Principles of Measurement & Instrumentation I

PHYS417

Topic: Stress-Strain Measurement Techniques and Systems

Midterm Paper

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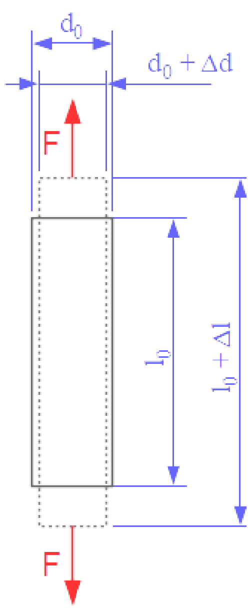
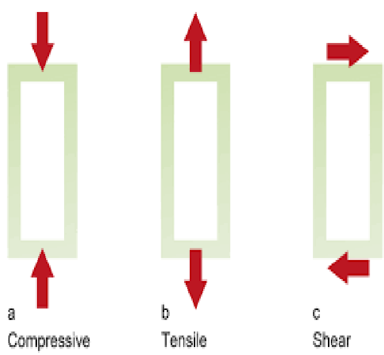
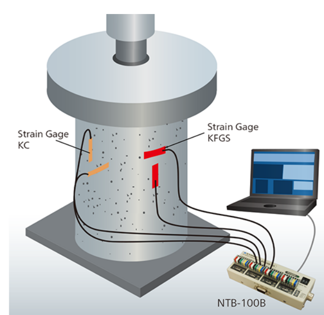
Introduction

In this report, Stress-Strain measurement techniques that are used and their system designs will be covered. Before giving details of the techniques that are used. There will be a part that will define the subjects that are covered in the report to give definitions beforehand to the reader who may not know what are some terms are. Stress mostly is used in fluid mechanics, but when combined with the strain it is mostly used to describe another phenomenon. They are altogether used for material elasticity, fragility and so, and in this report these systems that can measure this elasticity, fragility, maybe some other technical concepts like ultimate tensile strength will be discussed, but will not be focused on since they are just definitions in a system that will measure stress and strain.







(Figures from left to right, Uniaxial Stress State, All stress Types, Stress measurement device) [1],[4],[5]

Quick Review of Definitions

First of all, let's start with what is stress and what is strain then we need to build upon these and define more joint structures that come up from these.

Stress

Stress is what is defined as $\sigma = \frac{F}{A}$ or force per unit area within materials. Arises from external forces, such as; uneven heating, or permanent deformation and this permits an accurate definition and prediction of elastic, plastic, and fluid behaviour of a material.

σ is the applied stress, F is force that is applied, and A is the area of force application. Also the unit of stress is $\frac{N}{m^2}$. There are three types of stresses that should be mentioned.

Types of Stress

Stress that is applied to a material can be of three types as follows:

Tensile Stress

Tensile stress is the force that is applied per unit area and is the stress that happens when a body's length (or area) increases under this type of stress. Hence, objects under **Tensile stress** become thinner and longer.

Compressive Stress

Compressive stress can be said as the force that is applied per unit area, that decreases the length or area of the body. That being said the **compressive stress** makes objects thicker and shorter.

Shear Stress

Shear Stress, is the force that has the tendency to cause a deformation of a material by slippage along its plane or planes parallel to the imposed stress. This stress is important due to the resultant shear has a big impact on nature, and is related to the earth's movement of materials, hence earthquakes[2].

Strain

Strain is the amount of deformation that is mentioned in the stress part, hence that is experienced by the body in the direction of the force that is applied to make the stress. This change is divided by the initial dimensions of the object.
Here we can give the deformation equation in terms of an object that is solid, it is for its length.
$\epsilon = \frac{\delta l}{L}$. Here we will describe two of the types of the strain.

Types of Strain

Strain, experienced by an object can be named as of two types depending on the stress application as following:

Tensile Strain

Tensile strain can be said as the change in length or area of an object, due to the tensile stress that is applied.

Compressive Strain

Compressive strain is as mentioned above in Tensile Strain, is the change in the length or area of an object, but with the application of compressive stress this time.

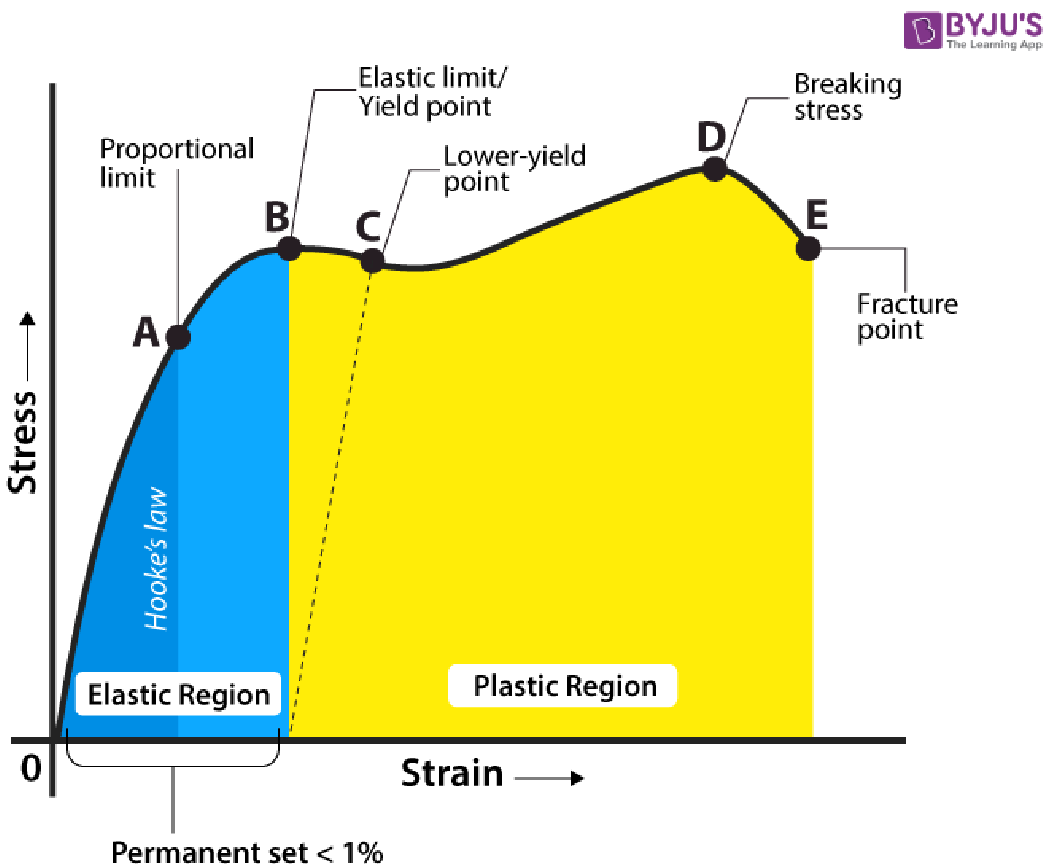
Shear Strain

Shear strain can be defined as the ratio of displacement to an object's original dimensions due to shear stress that is applied and can be said as the amount of total deformation perpendicular to a given line rather than parallel to it[3].

Stress-Strain Graph

In the study of solids and their mechanical properties, information about their elastic properties has one of the most significant in studying solids. From there on we can learn about the elastic properties of materials by studying the stress-strain relationship, under different loads, in these materials (solids).

The solid body's stress-strain curve gives us the relationship between the stress-strain from obvious reasons. In this curve, the stress and its corresponding strain values are given, from that, they are plotted. Here we have an example from byju's website:



[6]

Figure 4. Shows the Stress-Strain Graph

Some details about the Stress-Strain Graph will be given below.

Explanations on Stress-Strain Graph

The different regions that are named in the diagram are described below:

Proportional Limit (Maximum allowable stress)

In this region, the stress-strain curve obeys Hooke's Law. At this limit, the stress-strain ratio gives us a proportional relationship between the stress-strain, which is a proportionality constant known as the Young's Modulus (E represented in GPa or $E = \frac{\sigma}{\epsilon}$)[7]. The point that is OA in the figure 4 represents this proportional limit.

Elastic Limit (Yield Strength)

This is the point limit that shows us the final ground that the material can return to its original position when the load action on it is fully removed. Beyond this limit point called Elastic Limit, the material doesn't return to its original position, hence plastic deformation starts to appear in it.

Yield Point

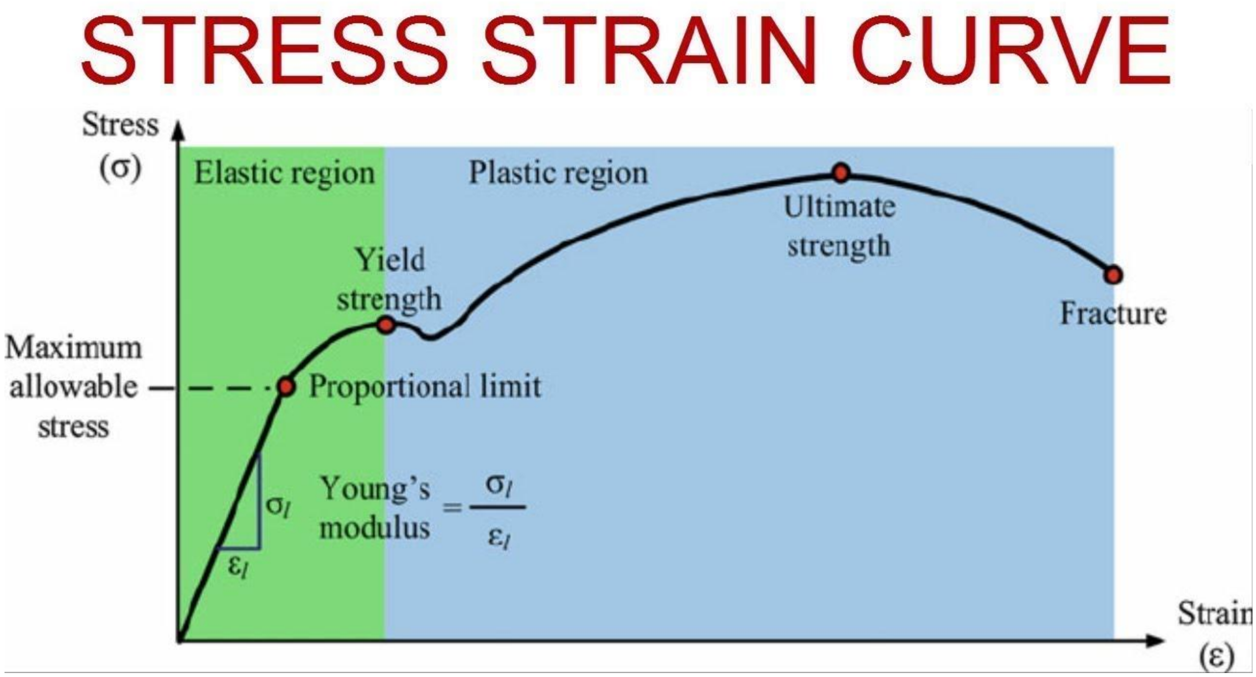
This is the point that defines the point that the material starting to deform plastically. After the so-called Yield Point is passed, permanent plastic deformation starts to occur. There are two of these points, Upper Yield Point and Lower Yield Point

Ultimate Stress Point (Ultimate Strength/Ultimate Tensile Strength)

The point represents that the maximum stress that a solid body or material can endure before failure/fracturing. Beyond this point, failure starts to occur.

Fracture or Breaking Point (Fracture)

At this point, the stress-strain curve shows us that the failure point of which the material failure takes place.



[8]

Figure 5. Shows Stress strain curve with regions

Hooke's Law

In the 19th century, while studying elasticity and the springs, the well-known English Scientist Robert Hooke, discovered that many of the materials exhibit a property that is similar when the strain-stress relation is studied. There was a linear region that he discovered that the force required to stretch the material was proportional to the extension of the material itself, which is now known as Hooke's Law. Mathematically speaking it is represented as, $F = -k * x$ in which F is the force, x is the extension or compression of the length, and k is the constant that shows the proportionality that is known as spring constant which has units of $\frac{N}{m}$.

Poisson's Ratio

In mechanics, Poisson's Ratio is defined as the negative of the ratio of transverse strain to lateral or axial strain. Name of Poisson Ratio is given after Siméon Poisson, and the Greek letter name of it denoted by "$\nu = nu$", this is the ratio of the amount of transversal expansion to the amount of axial compression for small values of these changes. "$\nu = \frac{-\epsilon_{trans}}{\epsilon_{longitudinal}}$" ϵ *is Strain.* [9][10]

Also it is important to add that Poisson's ratio can be shown in another terms. V_p, P-waves, and S-waves, V_s as shown below. $\sigma = \frac{1 \times (V_p^2 - 2V_s^2)}{2 \times (V_p^2 - V_s^2)}$. If velocity of S-wave is 0, then Poisson's ratio equals to 0.5, indicating either a fluid, due to shear waves don't pass throughout the fluids, or a material that maintains constant volume regardless of the stress, which is also known as ideal incompressible body/material. E.g for Carbonate rocks this ratio is 0.3, for sandstones it is 0.2, and for shale more than 0.3. For coal it is 0.4.[11]

Transducer

Transducer is a device that converts one form of energy to a readable signal. Many of the transducers have the input to get it converted to a proportional electrical signal. Common inputs can be said as energy, torque, force, light, position, acceleration, and other mechanical properties.[14]

X-ray Diffraction Analysis (XRD)

XRD is a technique that is used in material science to determine the crystallographic structure of a material. XRD's working mechanism is irradiation of material with incident X-rays and then measuring the intensities and scattering angles of the X-rays that leave the material. XRD yields information about how the actual structure deviates from the ideal one, thanks to internal stresses and defects.[20]

Measurement Techniques and Systems

Here we will talk about which measurement devices, systems, and techniques are used in measuring stress, strain, force, weight, and rest that are required to analyze the strain-stress curve and so.

Strain Measurement

First of all, it is important to know the usual way of assessment in structural parts of machinery, buildings, vehicles, aircraft, ships, etc. is based on the strength of material calculations.

Calculations based on strength of materials are satisfactory if component loads provided are known both qualitatively and quantitatively, hence the method is appropriate for measurement. We start to have issues related to calculations when the loads are unknown or in a system where they are only known as rough approximations. In the past, the risk of overloading (which indicates the risk of passing the ultimate tensile strength as mentioned in the part of the definition or there is the risk of the plastic deformation.) was eliminated by the usage of safety margins, i.e. through over dimensioning. So, the limits are not well known but in a small size. Since, modern designs require strategies that lessen the usage of excess material, partly for reasons of cost and partly to save weight; it can be clearly seen in the aerospace industry. Hence, to satisfy the safety requirements and to provide an appropriate component service lifetime, the material stresses must be known. Henceforth, we require the measurements tests that show under operational conditions of the materials are necessary for the production.

An important arm/branch of the experimental testing of stress to have the stress analysis are based on the strain measurement principle at the core. At the beginning of the analysis, stodgy mechanical devices were used for strain measurement, which displays the strain using a lever ratio of one thousand or more. These devices were for generations the only method to carry out the measurements that are essential for stress analysis. Despite the fact that they are ingenious in their design and precise in construction, they possessed intrinsic disadvantages that severely restricted their range of applicability in other services, and therefore reduced their significance. In these:

- Static processes are the ones that could be observed,
- Strong clamp forces are required to prevent devices to slip under vibrational motion,
- Test sample needed to be fixed with respect to the observer,
- Due to the size of the devices places had restrictions on their use for small test samples and in some cases, this made the measurements impossible,
- For long measurement bases, it only gives correct results if uniform conditions of strain are managed, hence close situated stress concentrations are not measured,
- Local conditions might be insupportable for the observer,
- There cannot be automatic recordings of these measurements.

Hence, as a result of these shortcomings, the restriction of making only static measurements was regarded as a severe disadvantage. In the end, electrical measurement techniques gave the solution.

Let's look at the operating principles of the strain gage then shortly look at the strain gage types.

The operation principle of the strain gage

Strain gages are used to measure the strain approximates that the strain on the object under investigation is transferred without loss to the strain gage. This approximation has the requirement of a close bond between the strain gage and the object that is measured. In many cases, only the open surface of the object that is measured is accessible for the measurement, even though the open surface can be the internal cavity as well as, a place that is located outside of the object. So, the very close bonding which is required between the measurement object and the strain gage is best provided by an adhesive.

Internal measurements on the object, i.e. measurements within itself of the object, are possible only under special circumstances for strain gages. Perhaps, these might occur, e.g, when with plastic measurement objects in modeling techniques, in which the gage is molded during the part's manufacturing process or with concrete structures where gage is embedded to concrete during the pouring process. The latter case requires encapsulated strain transducers.

Other bonding materials and methodologies are mainly limited to some special applications, such as ceramic bonding for high-temperature ranges and spot welding for steel construction are needed. Also, both of these processes that are discussed require specially designed strain gages. Here in this report, there won't be any emphasis on the different types of specially designed strain gages rather a general understanding of various types of strain gages.

With the usage of electrically resistive strain gages, the strain transferred to the gage from the object causes a change in the electrical resistance in the gage. There are two types of these resistive strain gages, which are metal, and semiconductor strain gages.

Metal Strain Gages

In the second half of the decade of the 1930s, the attention was on an effect that is mentioned by Charles Wheatstone, who is the inventor of the Wheatstone bridge circuit, that shows the change of resistance in an electrical conductor due to the effects of mechanical stress, but his phenomenon could not be technically applied at the year of 1843, which is the year he published the effect.

The reasons are the change of resistance of a wire under tension was very small. For his measurements, later on, Thomson used highly sensitive galvanometers, William Thomson and Lord Kelvin are the people who added more to his work orderly in 1856 and 1892, which are unsuitable for general technical applications of the industry. Furthermore, they were only suitable to be applied as a measurement to static processes.

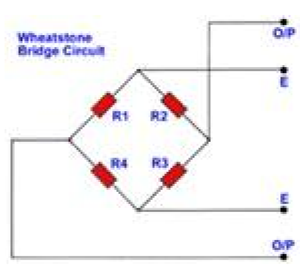
Finally, *Arthur Claude Ruge,* who worked at MIT at the time wanted to measure stress due to vibrations of earthquakes on a model of an earthquake-resistant water tank. Since the system at the time was not capable of measuring at very thin-walled models. As a last attempt, Ruge took a very thin resistance wire, stuck it in a meander shape onto some thin tissue paper, and terminated the ends with thicker connections. To investigate the properties of this device of his, he glued it to one of the bending beams and compared measurements of his with the traditional strain measurement device (calibration). He found that there is a good correlation with a linear relationship between strain and the displayed values over the complete measurement range, both with positive and with negative, i.e. compressive, strain, including well zero-point precision. Then, the "electrical resistance strain gage with bonded grid" was invented. The shape used in those very first tests was the same as that is normally used in today's world.

His accomplishments in inventing the new gage turned strain gage into a reliable measurement instrument in stress analysis.

In later decades various modifications were tried in order to rationalize production. Paul Eisler's *printed circuit*, which in its refined form led to the development of the "Foil strain gage" in 1952.

This new model compared with the wound-wire techniques, it is substantially extended the possibilities of design since all gage shapes could be made in one plane without additional efforts given. Spiral shapes as HBM company does can be easily reproduced, which can complete networks. Such as those that are used in transducers for the measurement of force, pressure, torque, and other mechanical properties.[12][13]

Here are some examples representations of the built of the metal strain gage:



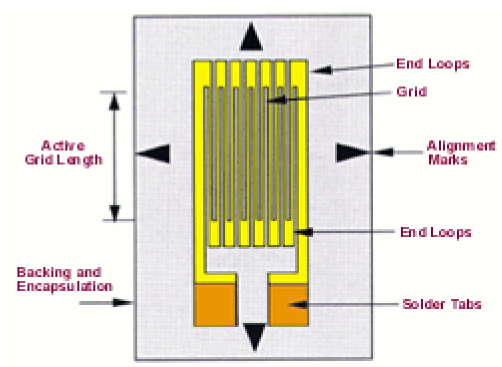
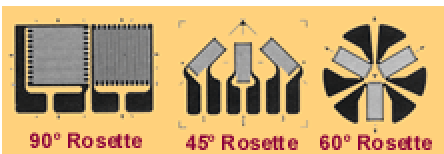


Figure 7 (On the left) shows the system of Wheatstone bridge used in strain gage[16]
Figure 8 (On right) shows the printed circuit metal strain gauge with its descriptions written inside[16]



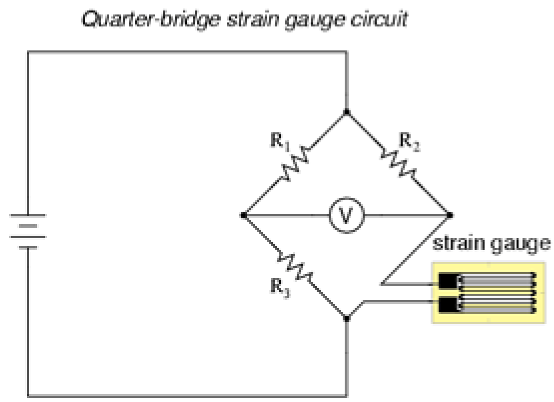


Figure 9 (On the left) shows different angle systems of metal strain gage[16]

Figure 10 (On right) shows Quarter-bridge strain gauge circuit[16]

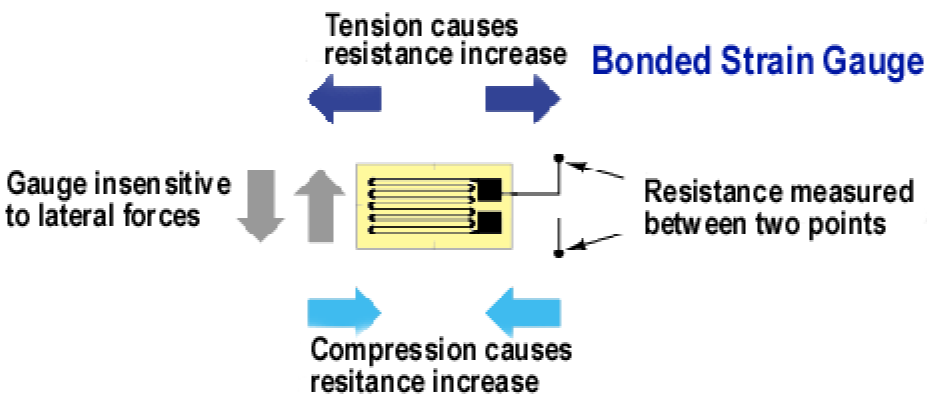
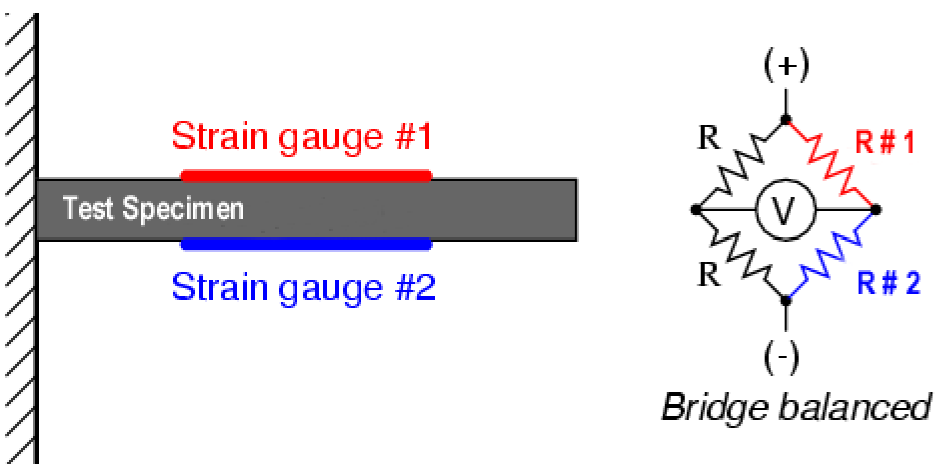


Figure 11 shows Bonded Strain Gauge and how does it work[16]



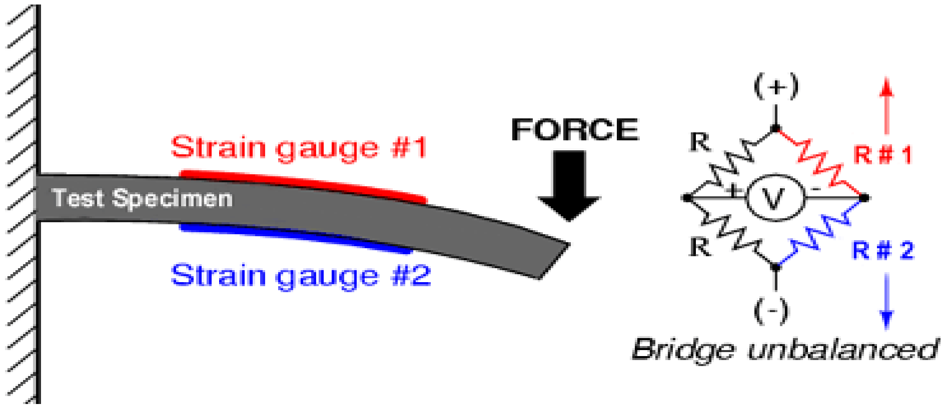


Figure 12 (On Top) and 13 (At the bottom) illustrates the inner mechanics of strain gauge and the difference it does in the bridge[16]

Semiconductor strain gages

Other than metal strain gages there can be named other various types of electrical resistive strain gages, Semiconductor strain gages that will be discussed here belong to these other types and they are extending the range of applications in strain gage technology. Their measurement principle is based on the semiconductor piezoresistive effect which is discovered by C.S. Smith in 1954. In the beginning, the Germanium (Ge) element was used, later on, it was superseded by Silicon (Si).

In the construction design, they are mostly the same as metal ones. Elements for measuring include a strip that is a few tenths of a millimeter wide and a few hundredths of a millimeter thick which is fixed to an insulating carrier foil and is provided with connecting leads. Effects of the diode are prevented by the usage of thin gold wire as a connection between the semiconductor element and the strips connecting.

The ratio between a strain that is measured and the signal is given by the strain gage, which is called gage factor, is about fifty to sixty times that of metal strain gages, this is the most available gage factor for semiconductor strain gages. Therefore these gages are mainly used in transducer manufacture for the measurement of other physical quantities that are being supplemented by simple electronic devices to form transmitters.

Semiconductor strain gages are not widely used in experimental stress analysis as metal ones and there are several reasons:

- Non-linear characteristics of the semiconductor strain gage call for measurement correction demands high accuracy
- Semiconductor strain gages are substantially more expensive than metal ones.
- Even though greater sensitivity is available, adverse temperature-dependent effects are more severe with semiconductor gages than with metal ones, and these effects are more difficult to compensate.
- Handling is much more difficult due to the semiconductor's brittle nature.

On the other hand, the semiconductor has high sensitivity which is a reason for using semiconductor gages on measurements of very small strains. The large signal given by this type of strain gage is of particular importance, and advantage in the presence of strong interference fields.

Here is an example of semiconductor strain gage

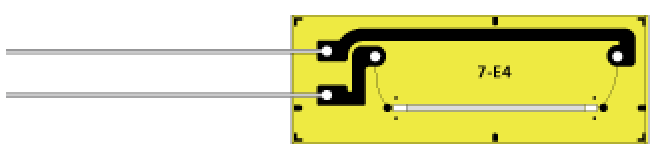


Figure 14 shows a semiconductor strain gage design[17]

Apart from conventional strain gages, there are other types that are only be mentioned in their quintessential parts.

Vapor-deposited (thin-film) strain gages

The third type of strain gage that is electrical resistive is provided by the vapor deposition technique. The measurement element in this gage is directly deposited onto the measurement point under a vacuum by the vaporization of the alloy constituents.

Its applicability range is highly limited, one can say that it is there to only produce transducers. Usage of this technique in various other fields of production has been tried various times, but no satisfactory end result has been achieved. Therefore, attempts were abandoned. There are several other efforts tried on vapor-deposited semiconductor strain gages, but there is no noticeable increase in its market capitalization.

Here is an example thin-film strain gage:

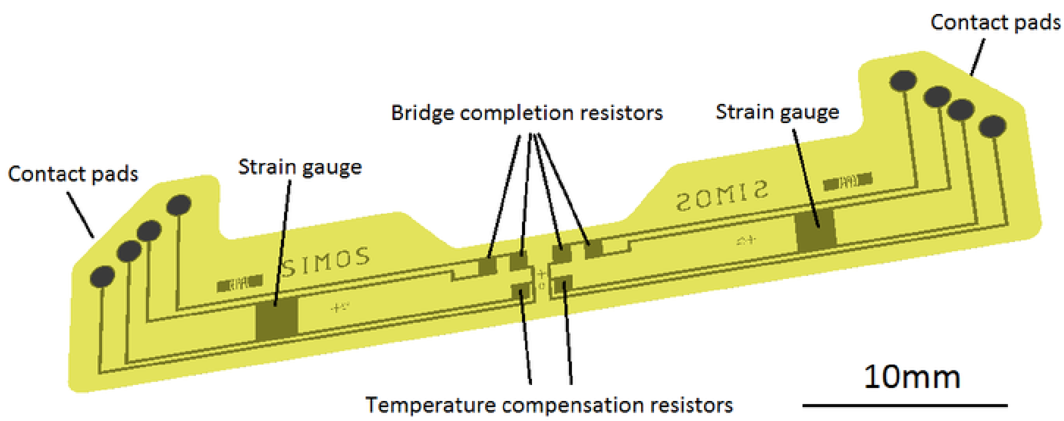


Figure 15 shows a sample thin-film strain gauge [18]

Brand K-Space designed a new kSA MOS (Metal-Oxide-Semiconductor) thin-film strain gauge to analyze thin-film stress that has dynamic changes. Hence, the semiconductor-thin film strain gauge in 2020s are developing and may be the leading most used measurement instrument for strain in future cutting-edge researches.[19]

Capacitive strain gages

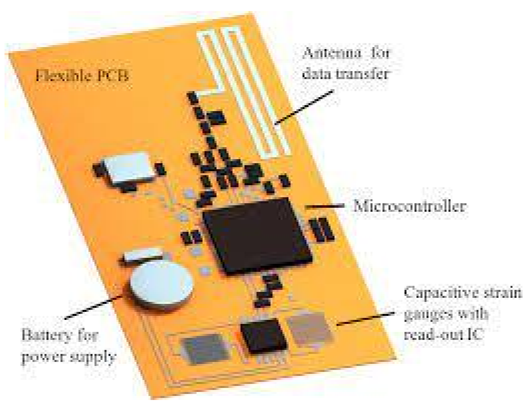
This is a rather new development, which is primarily regarded as an alternative to conventional strain gages for use at high temperatures beyond the limit of metal strain gages. At the present day there are three known versions of these gages:

1. Central Electricity Research laboratories (C.E.R.L.) in cooperation with the company planer, British made named CERL-Planer capacitive strain gage is made.
2. American made capacitive strain gage that is constructed as a differential capacitor by Boeing Aircraft
3. German-made plate capacitor that is made my Interatom.

Good results for these capacitive strain gages can be obtained in a temperature range up to $500^{\circ}C$. These results are usable for a range up to $800^{\circ}C$.

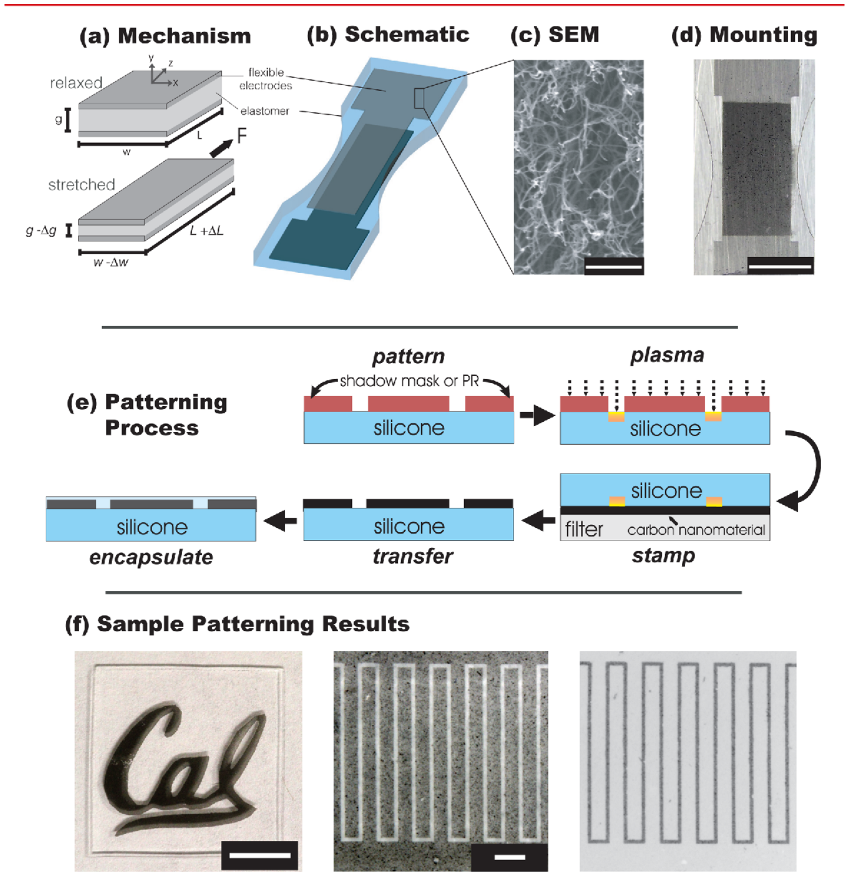
As I mentioned earlier in the report I am not going to discuss these new techniques further since it may make this report up to several hundred pages with hundreds of references, hence if interested one can further look into the literature to learn more about these three known versions and beyond after the references used in this report.

But let’s give examples capacitive strain gage in figures below:



[21]

Figure 16 shows Capacitive strain gauges on flexible polymer substrates for wireless, intelligent systems



[22]

Figure 17 shows a highly elastic, capacitive strain gauge based on percolating nanotube networks

Piezoelectric strain gages

Piezoelectric strain gages are active devices, it uses Barium titanate as its strain sensing material. As with piezoelectric transducers using quartz as the sensing material, the strain gage provides an electrical charge on its surfaces that is proportional to strain and can be measured with charge amplifiers. In this gage, static measurements are only possible under certain conditions.

Piezoelectric strain gages have only achieved limited recognition. In modern times mostly used in force sensors.

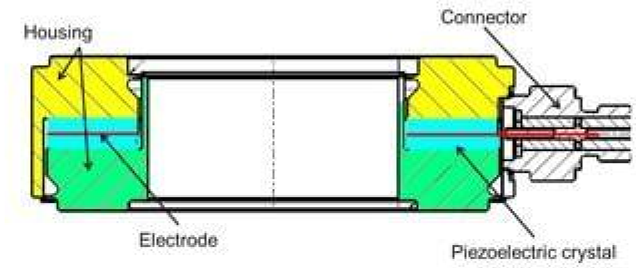


Figure 18 shows an example of HBM designed piezoelectric strain gauge[23]

Photoelastic strain gages

This gage is a strip that is made from optically stressed active material which exhibits an isochromatic field as a result of a "frozen", continually increasing stress level. Due to the strain, the isochromatics become displaced. The degree of displacement that is read off a scale is the measure of the strain. These strain gages are the types that are produced in the USA. They have not achieved practical significance and are therefore no longer commercially available.

If interested one can read the article about Photoelastic strain gages (***Photoelastic strain gages - G.U. Oppel, March 1961, Experimental Mechanics***) that is written in 1961, as one can see even the latest articles are really old on the technique. [23]

Mechanical strain gages

These devices are rarely seen in the market, but they have a long tradition. Due to their built, they can only be used on large objects. The measurement effect is shown by a trace scratched on a metal plate or on a glass cylinder, which however can only be evaluated at the end of the test under a microscope. This disadvantage is offset somewhat by the large temperature range. The recorded measurement can still be read for example, if the transducer is subject to fire following an accident.

Various other systems

Numerous other devices are available under the designation of the name of “Strain Transducer”. Strain gages are mainly used as resistive systems, inductive systems (differential inductance and differential transformers, etc.), and the vibrating wire method all belong to this group, which also includes a few various devices that are operating on mechanical and optical principles. There can be also some new optical strain sensors that can be named, but since they are actually in one of these systems that are mentioned above but recently started to develop due to digital image processing techniques. If further research is done in the measurement techniques one can get into details about those as well.

The Measurement System

The strains that we measure with the strain gages are normally so tiny, hence the changes of resistances are also very small too and cannot be measured directly, let’s say with an ohmmeter. The strain gage therefore must be included in a measurement system where the precise determination of the strain gage’s change of resistance is possible.

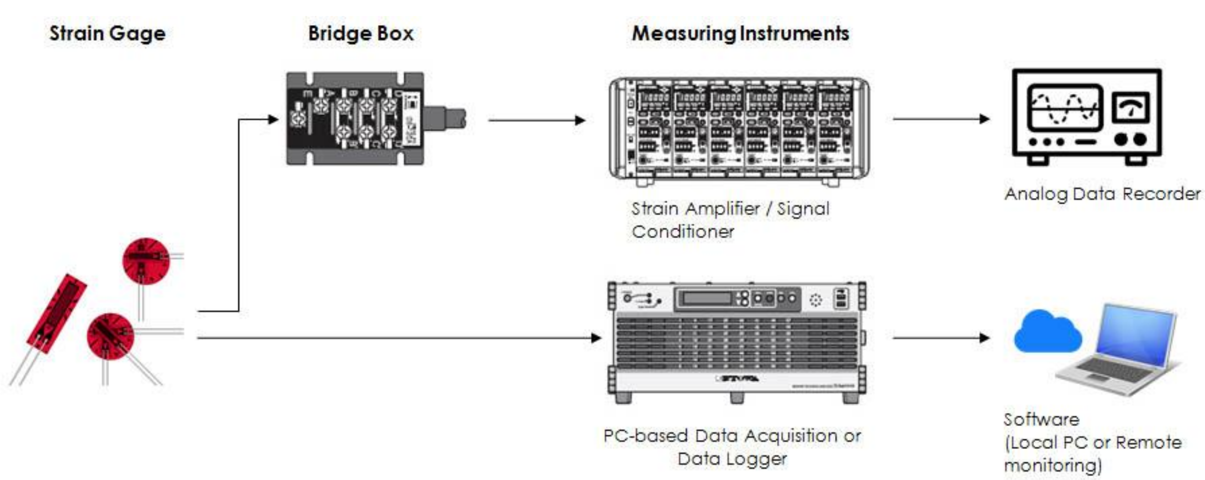


Figure 19 shows the Strain Gage Measurement System

The first component of the system in a strain gage system is the strain gage itself, in the beginning, it converts the mechanical strain into a change in the electrical resistance.

The second component is the circuitry that is built for the measuring, mostly the Wheatstone bridge that has strain gage on one of its arms. In the physical sense, both the first and second components are passive components. What is meant by that is energy must be passed to them to obtain a useful signal. This auxiliary energy is taken from a separate source, usually from a constant electrical source that gives constant electrical voltage, but constant current can also be used.

When the strain gage's resistance changes due to the staring, the Wheatstone bridge circuit loses its symmetry and becomes unbalanced, therefore we will have a voltage difference, and a proportional voltage is obtained to this unbalancing.

As the third component, there is the amplifier with an op-amp which amplifies the bridge output voltage to a level suitable for reading the difference at a meaningful level. With a linear amplifier, the output voltage or output current is proportional to the amplifier input voltage which is also the bridge output voltage and this is, in turn, proportional to the measured strain.

The fourth component that we can mention is the display of the system. It converts the amplifier's output signal into a form that can be observed by the human itself. If to be described in much simpler terms, the measurement is displayed by the indicating scale of a voltmeter or ammeter or the figures on the digital measuring device that is used. If it's a dynamic process, recording instruments are better suited than pure indicators, since the time-series analysis will be necessary due to the change of strain in time. Many amplifiers in the current day offer connection to both types together, either as an alternative or as parallel.

This description of a strain gauge measurement system only outlines the core elements, but the system in practice can be extended with additional equipment, such as; scanners, filters, peak value storage, limit switches, transient recorders, etc. Electronic data processing systems can also be connected to the system instead of the indicating instruments and in the latest researches, it is seen that this significantly increases the versatility of the measurement system.

Conclusion & Discussion

As to conclude, now the reader knows some background knowledge on what is strain, stress and what do they represent, what is a strain-stress measurement device, its history, main areas that they are used., techniques of measurement in general, what is the system to measure strain-stress, what can an extended system have and so.

Furthermore one can think about how to implement new optical systems or quantum devices into measuring strain more precisely and accurately. One can also think about why do photoelastic strain gauges are now extinct and were never used widely, since they may have some potential that is never discovered due to it having a really low amount of data on them. Is it really a failure or can someone discover a new undiscovered part in photoelastic strain gauge technology?

Hope the reader gets the methodologies, notions behind the techniques and the system and will continue with the mathematical understanding of these devices and build their own strain gauge.

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