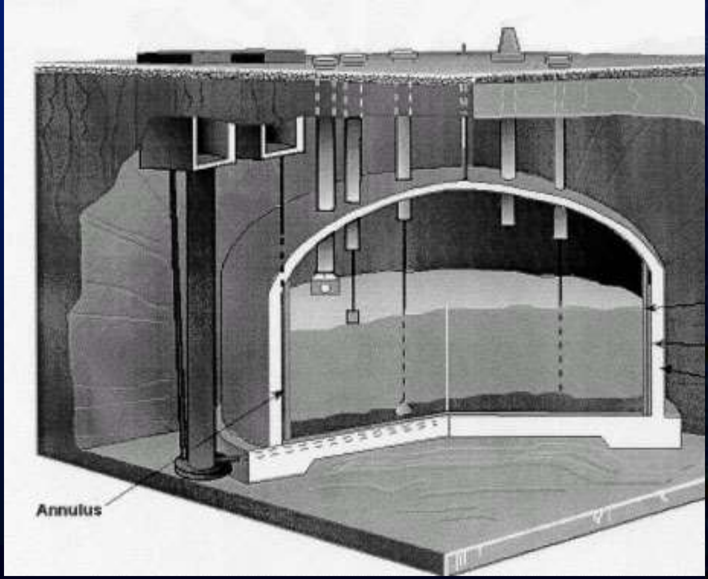
Wire Rope Inspection

Electromagnetic devices and visual inspections are used to find broken wires and other damage to the wire rope that is used in chairlifts, cranes and other lifting devices.

Storage Tank Inspection

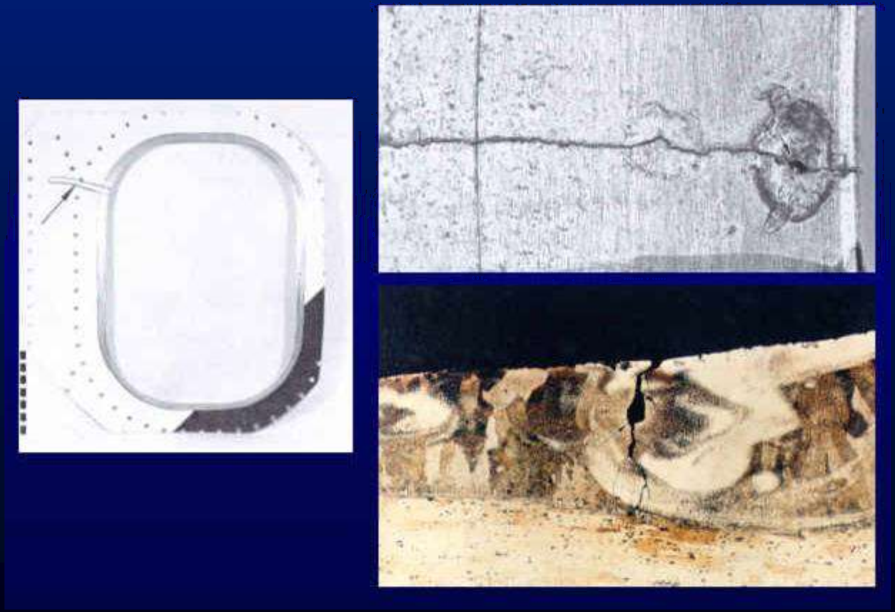
Robotic crawlers use ultrasound to inspect the walls of large above ground tanks for signs of thinning due to corrosion.

Cameras on long articulating arms are used to inspect underground storage tanks for damage.



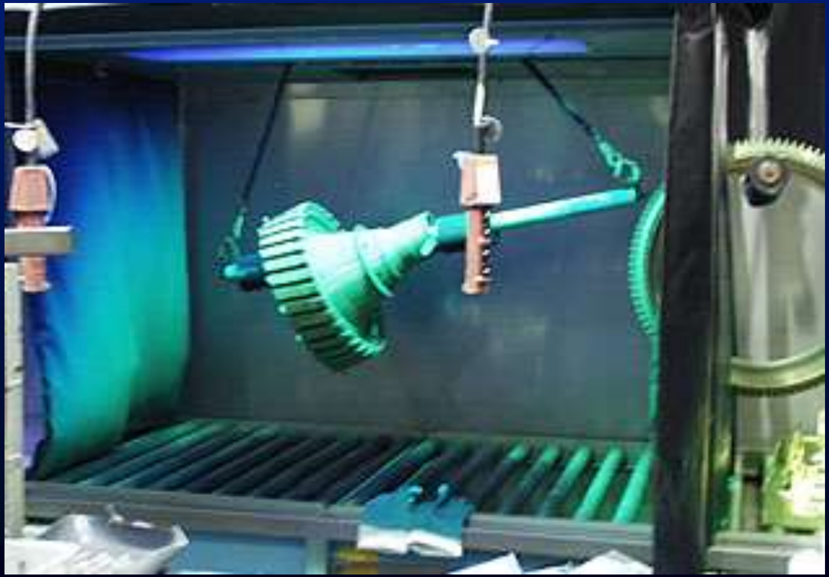
Aircraft Inspection

- Nondestructive testing is used extensively during the manufacturing of aircraft.
- NDT is also used to find cracks and corrosion damage during operation of the aircraft.
- A fatigue crack that started at the site of a lightning strike is shown below.



Jet Engine Inspection

- Aircraft engines are overhauled after being in service for a period of time.
- They are completely disassembled, cleaned, inspected and then reassembled.
- Fluorescent penetrant inspection is used to check many of the parts for cracking.



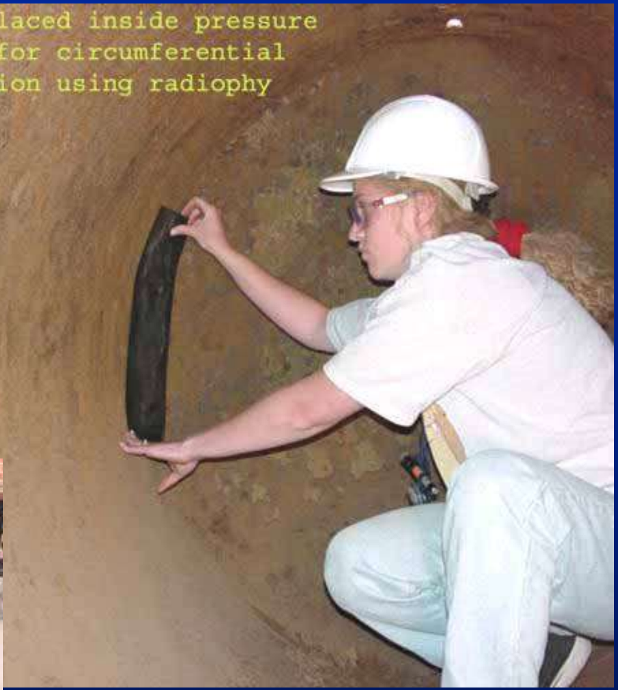
Crash of United Flight 232

Sioux City, Iowa, July 19, 1989

A defect that went undetected in an engine disk was responsible for the crash of United Flight 232.

Pressure Vessel Inspection

The failure of a pressure vessel can result in the rapid release of a large amount of energy. To protect against this dangerous event, the tanks are inspected using radiography and ultrasonic testing.



Film being placed inside pressure vessel I.D. for circumferential weld inspection using radiophy

Isotope radiography of weld on pressure vessel

Rail Inspection

Special cars are used to inspect thousands of miles of rail to find cracks that could lead to a derailment.

Bridge Inspection

- The US has 578,000 highway bridges.
- Corrosion, cracking and other damage can all affect a bridge's performance.
- The collapse of the Silver Bridge in 1967 resulted in loss of 47 lives.
- Bridges get a visual inspection about every 2 years.
- Some bridges are fitted with acoustic emission sensors that "listen" for sounds of cracks growing.

Photo Courtesy of Physical Acoustics Corporations

Pipeline Inspection

NDT is used to inspect pipelines to prevent leaks that could damage the environment. Visual inspection, radiography and electromagnetic testing are some of the NDT methods used.


Photo Courtesy of Inuktun

Remote visual inspection using a robotic crawler.

Magnetic flux leakage inspection. This device, known as a pig, is placed in the pipeline and collects data on the condition of the pipe as it is pushed along by whatever is being transported.


Photo Courtesy of Yxlon International

Radiography of weld joints.

Special Measurements

Boeing employees in Philadelphia were given the privilege of evaluating the Liberty Bell for damage using NDT techniques. Eddy current methods were used to measure the electrical conductivity of the Bell's bronze casing at various points to evaluate its uniformity.

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The Focal Point for NDT Education

Welcome to the NDT Resource Center.
This site was designed to be a comprehensive source of information and materials for NDT and NDE technical education. The site was created by NDT professionals and educators from around the world.

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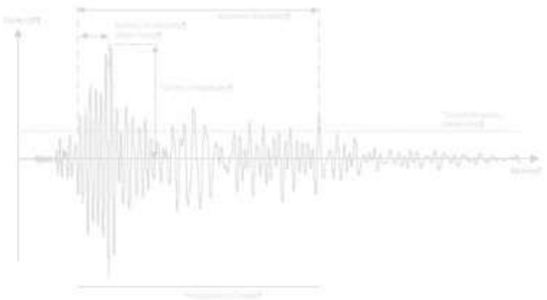


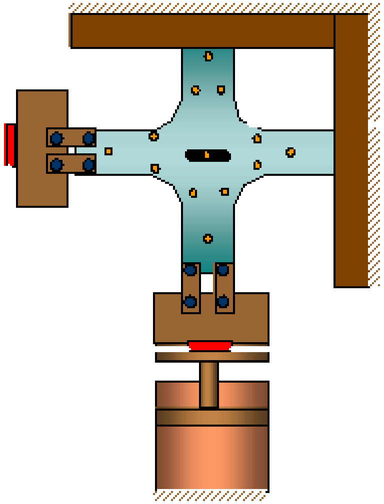
Acoustic Emission Test Platform

Introduction

- Acoustic Emission Applications
  - Method of Non-Destructive Evaluation (NDE)
    - Metals, composites, ceramics, concrete, etc.
- Advantages
  - Passive method of testing
    - Waits for Acoustic Emission to occur
    - Can be used as a trigger to activate another form of NDE
  - Cost Effective
- Disadvantages
  - AE alone allows only for location of defect, but not size and shape

Purpose (WHY?)

- Develop a system of inspection for non-piggable gas pipelines.
  - 280,000 miles of 24-36 in diameter pipeline
- Biaxial loading of specimen simulates axial and hoop stresses of a pressurized pipeline.
- Determine if a difference is present in Acoustic Emissions between 1 and 2D stresses.



Semester Objectives

- Modification and Perfection of AE test platform
  - Biaxial Loading of Specimens with stresses up to 30ksi
  - Incorporate hydraulic components

- Develop method of signal processing AE data
  - Filter out all extraneous noise from testing platform
  - Only analyze “AE Hits” directly around defect

- Development of empirical relationships quantifying the effects of biaxial stress loading on AE signatures

Specimen Fabrication

- Provided by Shell Oil Co.
- 0.5” Thick SA-516 grade 70 Steel Coupons
- Simulated Cracks of varying depths
  - .08”, .16”, and .32” deep
- Two sets of 3 specimens each
- Uniaxial and Biaxial Loading
  - simulates axial and hoop stresses of a pressurized pipeline
- Also machine specimens in house with saw cut defect

Specimen Fabrication

- Specimens made on Water Jet Machine
- Defect manufactured on Milling Machine

Rowan Water Jet Machining Center

Test Platform Design Criteria

- Design Challenges
  - Rigid Frame

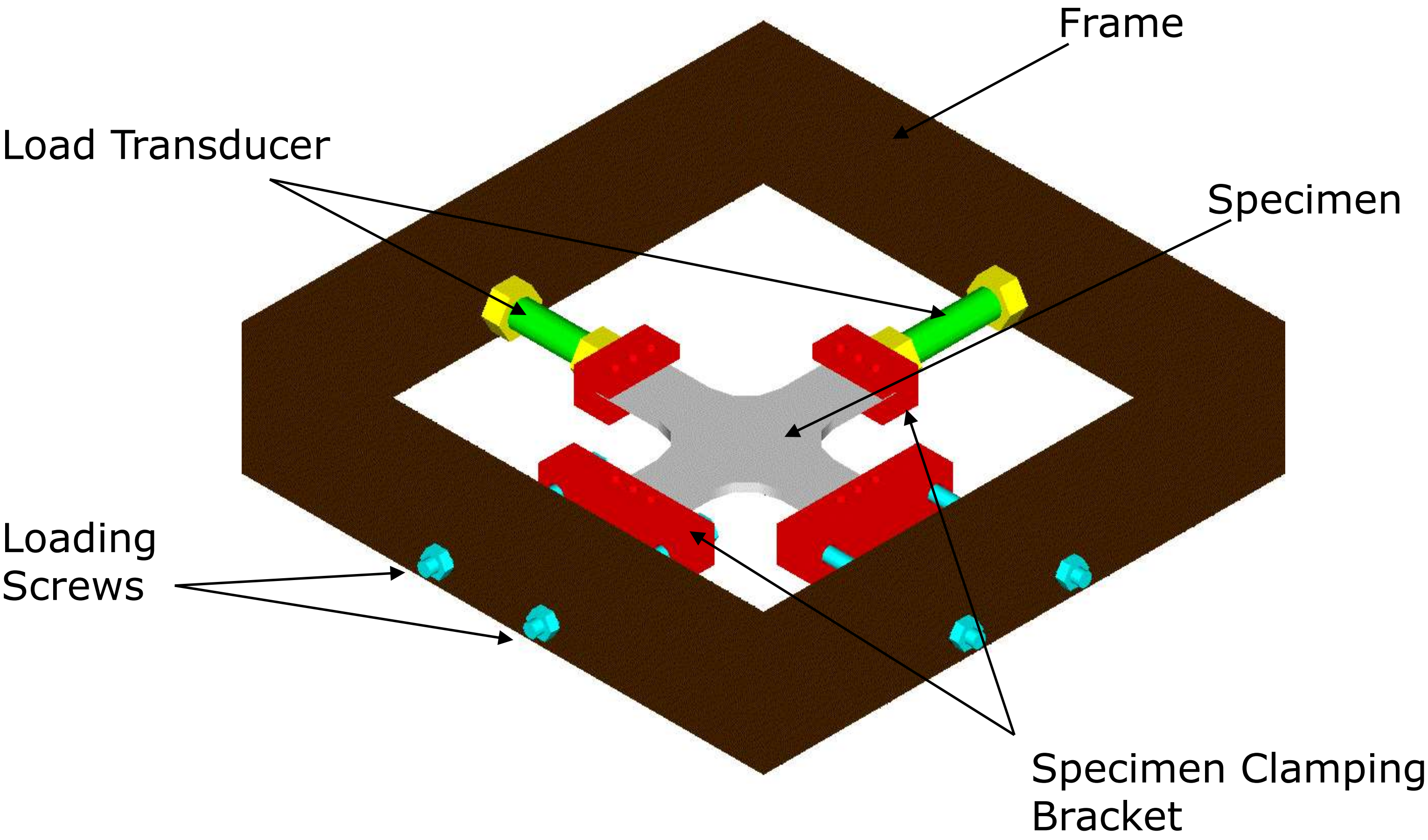
  - Perform Biaxial Loading of Specimen
    - 30,000 psi (45,000lbs) 1st Dimension
    - 15,000 psi (22,500lbs) 2nd Dimension

  - Short Manufacturing Time
  - Low Cost

Mechanical Test Platform

- Version 1
  - Prototype Design
  - 13.5ksi (20,000lbs) max load
- Version 2
  - Clamping Bracket Modification
  - 20,000ksi (30,000lbs) max load
- Version 3
  - Hydraulic Rams
  - Full Desired load of 30ksi (45,000lbs)

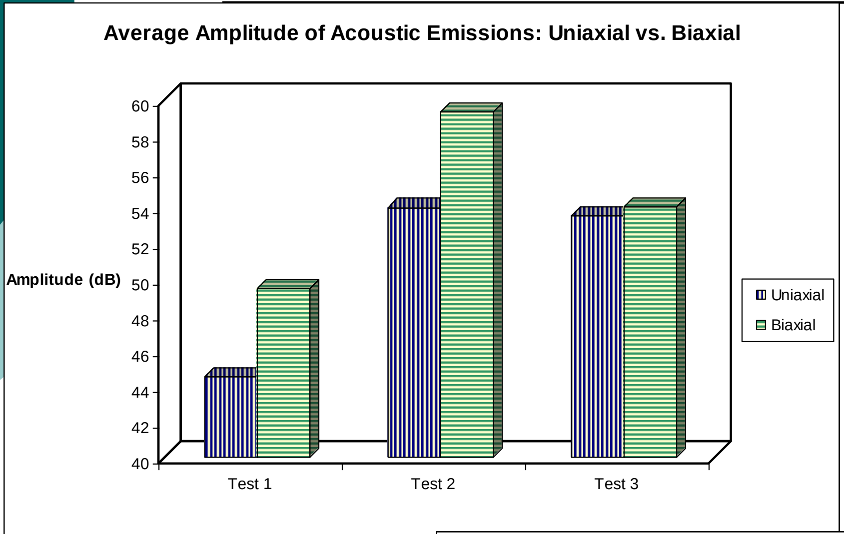
Version 1


Frame
Load Transducer
Specimen
Loading Screws
Specimen Clamping Bracket

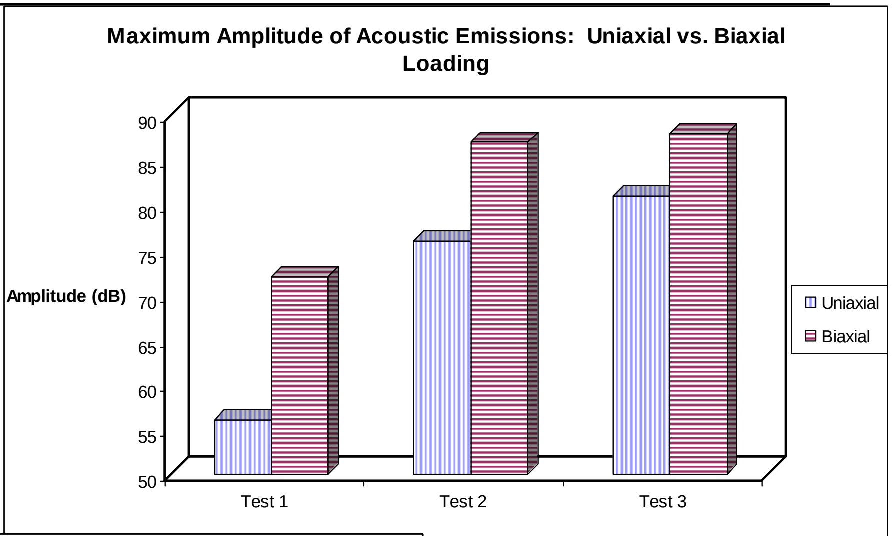
Testing Parameters

- Specimen was preloaded to:
  - Axis 1: 10,000 lbs
  - Axis 2: 20,000 lbs
- AE sensors activated and test run for approximately 30 minutes
- Crack Depth 60%, Length 2.5”

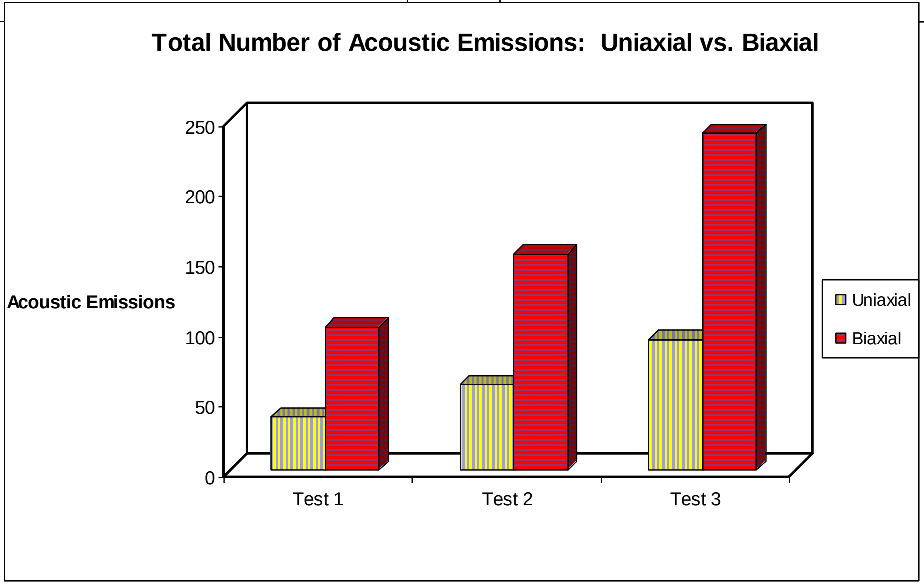
AE Results: Version 1



Average Amplitude of Acoustic Emissions: Uniaxial vs. Biaxial



Maximum Amplitude of Acoustic Emissions: Uniaxial vs. Biaxial Loading

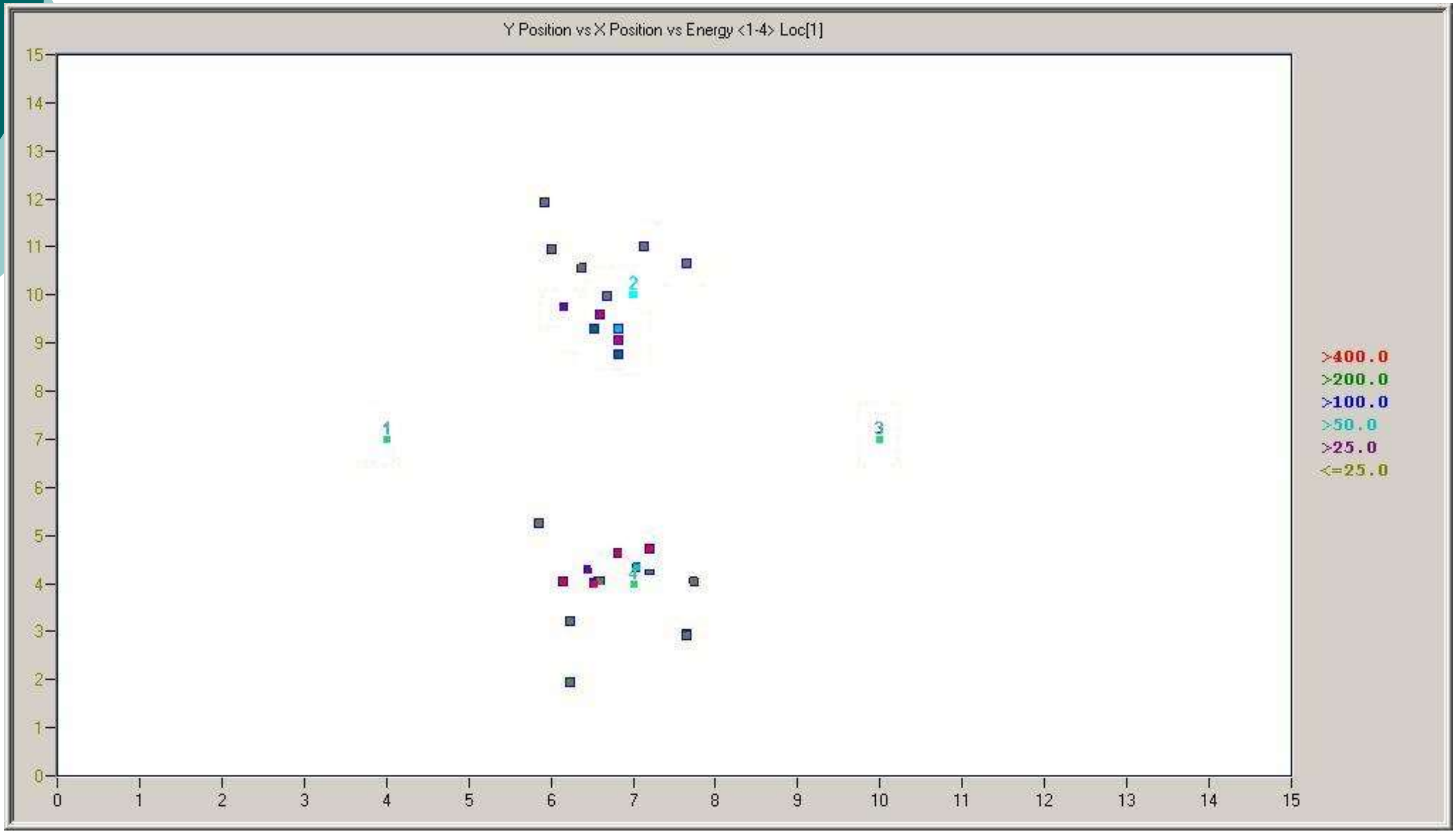


Total Number of Acoustic Emissions: Uniaxial vs. Biaxial

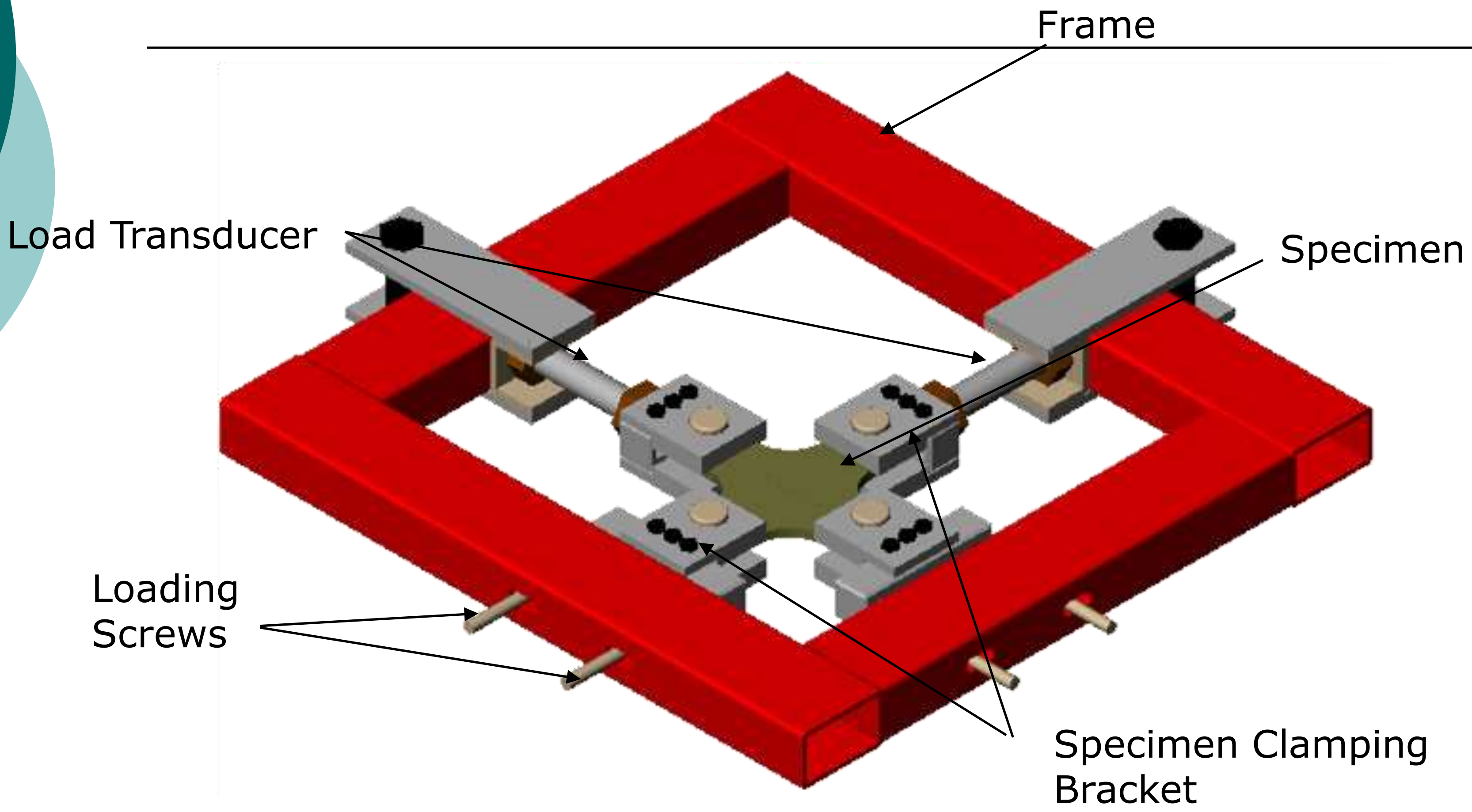
Version 1 Design Limitations

- Clamping method caused deformation of specimen producing spurious AE data.
  - Location View shows AE Hit concentration in proximity of clamping brackets
- Connection from load cell to specimen fixed, causing bending moment and non-uniform loading of specimen
- Inability to reach desired load

AE Location View: Version 1



Version 2



- New Clamping Brackets
- Pinned connections for ensure uniform loading
- Max of 30,000 lbs

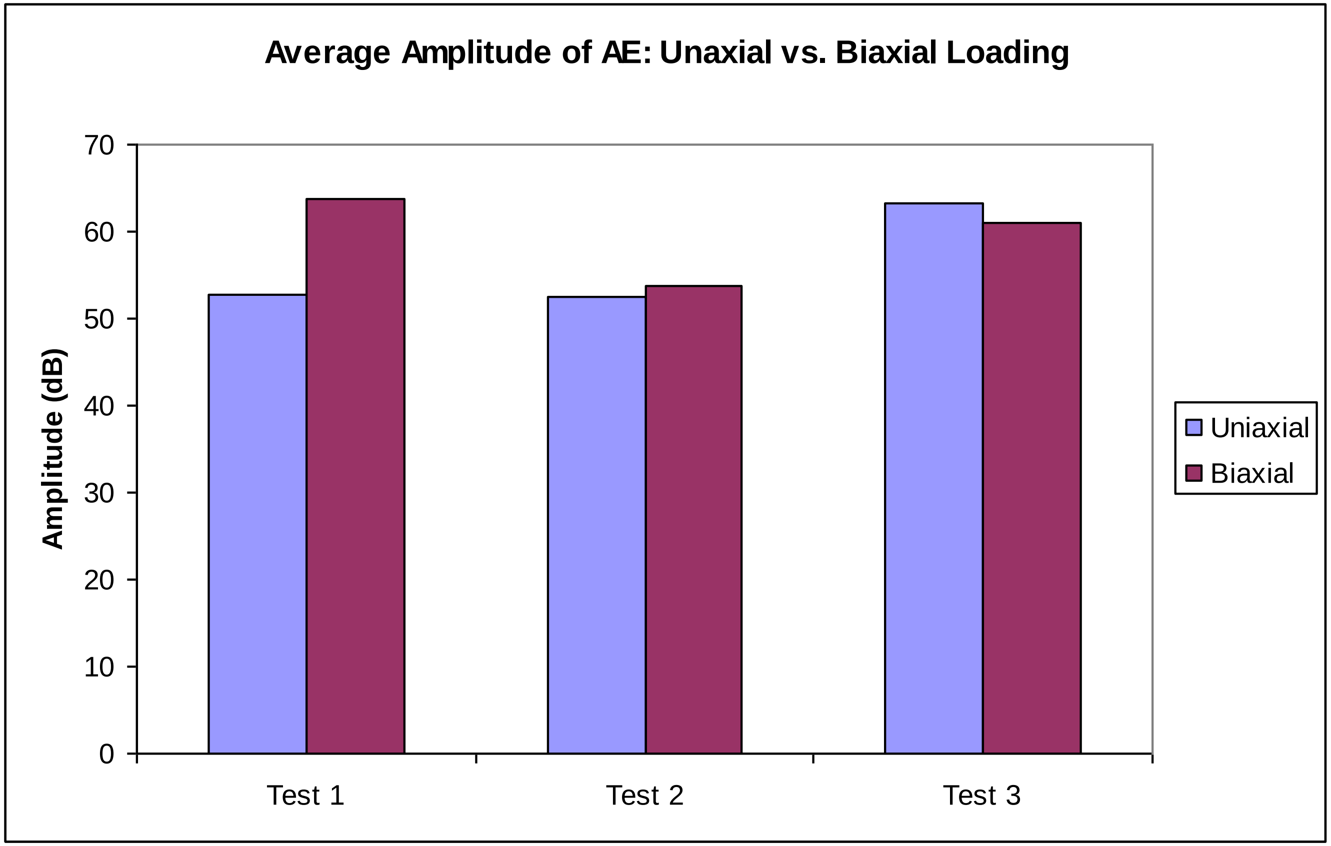
Testing Parameters

- AE sensors active throughout loading of specimen
- Specimen loaded in steps of 2000lbs to:
  - Axis 1: 30,000 lbs
  - Axis 2: 15,000 lbs
- Signal Processing performed to remove spurious data due to loading of test platform
- Crack Depth 80%, Length 2.5”

AE Results: Version 2

Average Amplitude

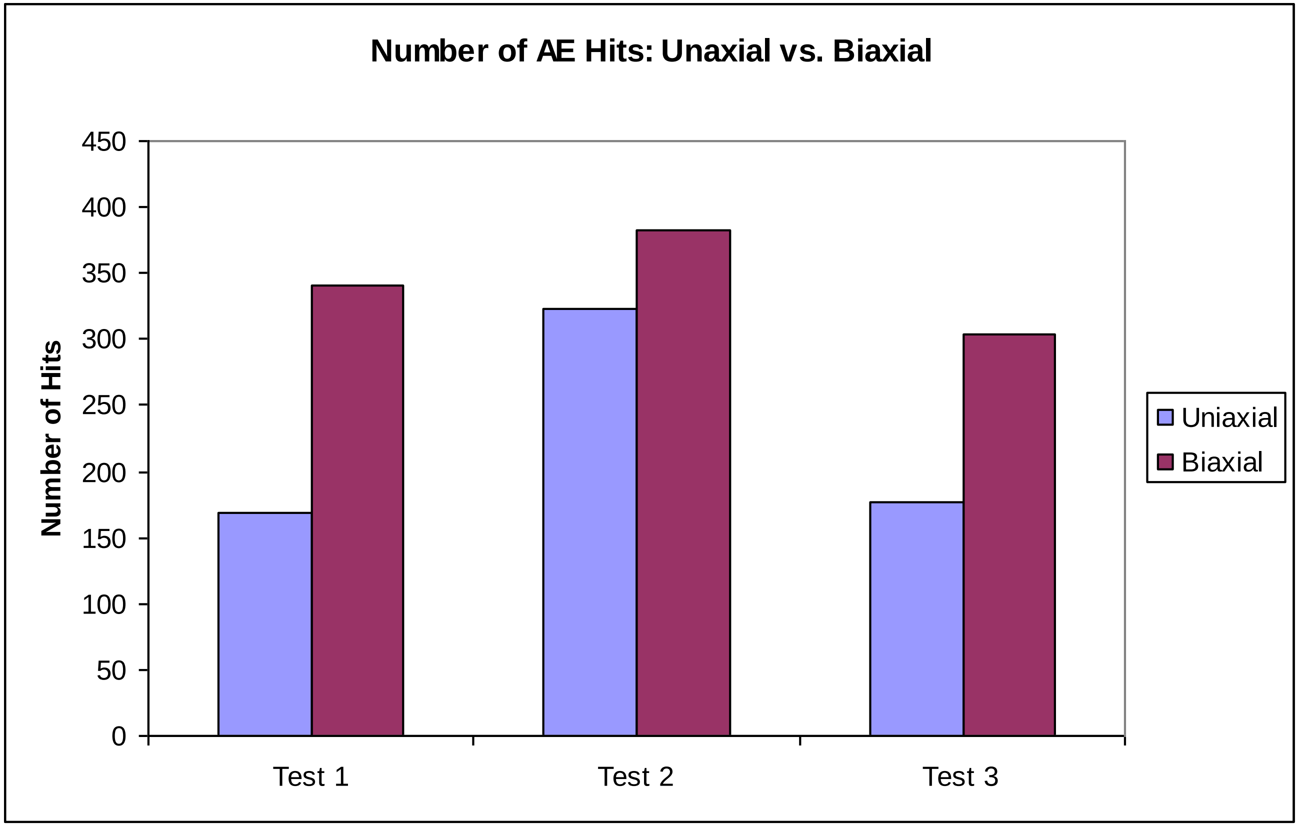
- Test 1
  - Uniaxial: 53 dB
  - Biaxial: 64 dB
- Test 2
  - Uniaxial: 52 dB
  - Biaxial: 54 dB
- Test 3
  - Uniaxial: 63 dB
  - Biaxial: 61 dB



AE Results: Version 2

Number of AE Hits

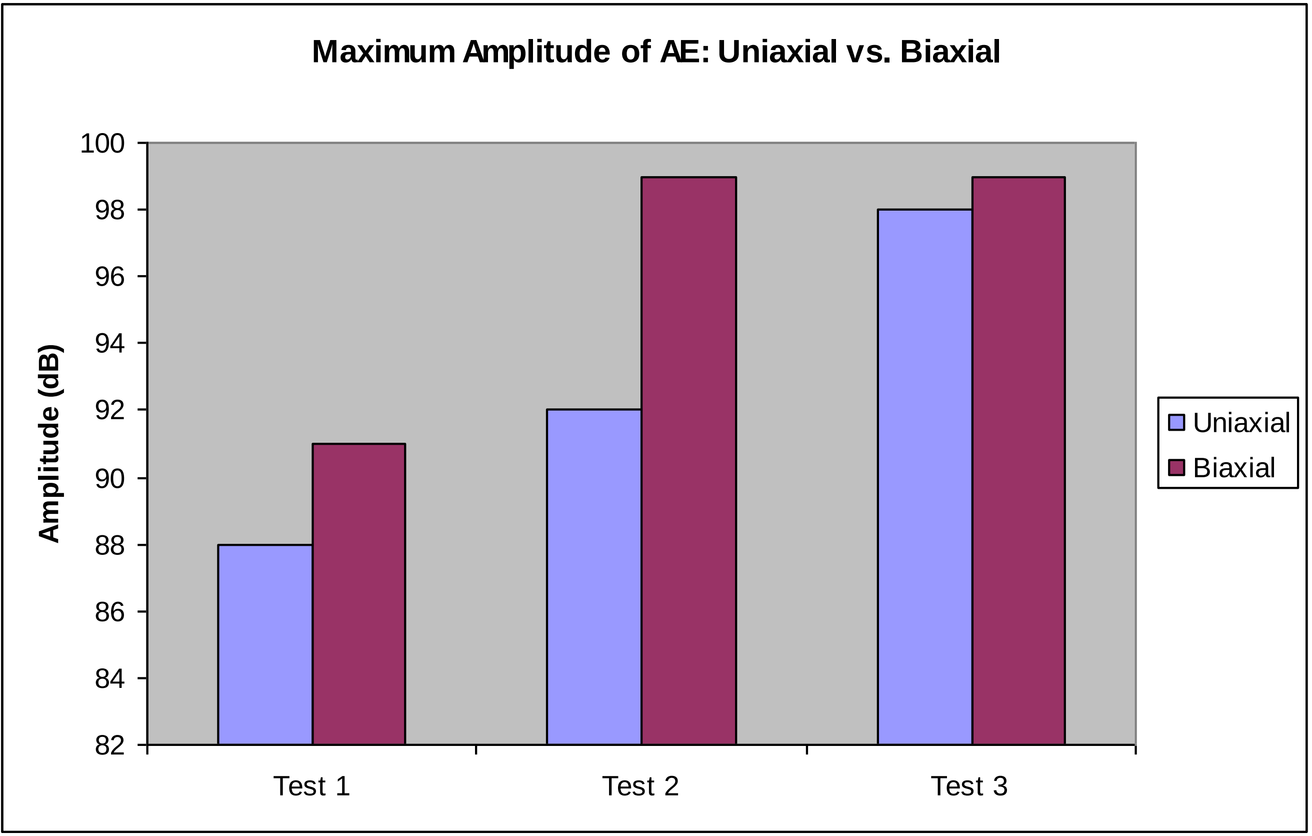
- Test 1
  - Uniaxial: 168
  - Biaxial: 340
- Test 2
  - Uniaxial: 323
  - Biaxial: 382
- Test 3
  - Uniaxial: 177
  - Biaxial: 304


Number of AE Hits: Unaxial vs. Biaxial

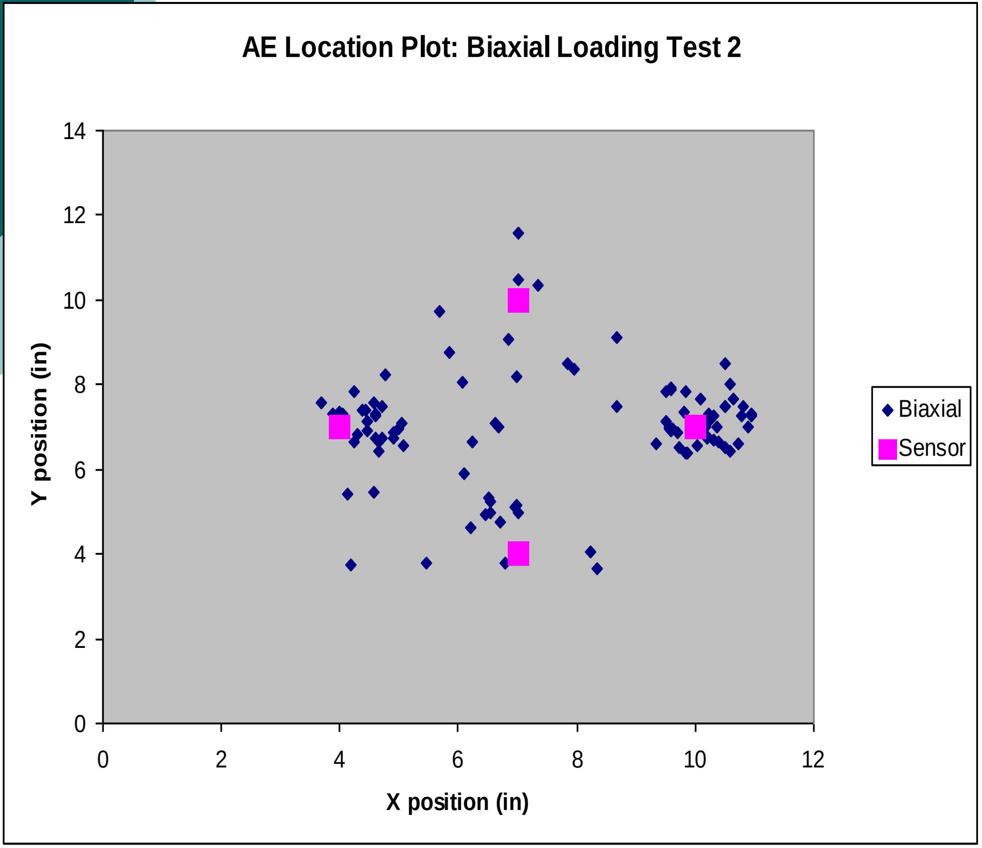
AE Results: Version 2

Maximum Amplitude

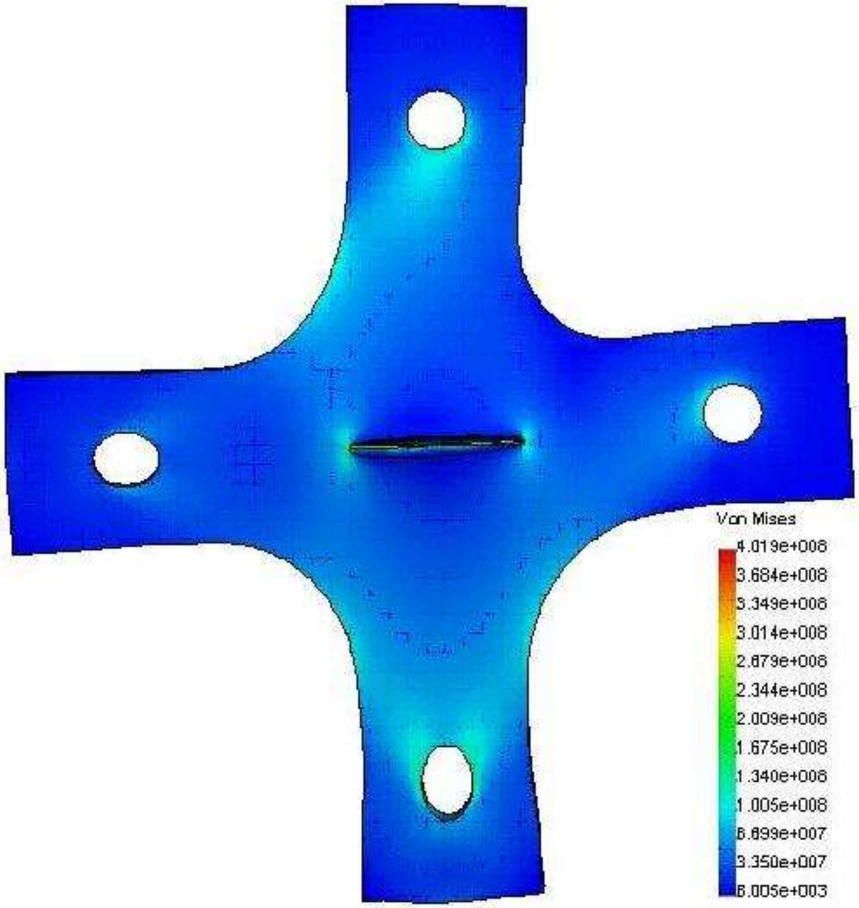
- Test 1
  - Uniaxial: 88 dB
  - Biaxial: 91 dB
- Test 2
  - Uniaxial: 92 dB
  - Biaxial: 98 dB
- Test 3
  - Uniaxial: 98 dB
  - Biaxial: 99 dB



AE Location: Version 2



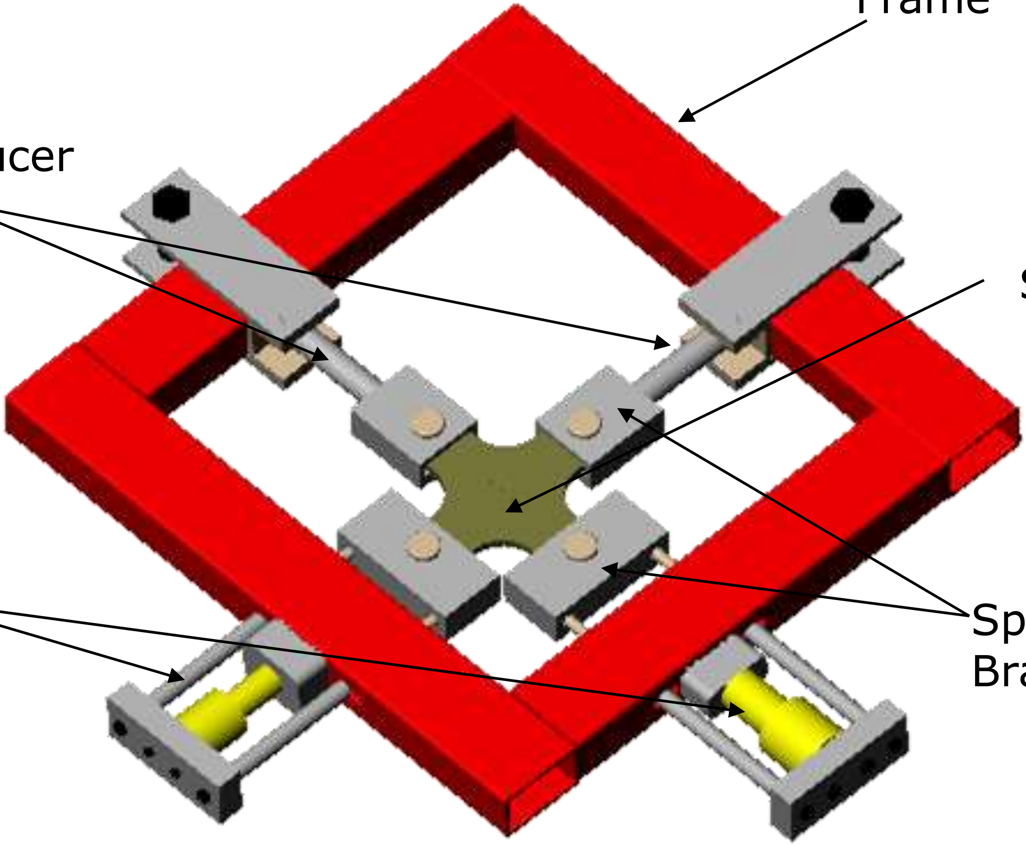
AE Location Plot: Biaxial Loading Test 2



Why version 3?

- Hydraulic design
  - Allows for increasing max load to 30ksi
  - Controlled loading environment
- New clamping bracket
  - Single pin piece – minimizes noise

Version 3



Frame

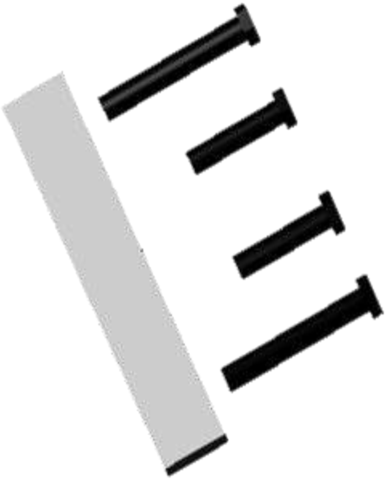
Load Transducer

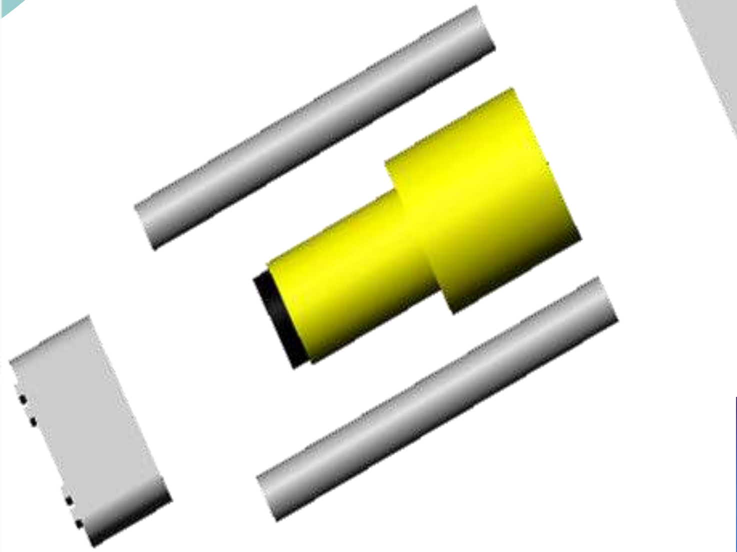
Specimen

Hydraulic Cylinders

Specimen Clamping Bracket

Hydraulic Design





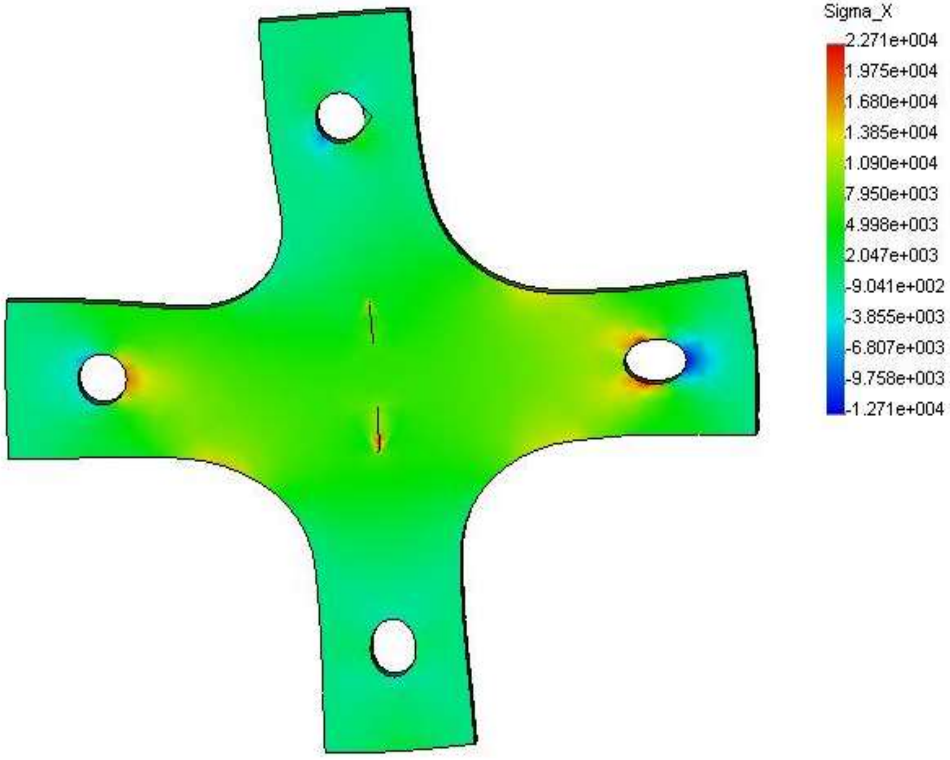
- Hydraulics
  - Enerpac RC-Series Single Acting Cylinders
    - 15 & 25 Ton Capacity
  - Hand Pump
    - 10,000PSI
    - Reach Full Load
- Cost Estimation
  - Approx. $2000 for hydraulic setup

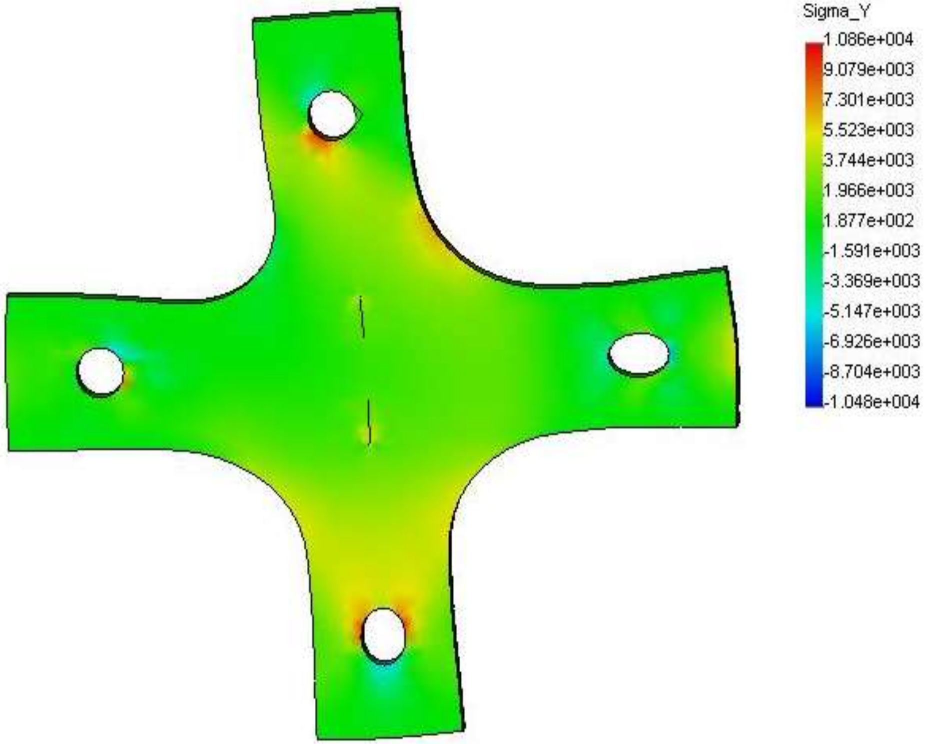
Finite Element Analysis

- Solid Works Modelling
- Cosmos Static Analysis

Specimen Analysis

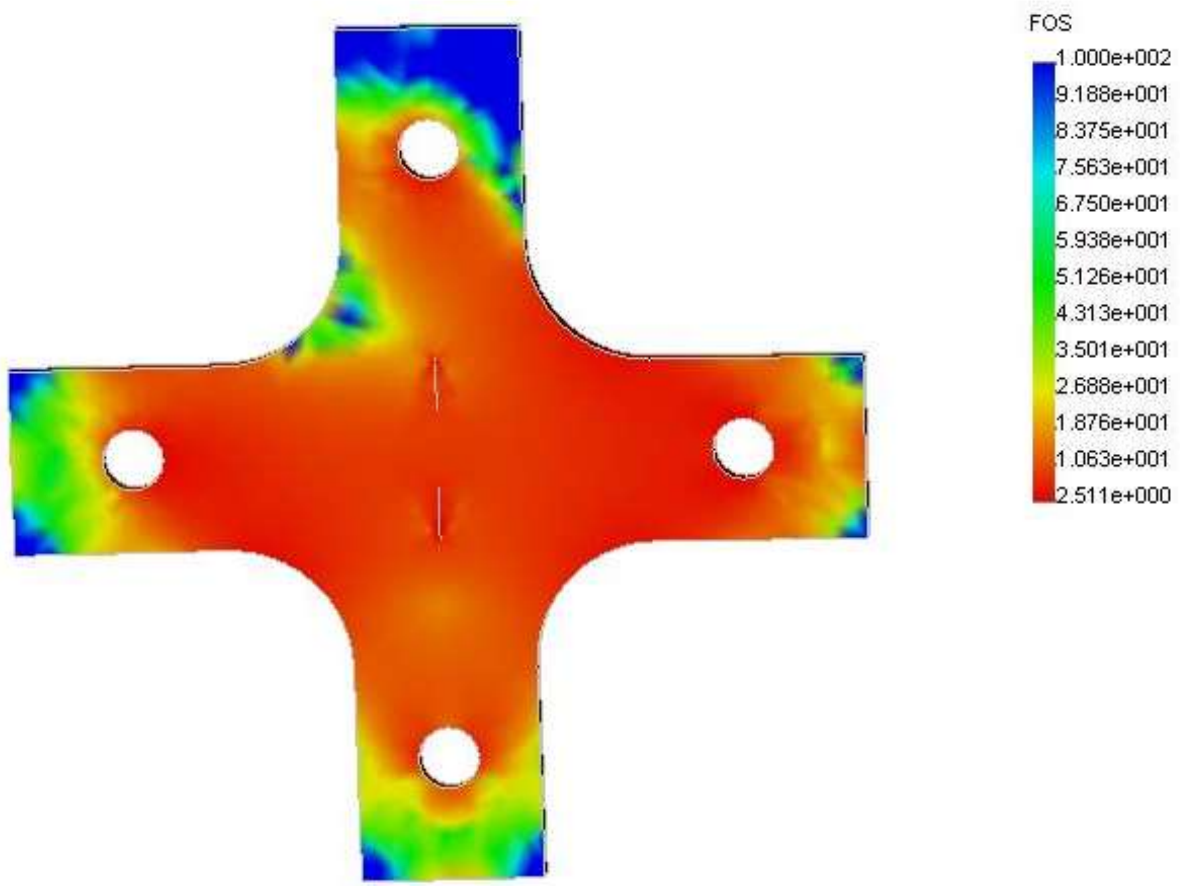
Normal Stress
X Direction





Normal Stress
Y Direction

Specimen Analysis

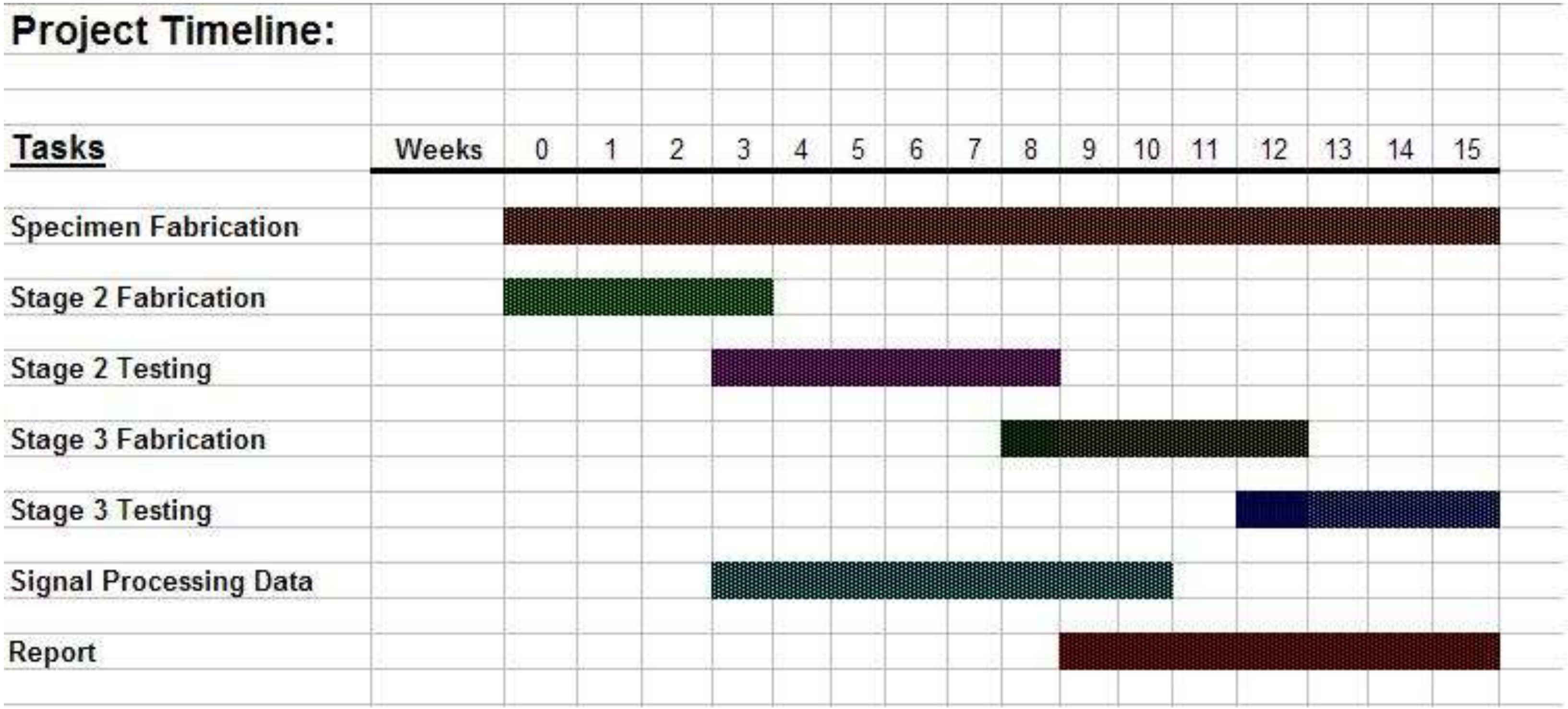


Factor of Safety Plot

Future Plans

- Complete Version 3 of Test platform
- Perform AE testing under full load of 30ksi on Shell Oil Specimens
- Prove Differences between Uniaxial and Biaxial loading
- Develop Calibration Curves of AE signatures

Gantt Chart


Project Timeline:
Tasks
Weeks
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Specimen Fabrication
Stage 2 Fabrication
Stage 2 Testing
Stage 3 Fabrication
Stage 3 Testing
Signal Processing Data
Report