Lecture-36
Correction Factors for Special Applications

We have been looking at finer aspects of strain gauge instrumentation, and in the last class we took up how do you account for transverse sensitivity effects? And we looked at because I need to have a strain gauge as a grid, it occupies a finite area, in view of this it is sensitive to some extent in the transverse direction. Knowing that it is sensitive in the transverse direction is not going to help me unless I know how to account for these errors.

And we also looked at the transverse sensitivity factor was around 2%. It is quite small, only in some cases it was going up to 10%, but it is around 2%. So we are really talking about small changes, but nevertheless when you want to go for fine measurement, you need to account for these small effects too.

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And we looked at the 2 possibilities. The first case we looked at was, we know the ratio of the transverse strain to the axial strain. If I know this ratio, then whatever the error due to transverse sensitivity effects could be easily handled by defining a modified gauge factor, and this can be

determined from the parameters that you know. If I know epsilon t/epsilon a, I know the numerator completely, I also know the denominator completely.

And what I need to do is I need to simply put this new modified gauge factor in the gauge factor knob. If I am using a software feeding this new gauge factor. So this is possible if I know the ratio of epsilon t/epsilon a. This is where we stopped in the last class.

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Now, let us take up a generic case, I do not know the ratio. Then what I need to do? Then I need to do more work. If I do not know the ratio, I need to do more work, and how do I do this? Instead of one strain gauge I need to paste 2 strain gauges and measure the apparent strain. See when you are looking at finer aspects of strain gauge instrumentation, I introduce the concepts of apparent strain which we will also see in other cases.

So whatever you see in the strain meter, it is only a apparent strain. We need to qualify it better, find out whether we have accommodated the errors, whether we have been able to correct them, then get the actual strain. Since in this case, I do not know the nature of the strain field. In order to account for transverse strain effects, you measure the apparent strain in both x and y directions, and we have already indicated if I put a cap it is called the apparent strain, which is seen in the strain meter.

So epsilon xx cap =1/1-nu 0 Kt*epsilon xx+ Kt*epsilon yy, and you have epsilon yy cap= 1/1-nu 0 Kt*epsilon yy+ Kt*epsilon xx. And what is the focus? Our focus is to find the true strain or actual strain. Now I have 2 equations, I have 2 unknowns and simultaneously solve them to get epsilon xx and epsilon yy. So if I do not know the nature of the strain field, I need to do more work, and find out what is the actual strain?

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XPERIMENTAL STRESS ANALYSIS   Strain Gauges

Corrections for transverse strain effects   ....contd

- The actual values of strain are obtained as

$$\varepsilon_{xx} = \frac{1 - v_0 K_t}{1 - K_t^2} \left(\hat{\varepsilon}_{xx} + K_t \hat{\varepsilon}_{yy} \right)$$

$$\varepsilon_{yy} = \frac{1 - v_0 K_t}{1 - K_t^2} \left(\hat{\varepsilon}_{yy} + K_t \hat{\varepsilon}_{xx} \right)$$

- The capped quantities indicate apparent strain noted from the strain indicator.

So the actual values of strain are obtained as epsilon xx =1-nu 0 Kt/1-Kt square multiplied by epsilon xx cap +Kt epsilon yy cap. And these are the values measured by 2 strain gauges what the strain meter directly gives. Normally, if you are not introduced to strain gauge instrumentation, what you will do? You will only look at the reading and note it and say that is the strain measurement.

But what we find here is those transverse sensitivity effect is minimal for final measurement, we need to account for it. In such a case we label what you see on the meter as only apparent strain. You need to correct for that and the methodology of correction differs if I know the ratio of the transverse strain to axial strain, it was much simpler. On the other hand, if I do not have the knowledge of the strain field, then I need to do more work and do additional measurement and then only get the actual strain.

So we similarly, get epsilon yy =1-nu 0 Kt/1-Kt square multiplied by epsilon yy cap+ Kt epsilon xx cap. And what you need to understand is suppose somebody comes and gives you a strain gauge. We have already seen in strain gauge instrumentation, what you have as gauge factor is experimentally measured. It is not a value calculated from analytical equation. The manufacturer does this experiment pasting it on a cantilever beam and then finds out and reports you for each batch.

Similarly, suppose somebody gives the strain gauge and ask you to find out what is the transverse sensitivity factor? Now we have the via media. So what I do here is I make 2 measurements, I go back to the earlier set of equations from analytical expression I know the true strains or the actual strain. From my strain gauge measurement, I get this expression involving Kt, so Kt becomes an unknown and you evaluate Kt from these equations.

So the generic case also provides you a methodology to find out the transverse sensitivity factor for an unknown gauge configuration. Suppose, I design a new gauge configuration, I need to find out what is the transverse sensitivity effect? Then I go to a problem wherein I know the axial strain as well as the transverse strain from analytical expressions. Make measurements and from those measurements find out what is Kt.

In fact, one of the assignment problems has this as the question and this is how you proceed. You use these set of equations to find out the transverse sensitivity factor.
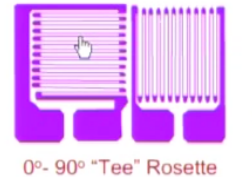**(Refer Slide Time: 08:28)**

T-rosette

- Ideal choice of the gauge when the principal strain directions are known.
- When the two elements are connected to adjacent arms of the Wheatstone bridge, it gives shear strain along the bisector.
- If both the gauge elements have the same K_t,

$$\varepsilon_a = \frac{1 - v_0 K_t}{1 - K_t} \hat{\varepsilon}_a$$

- Alternately, change the gauge factor to

$$\hat{S}_g = S_g \frac{1 - K_t}{1 - v_0 K_t}$$

0°- 90° "Tee" Rosette

- Thus, accounting for transverse sensitivity effect is quite simple.

And then what we have to do is we have also looked at for finer strain measurement, we need to going for using rosettes appropriately, and T-rosettes are ideal choice when the principal strain directions are known, this is one way of using it. And when I discuss these rosettes, I also mentioned normally, you connect each of the strain gauges in a rosette to a separate Wheatstone bridge. So I will be able to find out the state of strain at the point of interest that is how I will proceed.

There are also special occasions where I can connect these 2 strain gauges on adjacent arms of the bridge. Then it functions like a special gauge to measure shear strain. We will take this mathematics in the next class. So you also have special occasions where you connect the strain gauges in one Wheatstone bridge on adjacent arms. Suppose, I have both the gauge elements having the same transverse sensitivity factor Kt.

Then the axial strain is simply given as 1-nu 0 Kt/1-Kt into the apparent strain epsilon a cap. Alternately, change the gauge factor S g cap is given as S g*1-Kt/1-nu 0 Kt. So you have a via media, when I have a single strain gauge, how do I account for transverse sensitivity effect? We saw if I know the ratio, I can simply change the gauge factor suitably. A similar possibility exists in a T-rosette to.

And you also have methodologies to find out corrected strain values in a rectangular rosette or a delta rosette, but those expressions would be very complex. And nevertheless, you know you can have a look at it and take a values for one of the rosettes for your benefit.

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Now I have a rectangular rosette and whatever the expression I am going to give is arrived with the assumption Kt is same for all. And I have the expression like this, and I will enlarge it and you can have a look at this. So what I have here is epsilon A=1-nu 0 Kt/1-Kt square multiplied by epsilon A cap-Kt epsilon B cap. You know these derivations are not discussed here, but it is possible to arrive at these final set of expressions.

So what does the show is how important these effects become when you want to go for verifying measurements using strain gauge technology. See normally, you paste a strain gauge and make the strain measurement, may you do not know, you get only a component of strain along the gauge length. This is one concept which I emphasize all along. On the other hand, if I have to find out state of strain at a point of interest, then I need to go for rosette.

In general, 3 element rosette. Before we looked at transverse sensitivity effects, we were directly taking this, then you use strain transformation laws and found out what is the state of strain? Now, what you are looking at is, what is the strain measurement in the gauge A B and C? Its cell

has to be corrected by looking into transverse sensitivity effect. So you are graduating from simple measurements to complex measurements, and those expressions are like this.

So this finally gives only epsilon A, epsilon B and epsilon C, but using this you have to go back and find out epsilon xx, epsilon yy and gamma xy or epsilon xy from your strain transformation law. So the expressions involve on the right hand side, what is directly red from the strain meter? So that is what you have, and if I know the Kt value, it is possible for me to get the corrected value for each element of the strain gauge rosette.
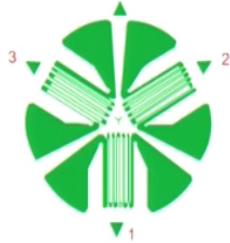
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Delta rosette

- If K_t is same for all,

$$\varepsilon_1 = \frac{1-v_0 K_t}{1-K_t^2}\left[\left(1+\frac{K_t}{3}\right)\hat{\varepsilon}_1 - \frac{2}{3}K_t(\hat{\varepsilon}_2 + \hat{\varepsilon}_3)\right]$$

$$\varepsilon_2 = \frac{1-v_0 K_t}{1-K_t^2}\left[\left(1+\frac{K_t}{3}\right)\hat{\varepsilon}_2 - \frac{2}{3}K_t(\hat{\varepsilon}_3 + \hat{\varepsilon}_1)\right]$$

$$\varepsilon_3 = \frac{1-v_0 K_t}{1-K_t^2}\left[\left(1+\frac{K_t}{3}\right)\hat{\varepsilon}_3 - \frac{2}{3}K_t(\hat{\varepsilon}_1 + \hat{\varepsilon}_2)\right]$$

$\hat{\varepsilon}_2$, and $\hat{\varepsilon}_3$ indicates apparent strains

And you also have expression for delta rosette you can just have a look at it, you do not have to write them. The idea is to show such expressions do exist, that is the idea. You can just have a look at it. It is a very complex, and we need to look at other aspects of strain gauge instrumentation. So we save time on a going to the next topic, and you can just have a look at that you do have expression for rosettes to, how to account for the transverse sensitivity effects?

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Here, the topic itself says that what are the correction factors for special applications? You know you cannot be doing strain gauge only for simple applications you need to work and find out what happens inside a pressure vessel because you all known from Lamis problem, the inner surface of the pressure vessel is subjected to maximum amount of tensile stress. So there are occasions where you need to find out, what are the strain develop in the inner surface?

And you may have to work in nuclear establishments and find out the strain history of some of the vital components, and nuclear power is becoming very, very important these days. Then you will also have to work at very high temperatures, you look at temperature extremes, when I say temperature extremes, it could be high temperature or it could be cryogenic temperatures. And another aspect is when I involved in cyclical loading what precautions that I need to take for such measurements? So we will go one after another, we will first take up Hydrostatic pressure.

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Effects of hydrostatic pressure

- In stress analysis of piping systems or pressure vessels, strain gauges may be employed on interior surfaces.
- In such instances, the gas or fluid pressure acting on the sensing element alters the strain sensing behaviour of the strain gauge.
- This needs to be corrected or accounted for in interpreting the results.

What happens when I apply a hydrostatic pressure? And where this is important? So you have piping systems or pressure vessels where strain gauges may be employed on interior surfaces. So what happens in earlier occasions, you had strain gauges pasted on a free surface, it was only sensing the strain of the base metal, base specimen. There were no direct forces acting on the strain gauge, but the moment you come to internal pressure, what happens?

The gas or fluid pressure acting on the sensing element alters the strain sensing behavior of the strain gauge, which you cannot ignore. This really happens, in fact in 1960s you had series of paper published in experimental mechanics on various aspects connected with measurement of strain and a hydrostatic pressure. People have looked at it very closely and found out what way you can rely on the strain measurement finally.

So when fluid pressure is acting on it, these effects needs to be corrected or accounted for in interpreting the results.

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Effects of hydrostatic pressure ....contd

- Brace and Milligan independently studied this effect by mounting a gauge on small specimens, placing them inside a special high pressure vessel.
- The pressure of the chamber was increased to as high as 965 MPa and the strain indicated was monitored.
- The gauge is thus subjected to a state of hydrostatic pressure p.
- From stress strain relations, the actual strain introduced in the gauge is

$$\varepsilon = \frac{-p}{E} - \frac{\upsilon}{E}\left[\left(-p\right)+\left(-p\right)\right] \longrightarrow (1)$$
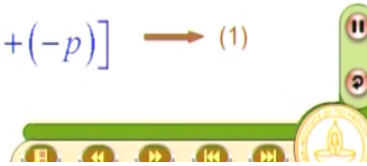
See when I have a hydrostatic pressure, you can theoretically calculate, what is the strain developed? You can do this from stress strain relations. I have this epsilon as –p/Young's modulus-nu/E*-p+-p. So I will have an expression based on my analytical calculation, what is the actual strain introduced? Because the problem is very important and also complex, as I mentioned series of experiments have been done by Brace and Milligan.

And the attach strain gauge to small specimens and placed them inside a special high pressure vessel. And what they did was they had increase pressure to the extent of 965 MPa. See the pressure effects cannot be modeled analytically. You need to do several experiments, based on experiments develop sudden empirical approach, and this is what was done. And you have serious of papers.

And suppose I take a flat specimen, put the strain gauge on it and put inside the pressure vessel. I know what is the pressure applied, then from my analytical calculation, I know what is the strain that should have been developed whether the measured strain =this anticipated value or not. What people found was up to certain pressure there is a match, beyond certain pressure there is deviation from the indicated strain value.

So whatever the indicated strain value needs to be corrected, and you need to have a methodology to develop the correction factor. So this is what we are going to look at, the correction factor is what we are going to look at how to get it?
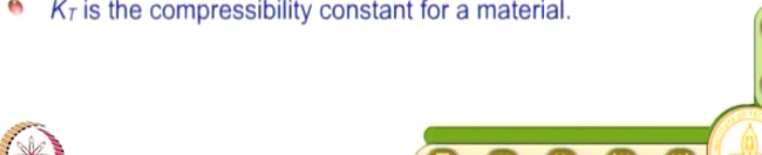
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Effects of hydrostatic pressure   ....contd

- The indicated strain was found to be less than the one shown by Eq. (1)
- Equation (1) can be rewritten as

$$\varepsilon = \frac{1-2\upsilon}{E}\,p \qquad \text{Where,} \quad K_T = \frac{1-2\upsilon}{E}$$

$$= K_T p \quad \longrightarrow \quad (2)$$

- K_T is the compressibility constant for a material.

So what you have is the analytical expression for strain could be simplified as 1-2 nu/Young's modulus E multiplied by the pressure p. This could be rewritten as KT*p, where you define KT as 1-2 nu/Young's modulus. And you also define a terminology you call this KT as the compressibility of constant for a material. So it is the function of the Poisson ratio and the Young's modulus of the specimen.

And this value is known, KT is known for a given experimental situation. Now what we are going to do is we are going to develop a empirical relation, which would correct the indicated strain, that is what we are going to do.

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- The true strain ε is obtained as
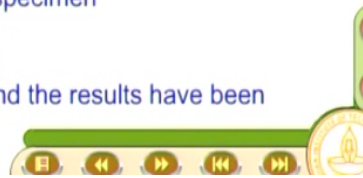
$$\varepsilon = \hat{\varepsilon} - \varepsilon_{cp}$$

Where $\varepsilon_{cp} = D_p K_T p$

- D_p depends on the following
    - K_T
    - Curvature of the specimen
    - Gauge material
- It is measured experimentally and the results have been reported by Milligan.

So actual strain or true strain is given as epsilon cap-epsilon cp, and epsilon cap is what you read in the strain meter. And epsilon cp is defined based on experimental observation as Dp*KT*p and the factor Dp is found to depend on the following. It is a function of KT, it is the function of the curvature of the specimen, it is also a function of the gauge material. See when you go for finer measurements, the specimen properties matter, the foil alloy properties is matter.

And also when you are looking for changes because of the pressure introduced. These changes have to follow a predictable path when pressure is increased gradually, and this demanded a very fine installation of the strain gauge on the specimen. What people found was you need to have a very thin bond line, and you have seen when we looked at epoxy cements, you can thin down whatever the adhesive, then apply greater pressure.

So that you finally, get a thin bond line that was very, very important in measuring the pressure effects. Because if I have to find strain and hydrostatic pressure by installation should be perfect, and it should behave in a same manner as the pressure is increase, at least for a given range. It should not vary randomly, if it varies randomly then correction becomes difficult. So when you are looking at hydrostatic pressure effects, you must also pay attention on whether you have followed the correct methodology of strain gauge bonding.

And we also looked at one of the test where you take a eraser and then rub it on the strain gauge installation if there are bubbles. Particularly, in hydrostatic pressure environment you should not have any micro bubbles. It should be free of that, then this correction factor will work. The correction factors will not work otherwise.

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Effects of hydrostatic pressure ....contd

- For flat steel specimen K_T = 1.93 x 10^{-12} m^2/N and D_P = 0.3.

- For 7 MPa pressure ε_{cp} = 4$\mu\varepsilon$, which is small.
- Up to 20 MPa pressure, pressure effects are neglected.

And you have one example problem, it just shows for a flat steel specimen KT=1.93*10 power-12 meter squared by newton's, and Dp is found to be 0.3. And for 7 MPa pressure epsilon cp is only 4 micro strain which is small, and the recommendation is up to 20 megapascal pressure effects are neglected, that is the outcome of the study. The outcome of the study was when the pressure that you are handling are of the order of 20 megapascal, you need not make any special efforts to correct for the hydrostatic pressure effects.
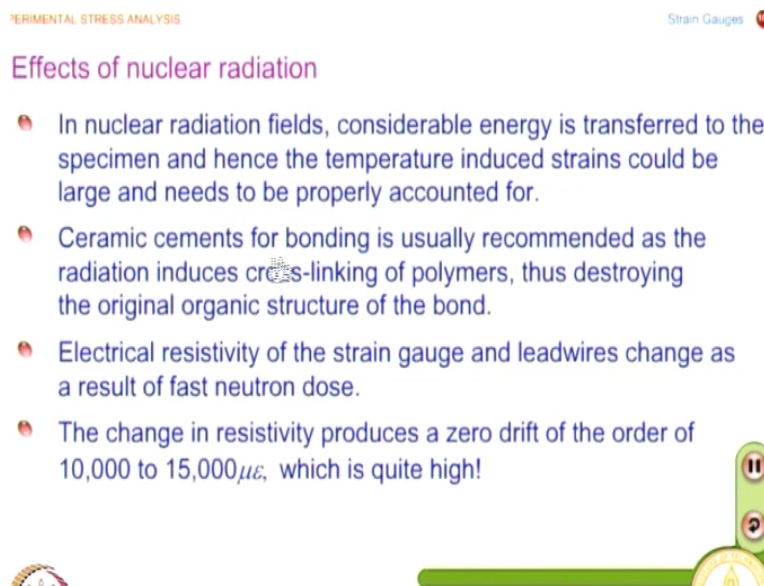
And another one you know we have also looked at a coefficient call Dp, which is also function of the curvature. See people found the Dp varies when I do it on a flat specimen or when I do it on a concave specimen or a convex surface. So people have done experiments on flat specimens, concave surfaces, convex surfaces, bond strain gauge on it, put in a pressure vessel. And then find out the readings and establish Dp for that material.

So you have such graphs available. So the idea is when you are working on pressures beyond 20 megapascal, you need to correct the indicated strain definitely. In fact, some of the students from

industry, when they had taken the course earlier, they were finding a deviation there measurement of strain in those applications. They were not knowing how to go about? The moment I discuss some of the issues in the class.

Then they found now we have a via media to go and improve the results. Sometimes, you know you get you come across an error you do not know what to do, you need to know that these are all finer aspects people have looked at it, you need to have knowledge of what the literature says. So hydrostatic pressure you cannot ignore it when it is beyond 20 MPa, you need to makes special effects to correct for it.

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And next we take up effects of nuclear radiation. The moment you get to nuclear radiation, you know you can imagine considerable energy is transferred to the specimen. And hence the temperature induced strains could be large and needs to be properly accounted for. See we have earlier looked at how to accommodate small temperature changes. Here it does not come under small temperature changes category.

You have large temperature changes possible, and in those occasions the recommendation is measure the temperature at the point of interest, with that data it is possible for you to go and do some corrective modification on the strain measure. I may have a temperature effect, as of graph,

if I know the actual temperature at the point of interest, it is possible for me to do some kind of a correction. So one of the first effects in nuclear radiation is temperatures may be high.

So it is proveden to measure the temperature which could be use later to initiate some corrective action, this is one aspect of it. The other aspect is you should also look at what kind of cements you use for bonding. You cannot go and use polymeric adhesives, you need to go for ceramic cements. This is peculiarity when I want to go and work in nuclear radiation environment.

The other aspect is the electrical resistivity of the strain gauge as well as the lead wires change as a result of fast neutron dose. So I see 3 effects, I need to go for special cements like ceramic cements to bond the strain gauge. It is proveden for me to measure the temperature at the point of interest, because considerable energy is transferred and the specimen is heated up. And the third effect is the electrical resistivity itself changes, and this change is not small.

And the electrical resistivity change produces a 0 drift of the order of 10,000 to 15,000 micro strains, which is very high. Say the pressure effect we saw 4 micro strains, we are very happy, up to 20 MPa, I do not have do any modification that gave a solace. The moment you come to nuclear radiation everything is complex here, because you have a radioactive effect, you need to have protective gear, even the handling the specimen is difficult.

You may need to have robots to do all your experiments, there are very many difficult aspects once you come to nuclear establishment, but what you need to understand is there is a change in the resistivity of the strain gauge. And this cannot be cancelled by using 2 strain gauges as 2 arms of the bridge and cancel it out, because it is a function of the load, it is also function of the amount of exportation.

So people said that this instrument correction, like what you do in temperature compensation will not work here, so I need to have a different approach all together. So one recommendation is the variation is linear.

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Effects of nuclear radiation   ....contd

- Change in resistivity appears to be a linear function of the logarithm of the dose.

- Recommendations are

    - Use pre-exposed strain gauge installations.
    - Reduce test times to the minimum.
    - Frequently unload and re-establish zero in the readings.

- The strain gauge alloy exhibits an increase in its yield strength, modulus of elasticity and a decrease in elongation capability.
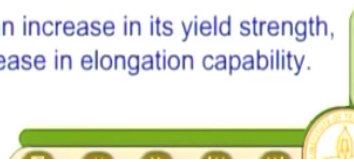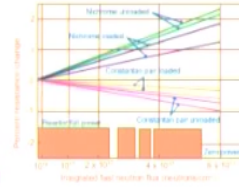
So it is predictable, the change in resistivity appears to be a linear function. So I can have these as the possible methodologies to improve, and what it says is use pre-exposed strain gauge installations. Before you make the measurement, let the strain gauge installation also goes through the same radiation dose, and other recommendation is reduce test times to the minimum. So quickly go and make the measurement, because I am go to have a drift.

Other recommendation is frequently unload and reestablish 0 in the readings. This is because you find that change in resistivity appears to be linear function that is what this graph shows, it is varying linearly. So I can at least follow some of these recommendations, and then improve the measurement capability. And another surprise thing also happens, when strain gauge alloy is exposed to radiation.

You need to look at surprisingly that there is increase in its yield strength as well as modulus of elasticity. See normally many of your heat treatment approaches are alloying will improve the yield strength, no doubt, but none of these operation will modify the elastic modulus. But what you find here is when you go for nuclear exposure the modulus of elasticity also change. So when I am going to have stress calculations, I need to use the appropriate modulus.

You cannot directly transfer the strain values into stresses, and other aspect is the strain gauge alloy exhibits a decrease in elongation capability. So you need to look at what damaging effects the nuclear radiation can introduce.

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Effects of high temperature

- At elevated temperatures, resistance R of a strain gauge must be considered to be a function of temperature T and time t in addition to strain ε.

$$R = f(\varepsilon, T, t)$$

- The resistance change $\Delta R/R$ is given by,

$$\frac{\Delta R}{R} = \frac{1}{R}\frac{\partial f}{\partial \varepsilon}\Delta \varepsilon + \frac{1}{R}\frac{\partial f}{\partial T}\Delta T + \frac{1}{R}\frac{\partial f}{\partial t}\Delta t$$

Now we move on to effects of high temperature, when we are talking about high temperature, we are really talking beyond 250 degrees. At elevated temperatures resistance R of a strain gauge must be considered to be a function of temperature T as well as time T that is the important factor here. So now resistance is a function of strain, temperature as well as time. So as a function of temperature there could be deterioration on the strain gauge system.

Because the bonding may relax, and then you also have phase transformation on the gauge alloy. It is very interesting you know unless you look at each aspect closely, you may ignore any one of these changes, because when I am exposing the foil alloy to high temperatures, and also subjected to load, you find there could be phase transformation. This also can affect your strain measurement. So what you have here is delta R/R is the function of strain.

So I have this as 1/R dou f/dou epsilon*delta epsilon+1/R dou f/dou T*delta T+1/R dou f/dou t*delta t. And similar to my Sg ST, I also introduce another factor S suffix t that is what I am going to do.

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Effects of high temperature   ....contd

Where

$$\frac{1}{R}\frac{\partial f}{\partial \varepsilon} = S_g = \text{Gauge sensitivity to strain (gauge factor)}$$

$$\frac{1}{R}\frac{\partial f}{\partial T} = S_T = \text{Gauge sensitivity to temperature}$$

$$\frac{1}{R}\frac{\partial f}{\partial t} = S_t = \text{Gauge sensitivity to time}$$

$$\frac{\Delta R}{R} = S_g \Delta \varepsilon + S_T \Delta T + S_t \Delta t$$

What I am going to have is the expression for delta R/R can now we thought of as Sg*delta epsilon+ ST*delta T and the nuisance factor is St*delta t. So you have a factor of time coming in to the picture. See in all these cases of nuclear radiation or effects of high temperature, you will have a drift. The cause of drift is different in each of the cases. When there is a drift, it is a function of time that is the reason why the recommendation is do it quickly.

If I do dynamic strain measurement, temperature effects are easy to handle, only when I have static measurement over a long durations of time, temperature effects become very cumbersome to handle. And also when I use self-temperature compensated gauges, they are varied only for a short range of temperature, it is not men for all temperatures range. So you need to account for these temperature effect specially.

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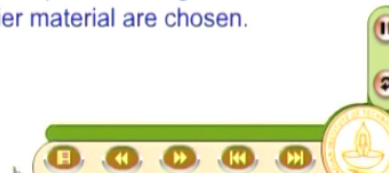
Effects of high temperature   ....contd

$$\frac{1}{R}\frac{\partial f}{\partial T} = S_T = \text{Gauge sensitivity to temperature}$$

$$\frac{1}{R}\frac{\partial f}{\partial t} = S_t = \text{Gauge sensitivity to time}$$

$$\frac{\Delta R}{R} = S_g \Delta\varepsilon + S_T \Delta T + S_t \Delta t$$

- S_T and S_t are negligible in the temperature range -18 to 65°C if proper gauge alloy and carrier material are chosen.

And what is mentioned here is the factors S capital T and St are negligible in this temperature range -18 to 65 degree centigrade. A variety of problems exists in this region, and what you need to careful about is you need to select the proper gauge alloy and the suitable carrier material for these applications. But when I work beyond this temperature, I need to account for the effect of time.

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Effects of high temperature   ....contd

- Karma alloy is better than Advance and it can be used upto 260°C with temperature induced apparent strain of less than ±100 $\mu\varepsilon$.
- Strain gauge drift is a serious problem in high temperature application.
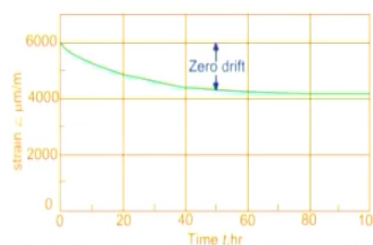
Typical zero drift as a function of time for a Karma alloy strain gauge with a glass-fiber-phenolic carrier at 560°F (293°C)
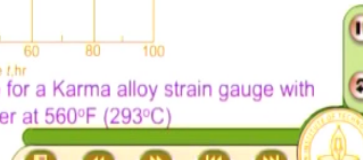
And you know, we have also looked at mentioned in several of our lectures, that Karma alloy is better than advance, because it can be used up to 260 centigrade. Whereas, advance only up to 205 or so. So it can work beyond 205, and the apparent strain is of the order of +or-100 microstrain. The error introduce because of temperature change is of the order of 100

microstrain, and what is recommend is when I said it is the function of time, to solve this develop a graph which is a function of strain versus time.

So I have a variation of this reading, and this is actually called as a zero drift. It is a function of a time as well as the strain gauge alloy. Here it is shown for a Karma alloy with glass fiber reinforced phenolic carrier, and this graph is done for 293 degree centigrade. So the recommendation is we know that resistance changes as a function of time, to solve this develop graphs for each specific temperature for the given strain gauge system and use that a ready reckoner to correct your zero drift, there is no other go.

When you have a given application you know what temperature range you are going to work at, so develop strain versus time for that temperature, and have the data and use it for your correction. So in all these applications it is proveden to measure the actual temperature at the point of interest, even if you do not have the data while you perform experiment, you can at least go back and develop for that particular temperature, a test data which would give you the change of zero drift as a function of time.

So for any temperature extremes, we will also see cryogenic temperature, there also it is proveden to measure the temperature at the point of interest, so that is what we are looking at.

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And you know to what extend karma alloy can be used is dictated by the carrier material. And as I mentioned earlier, glass reinforced epoxy phenolic carrier is rated for higher temperatures, but you have the problem of drift with time which is significant. So as I mentioned earlier, develop several strain time calibration curves for various temperatures, and choose the appropriate one for a particular application, there is no escape.

See if you want to make strain measurement for critical situations, you need to do more work, do not think I go paste a strain gauge look at the strain meter, and then come back and say this is what the strain measurement is. This will not be the correct value, you need to look at this special effects, find out what way modifies, look at the literature and find out how to initiate the corrective action, learn this and then interpret the measure strain value.

You cannot jump to conclusion that by pasting a strain gauge my job is over in strain instrumentation; it is not so. You need to apply appropriate corrective measures depending on the situations. You need to handle it differently for hydrostatic pressure, differently for nuclear radiation and differently for high temperature. We will also see for low temperature what we have to do.

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And you know before we go in to the low temperature, we also look at what to do If I have to measure beyond 288 degree centigrade? I need to go for special gauges as well as special

techniques for strain measurement. And we looked at earlier also that you had different alloying materials available for making a strain gauge. You have Nichrome V, Armour D or alloy 479 are available they are recommended as gauge material for temperature beyond 288 degree centigrade.

And what is mentioned here is alloy 479 which is the platinum tungsten alloy can work up to 870 degrees, but has a large apparent strain of 140 microstrain per degree centigrade. So if you understand this, you can at least go back and corrected. So it is always proveden to measure the temperature at which you are working, and in such high temperature applications use of signal subtraction by Wheatstone bridge is recommended, this works.

See in the case of nuclear installation, what we found was the nuclear exposure modifies the resistivity that cannot be cancelled by putting 2 strain gauges and adjacent terms and cancel the effects. On the other hand, the apparent strain because of high temperature effects could be managed if you use a half bridge or a full bridge configuration. So this is recommended when you go for high temperature application.

When you go for a high temperature application it is also proveden to measure the temperature not only this look for strain time calibration curves for the given temperature that we are working.

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Effects of cryogenic temperature

- Strains can be measured using strain gauges at -196°C or below.
- Usually, cryogenic temperatures are obtained by using liquid nitrogen, liquid hydrogen or liquid helium.
- They are excellent insulating materials. The strain gauge has to be coated with silicone grease to serve as a heat shield to eliminate the heating of the gauge due to the possibility of boiling of the liquid over the grid surface during the test.
- The elastic modulus increases by 5 to 20% at cryogenic temperatures.
  - ★ Use a higher modulus while converting strain data to stress!

Now we move on to how to consider the effects of cryogenic temperature, what happens? See what is mentioned is strain gauges can be used to strain below -196 degree centigrade, and one of the significant effect here is the elastic modulus increases 5 to 20% at cryogenic temperatures. This is very rare you know, as I mentioned earlier elastic modulus does not change by your heat treatment or by alloying. We saw that when it is exposed to nuclear radiation the elastic modulus changes.

Similarly, when it is exposed to cryogenic temperature, the elastic modulus changes. So when I you have to find out the stress measurement based on strain values, you have to use the appropriate elastic modulus. So this is important both in nuclear radiation and cryogenic temperatures. There is another interesting thing that happens. Usually, cryogenic temperatures are obtained by using liquid nitrogen, liquid hydrogen or liquid helium.

And what happens is at such low temperature, they can boil, and they should not heat the grid surface. So what is recommended is the strain gauge has to be coated with silicone grease to serve as a heat shield, in the very subtle point, you know I have a liquid nitrogen that can also boiled, and the process should not disturb the strain measurement. So the recommendation is put a coat of silicon grease is what is recommended.

See in all these applications what we are looking at is strain gauge installation itself has to be looked at very carefully. In the case of hydrostatic pressure, we mentioned go for thinnest bond line, you need to takes special effects to make it. When I come to nuclear radiation go for ceramic cements. When I come to cryogenic temperatures, I need to put a silicon grease on this, and when I go for high temperature select the suitable alloy of the strain gauge as well as the carrier.

So strain cage installation methodology goes with the application, you should not delink these 2. Whatever the correction that you do is valid only when you are followed this specific recommendation for that kind of situations. Those corrections are not valid if you violated any one of them, this is also you have to keep in mind. You have a thick bond line, and then apply the correction effect whatever you learned for hydrostatic pressure, it will not work, it will not give you the correct value.

That is the reason why we also spend sufficient time on strain gauge bonding, it is not a trivial procedure. And for special applications you need to find out look at the latest literature, find out any new recommendation have come, try to follow that.

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And there is also another interesting future when I come to this cryogenic temperature. You have a possibility of change of gauge factor, but that possibility is very small. So you do not have to

worry about change of gauge factor. But the other difficulty is the error in strain measurement can be very large when we work below-73 degree centigrade. So you will have a introduction of apparent strain for small changes in temperatures.

So there is a limit up to -73 centigrade you can do one type of measurement, but below -73 centigrade a small change in temperature introduces large value of apparent strain. And how to go about? How do remedy this? People are found very innovative way of doing it.
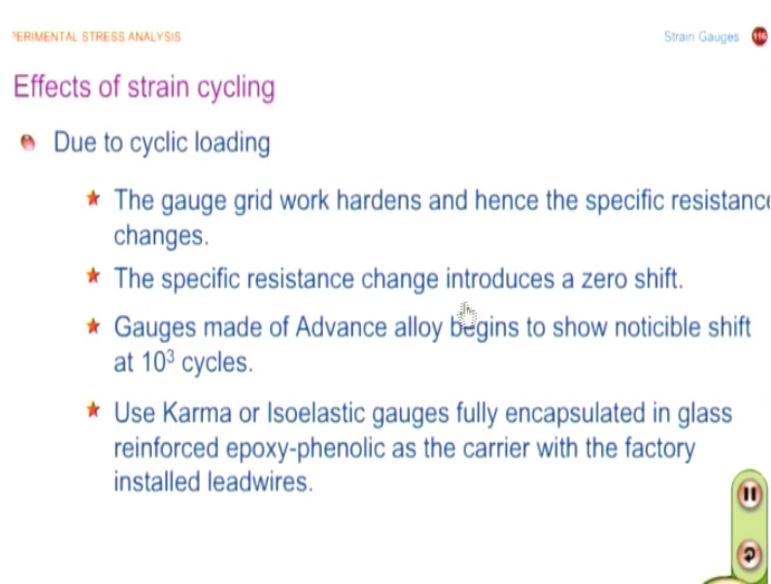
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I had mentioned in the discussion on self-temperature compensated gauges that use the self-temperature compensated gauge only for the specimen material for which it is compensated. You should not mix this self-temperature compensated gauges, then your measurement will be erroneous. See for any rule there will be exception, the exception applies in cryogenic temperatures.

So in cryogenic temperature the recommendation is use temperature compensated gauges or even try using mismatched gauges for the material. So I may have a STC gauge meant for a different material to be applied on this material. So that I account for the apparent strain because of low temperature below -73 centigrade. And as I mentioned earlier measure the surrounding temperature using temperature sensor, and use standard graphs for effecting the correction.

So this is the general recommendation. For temperature extremes as well as nuclear radiation measure the temperature at which you are doing the measurement. At least keep this, even if you are enable to interpret the strain readings when you find a deviation from your analytical or numerical calculation. At least another experimentalist can look at it, and suggest you worked at such and such temperature, why do not you look for strain time calibration graph?

If it is not available why you do not you develop it? So some such diagnose is possible, if you also measure the temperature at which you have done the experiment, so that is the Thumb rule that you can generally take care.

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And now we look at what are the effects of strain cycling? So it is very interesting to see, you know unless you look at each aspect closely, you will not even notice that such variations can happen. Because of cyclic loading the gauge grid work hardness. How interesting it is? And what happens because of that? The specific resistance changes, when the specific resistance changes it introduces a zero drift. So if you use advance alloy, it begins to show noticeable shift at 1000 cycles.

So if you want go for cyclic loading, go for Karma or Isoelastic gauges fully encapsulated in glass reinforced epoxy-phenolic as the carrier with the factory installed lead wires. So in essence what we are looked at is, in some cases even if you worry about the right selection of the alloy

and the backing and the method of installation, half of your problems are solved. So it is necessary how to select the strain gauge for a given application, you cannot ignore that.

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And finally, we look at what is the effect of moisture and humidity? You know water is elixir of life, without water nobody can live, but water is not good for strain gauge instrumentation. Where does the water come from? It is not that you are always making a measurement under water, even the water measure in the atmosphere as relative humidity that can affect your strain gauge installation and very interesting things happens.

See if you do not look at these very systematically, you will ignore all these effects. So water vapor present in the air is absorbed by both the adhesive and the carrier. And what happens because of that the gauge to ground resistance gets reduced. So you have first effect because of the water. This is similar to placing a shunt resistor across the active gauge. So this is the nuisance that you need to avoid.

And because of absorption of moisture it degrades the strength and rigidity of the bond, and reduces effectiveness of the adhesive in transmitting the strain. We have already seen the adhesive should faithfully transfer the strain developed on the base material to the foil alloy. It does not happens when there is expose to moisture, and what happens plastic also expands when it is wet, it expands.

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So you have strains developed and that strain also will be sensed by the strain gauge. Plastics expand and this will produce strains in the adhesive, which will in turn be transmitted to the strain gauge. And because there is a very complex effect, it cannot be subtracted by your temperature compensation methodology of putting 2 strain gauges on adjacent terms. It is not possible, it is interlinked, it is difficult to separate this effect.

And also another thing which is very, very subtle. Now I have the gauge alloy in a moisture environment, when current passes through the gauge, it will cause electrolysis. So what is the effect of this? The gauge filaments will erode and a significant increase in the resistance will occur. See how interesting it is? You know this have very, very subtle effects, you know unless you really look at and then want to get the maximum amount of strain gauge instrumentation.

You would have simply that what way the moisture is going to affect, I have the reading which is close to my wrongly calculated numerical value, you feel happy my experiment is matched with numerical result. And you will go with the beaming smile, but your structure collapse in actual practice. So if you want to have confidence in you experimental measurement, you need to know the nuances, you need to know the variations.

And what is the recommendation by the manufacturer, because you have research publications that are available as and when scientists find new effect. And you need to have a constant touch with the literature. So when you go for special applications ensure that you have taken special care to handle them. So in this class we looked at finer aspects of strain gauge instrumentation. We stared with accounting for transverse sensitivity effect.

We also saw, how the methodology can be extended to find out even the transverse sensitivity factor, I need to make 2 measurements and from that measure the transverse sensitivity factor for a known strain field. So that is the way you go about in calculating KT. Then we moved on to how to account for hydrostatic pressure, nuclear radiations, temperature extremes, cyclic loading and finally, environmental effect.

So what we found is moisture is very bad. So in instead of getting into problems protect your installations from moisture absorptions. So you hermetical sealing is very, very important, but when I do this what is the other aspects that I should keep in mind? When you put a coating you are preventing heat dissipation. So you need to take special efforts to improve that, select a suitable gate size or have some air circulation. So that you accommodate the heat dissipation properly.

And another general recommendation is when you are working at temperature extremes as well as nuclear radiation at least measure the temperature at which you are making the measurement. So that some diagnosis of your experimental instrumentation is possible later. If you do not have the data to correct then and there, at least you can do additional test generate appropriate data and subtract from your readings. So that you get the actual strain at the point of interest, thank you.