# Strain Gage

## Lab #3

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Abstract

Since 1856, when Lord Kelvin discovered that stretching and compressing wires changed their resistance, scientists have been developing methods to harness this fact to gather valuable data regarding strain, pressure, and more. The first gage invented specifically to measure strain was developed by Arthur C. Ruge at MIT in 1938. Today, strain gages and strain sensors find countless applications from engineering, to healthcare, to touch screens. Despite advancements in measuring technologies, strain gages continue to be utilized for their reliability, accuracy, and versatility. For the experiment outlined in this report, a strain gage is used to measure the strain induced in a cantilever beam when a load is placed at the free end. Data from the gage will allow for comparison of experimental to theoretical values, highlighting variations from ideal assumptions and conditions.

## Objective

The objective of this lab is to better understand how to use and understand strain gage readings. This goes into depth with understanding how a strain gage creates strain values using the electrical current and being able to verify that value of strain by using a more theoretical approach. Throughout the lab, there must also be familiarization with certain tools that will be used to carry out the experiment. This includes strain gages, dial indicators, weights, soldering tools, and cantilever beam. As mentioned, strain gages use changes in electrical current which can be applied to changes in voltage that are used to find the strain. This applies electrical systems concepts of resistance and correlates it to the mechanical properties of the material. Being able to apply the understanding of strain gages and being able to set them up can be very useful in scenarios when testing any changes in length of an object that is already in position to be used. An example of this could be studying the change in length for a beam that undergoes varying stresses over time such as roller coaster beams. Only when the coaster goes over the rail with the corresponding supporting beam, is when it would undergo stress. These beams are actually meant to fluctuate for flexibility and safety so a certain change in length can show signs of healthy strain. If a bad range of strain values is seen in the gage, something must be changed. This is only one example of many where strain gages can be applied but the way it achieves these strain values still must be understood.

## Introduction

Strain gages are very small tools that are used to measure strain and, in all cases, on the surface. The way it's done is through the concepts of resistors in electrical systems. A resistor is defined exactly as its name states, it resists. In this case, resistors are used in electrical applications so they resist current and can be defined by equation 1.

$$R = \rho \frac{l}{A} \tag{1a}$$

As seen in equation 1, the resistance values are dependent on the geometry of the resistor. To better imagine this, think of a roadway where it's easier for cars to drive if the road is wider meaning that the resistance is less if the area is bigger. If the road is longer, there are more cars to go through before it finds an area with no traffic, so the resistance is more when the wire is longer. Now, with an understanding of how changes in geometry can change the resistance of a material, this change in geometry is directly related to strain which is change in length. So, when the resistance changes, the strain changes which can be seen in equation 1b.

$$\frac{dR}{R} = GF * \varepsilon \tag{1b}$$

The change in resistance alone is not something that can be measured and only specialty tools can be used to do this because of how small the resistance values are. This is where simple circuits can be applied such as Wheatstone bridges to measure something easier like changes in voltage to get the strain values as seen in figure 1.

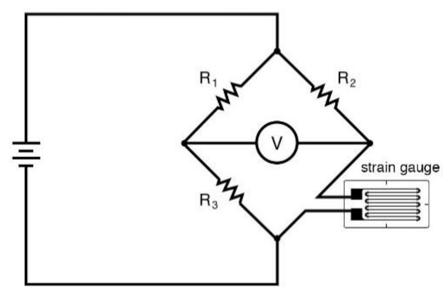


*Figure 1: Quarter Wheatstone bridge*

The "v" labeled in figure 1 is the voltage that is going to be measured which is known as the output voltage. If the Wheatstone bridge is balanced, the voltage measured would be a value of zero, suggesting that there has been no strain present because the strain gages has the same resistance as the rest of the resistors inside the circuit. If there is a strain present, then the output voltage would read a value and could them be applied to equation 1b to get the strain value.

$$\varepsilon = \frac{4*\frac{v_o}{v_i}}{GF\left(1-2\frac{v_o}{v_i}\right)} \tag{1c}$$

The derivation as to how the circuit analysis equations, such as Kirchoff's voltage and current law, are altered to include equation 1b and create equation 1c, will not be shown in this lab report as its not necessary for the conceptual aspect of strain gages in Wheatstone bridges. Really, it's more used for the theoretical calculations which is what the strain indicator is used for. This machine is used to apply all theory of the strain gage in a Wheatstone bridge and gives strain values when connected and stresses are applied. Now that there is a way to get measured values of strain using a strain gage and strain indicator, a more theoretical approach must also be considered to compare the values.

The theoretical strain values are found using Hooke's law with the ideal modulus of elasticity that is found during the experiment. Given the equation, shown in equation 2a, another variable is needed to complete the formula which is stress.

$$\varepsilon = \frac{\sigma}{E} \tag{2a}$$

This stress that is being considered is the surface stress of material at the point of the strain gage which is what is being measured. To find that stress on the surface where the strain gage is, formulas from mechanics of solids must be applied which are shown in equation 2b and 2c. The corresponding figures for those equations are shown in figure 2 and 3.

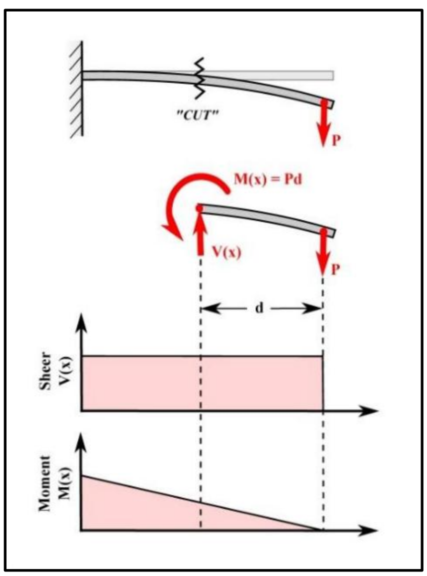


*Figure 2: Shear force and bending moment diagrams*

$$M(d) = P * d \tag{2b}$$

Since stress is a force over area, we need to apply the force to the position that the strain gage is at and that can be done with a moment. This moment is made with respect to the force that we are applying over the distance from the load to the center of the strain gage. However, this moment is force times length so what needs to be found to get the stress is what moment of inertia is being applied to, and where in the area this moment is being applied to. This is defined in equation 2c where the resulting variable found is stress and figure 3 can help determine the variables used.

$$\sigma(d) = \frac{M*c}{d} \tag{2c}$$

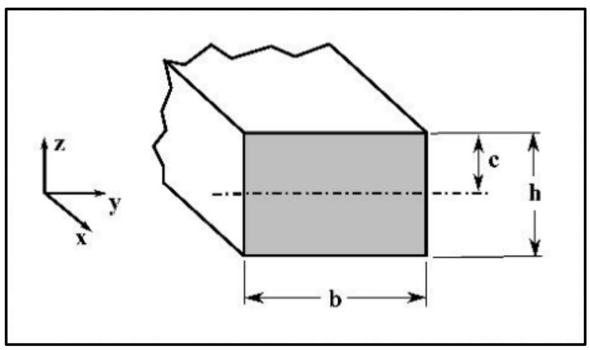


*Figure 3: The cross section of rectangular beam*

The measured strain values are found and now the theoretical stress values are found. These two values cannot be compared but as stated, Hooke's law can be used for the theoretical values to find the strain which is seen in equation 2a and this will be done using the ideal modulus of elasticity, being the one for the material that is closest to the modulus of elasticity found in our measured value.

To find the measured stress values, another form of measurement that is taken during the experiment will be used. This is the deflection of how much the beam has moved, at a certain location, after applying a load. With how much the beam has deflected and the variables needed for the location of the deflection, one can calculate the required modulus of elasticity for the beam to move that much. This can be seen in equation 2d, 2e, and figure 4. To conclude, the strain is measured, and the modulus of elasticity is calculated using the deflection measurement, an average is then taken for the ultimate modulus of elasticity, then, Hooke's law is used to find the stress for each measured strain values.

$$I_y = \frac{bh^3}{12} \tag{2d}$$

$$\delta(x) = \frac{Px^2}{6*E*I}(3L - x) \tag{2e}$$

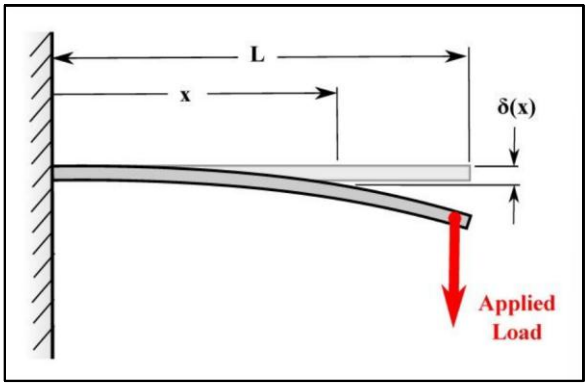


*Figure 4: Cantilever beam diagram with variable lengths*

Now, all data for both measured and theoretical values can be found and a comparison between the two can be made using graphs to see if the measured values in the strain gage make any sense or if there are present significant errors to be fixed.

## Procedure

The setup given to perform the strain gage test is a cantilever beam which would have applied loads on one side while both deflection and strain are measured from the dial indicator and strain indicator respectively. To set up the strain gage, a series of steps must be followed to ensure the best measured values with no human error.

As stated before, the strain gage measured surface stress and must be placed on the surface so the first step would be to prep the location of where the strain gage is going to be placed. This location must be near the base of the beam. After choosing the location, it must be cleaned and prepared for the strain gage to be glued on. First, take a piece of sandpaper and sand down the area of the surface which will be where ethe strain gage is placed. This area must be about three to four inches long at the width of the beam. After, use acetone to wipe down the surface, which was sanded and once again, with isopropyl alcohol. Now M-PREP conditioner A must be spread onto the bonding area. This is then wiped off clean with a piece of gauze. Repeat with M-Prep Neutralizer 5A.

The surface is now prepped and ready for the strain gage. Take the tweezers given in the lab and carefully remove the strained gage from the plastic sheath it comes in. Place the strain gage in the area which was prepped parallel to the length of the beam. Make sure that the terminals for the strain gage are facing the base to best route the wires that will go to the strain indicator. Once the strain gage is placed onto the surface, take a 4-inch piece of adhesive clear tape and place it over the strain gage parallel to the length of the beam where the strain gage is sitting in the center. Now lift the end of the tape not towards the base of the beam to the point where the strain gage face if fully off the beam while making sure not to touch the strain gage itself. The strain gages face should be fully uncovered and ready for adhesive. However, before putting the adhesive on the tape, a catalyst or M-Bond 200 must be applied. Be sure to apply a very thin coat so when taking the brush out, wipe it against the lip about 10 times, removing the excess. Take the brush and in a swab motion, gently cover the face fully and let sit for three minutes where the adhesive can then be applied. After three minutes have gone by, hold the tape up, so the adhesive can be applied, and the gage can be taped and glued down. Grab the adhesive or M-Bond 200 and apply two drops exactly on the surface of where the strain gage will be placed on the beam, now, immediately, place the tape down so that the gage is over the adhesive area. To finish, take a clean gauze sponge and slowly but firmly, wipe the area of the tape to set the gage and adhesive. Take your and apply a pressure over the strain gage for about one minute and then let it set for about two more minutes. The gage should now be bonded, and the tape can be removed from the surface.

Once the gage is bonded to the beam, the next step is to solder the wires into the gage terminals. Two wires will be soldered onto the gage, one at each terminal. Mask the non-terminal section of the gage with adhesive tape so it is not damaged during soldering. At this point, only the gage terminals should be exposed. Now, plug in the soldering iron and set the temperature as close as possible to 650˚ F. Moisten the sponge with water. To clean the iron tip before soldering the wires to the gage, tin the tip by completely covering with solder and remove with the wet sponge. Repeat if necessary. To prepare the gage terminals, gently scratch the adhesive residue from the terminals with a sharp metal object. Now, tin the terminal by melting a small bead of solder on the tip of the iron and placing it on one of the terminals. Repeat for the other terminal and allow beads to cool. Now cute two 2' sections of wire and strip both ends with wire strippers. Reheat one of the solder beads and place one of the stripped wire ends into the molten bead. Allow the bead to cool, ensuring the end of the wire is completely embedded in the solder. Now do the same with the other section of wire at the other terminal. On a multimeter, insert the red probe into the jack labeled V/F/C/Ω/ma/μA, and the black into the COM jack. Set the dial to measure continuity and measure across the two wire probes just soldered on. No "beep" signaling discontinuity should be produced. If no beep is produced, the resistance of the unstressed gage should be displayed on the multimeter. Alternatively, the meter dial can be set to resistance and measured in the same manner to obtain the unstressed resistance of the gage. Finally, secure the wires leading into the gage to the specimen with adhesive tape such that they wont be accidentally pulled out. Provide a "stress relief loop" between the gage and the taped point so the wires don't get pulled out as the specimen is stressed.

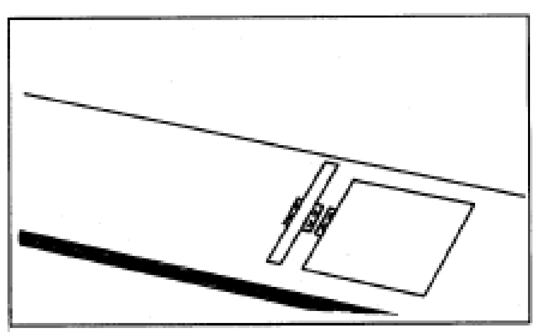

*Figure 5: Masking to Protect Gage while Soldering*

Connect the two wires to the strain indicator. Set the strain indicator to a quarter Wheatstone bridge for one gage. If the strain indicator is an older model utilize the remaining steps in this paragraph. If the strain indicator is a newer model, use the steps in the next paragraph. On the strain indicator, adjust "AMP

ZERO" to read zero. Then, select "Gage Factor" and type in the gage factor provided on the gage packaging. Calibrate the strain indicator by pressing "RUN" and rotate the "BALANCE" knobs until it reads zero micro-strain. If zero cannot be obtained, set it to a nearby rounded off number and use as a reference in measurements.

If utilizing one of the newer strain indicators, first ensure that only channel 1 is active with the "CHAN" key. Then, use the "BRDIGE" key to set the indicator to a quarter bridge. Enter the gage factor using the "GF/SCALING" key. Finally, balance the bridge using the balance key.

After balancing the bridge, manually press down on the free end of the cantilever beam to verify that measurements are realistic. The strain should increase.

After setting up the strain indicator, the dial indicator should now be set up so measurements can start to be taken. Place the dial indicator underneath the beam, closer to the load than the base but the location is arbitrary since the formulas do not require specific lengths. Once the strain indicator is underneath the beam, loosen the bolt for the rod that the strain indicator lies on so that it can be zeroed out with the surface of the beam. Either raise or lower the indicator to the point where the tip is just barely touching the surface of the beam and then tighten the bolt back up. If the indicator reads a slightly bigger number, the gage itself on the indicator can be moved around to zero it even further.

The dial indicator and strain gage setup are now complete and ready for loads but make the calculations, measurements of the following need to be taken distance from load to center of strain gage, distance from base of beam to tip of dial indicator, distance from base of beam to applied load, height of beam, and width of beam.

In this order, take the hanger, weigh it with the provided scale, write the measurement down and place it on the beam, then record both the dial indicator and strain indicator values. Before placing the next 6 weights on the hanger, be sure to weigh them beforehand with the scale provided. Now, place the weights on the scale one by one, while recording measurements to finish the experiment.

## Results and Discussion

After all calculations for the measured stress value and theoretical strain values, data that resulted was put into scatterplots with their respective counterparts so that a comparison can be made between the two. Ideally the measured values that are calculated should match up with the measured values that were found in the experiment. Starting with what should be expected from the graphs, it needs to be understood before considering any conclusions. The stress vs. applied force graph should have a perfect linear graph with a y intercept at 0 because as the force increases so should the stress and since the variables considered in equation 2b and 2c are all constant, the rate at which the stress increases should not change. With the strain vs. applied force graph, once again a perfect linear graph should be shown with a factor of the young's modulus taken out since ideally, the curve would follow Hooke's law.

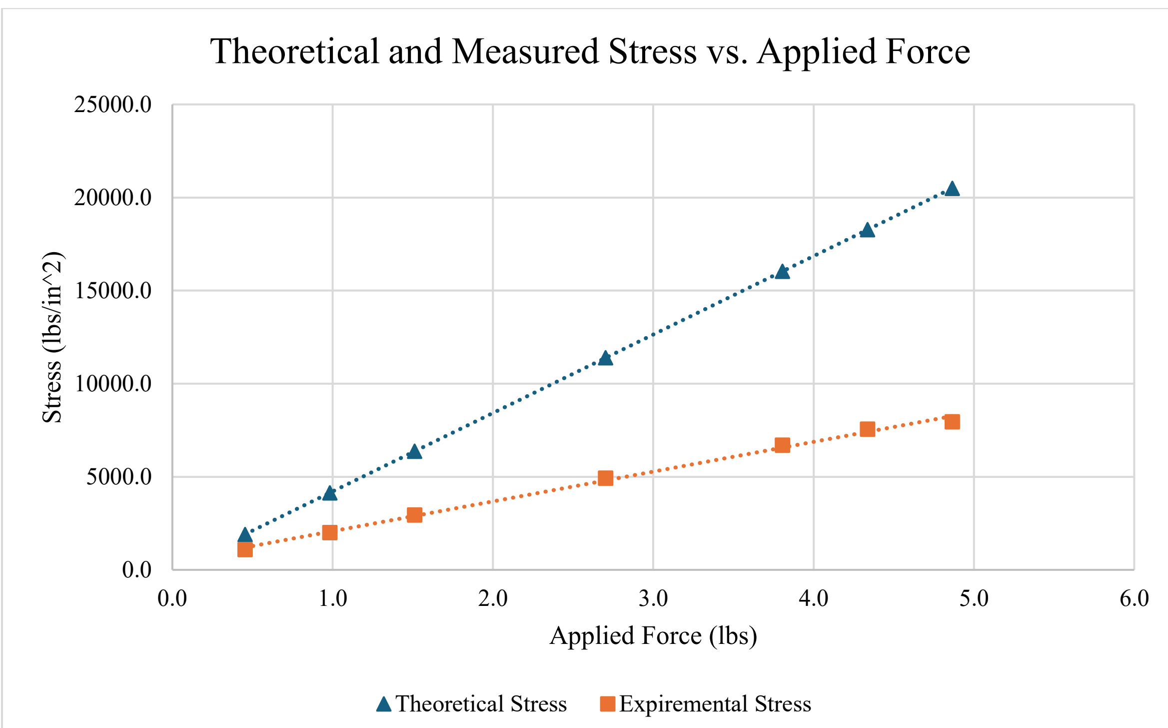


*Figure 6:Theoretical and Measured stress vs. Applied Forces*

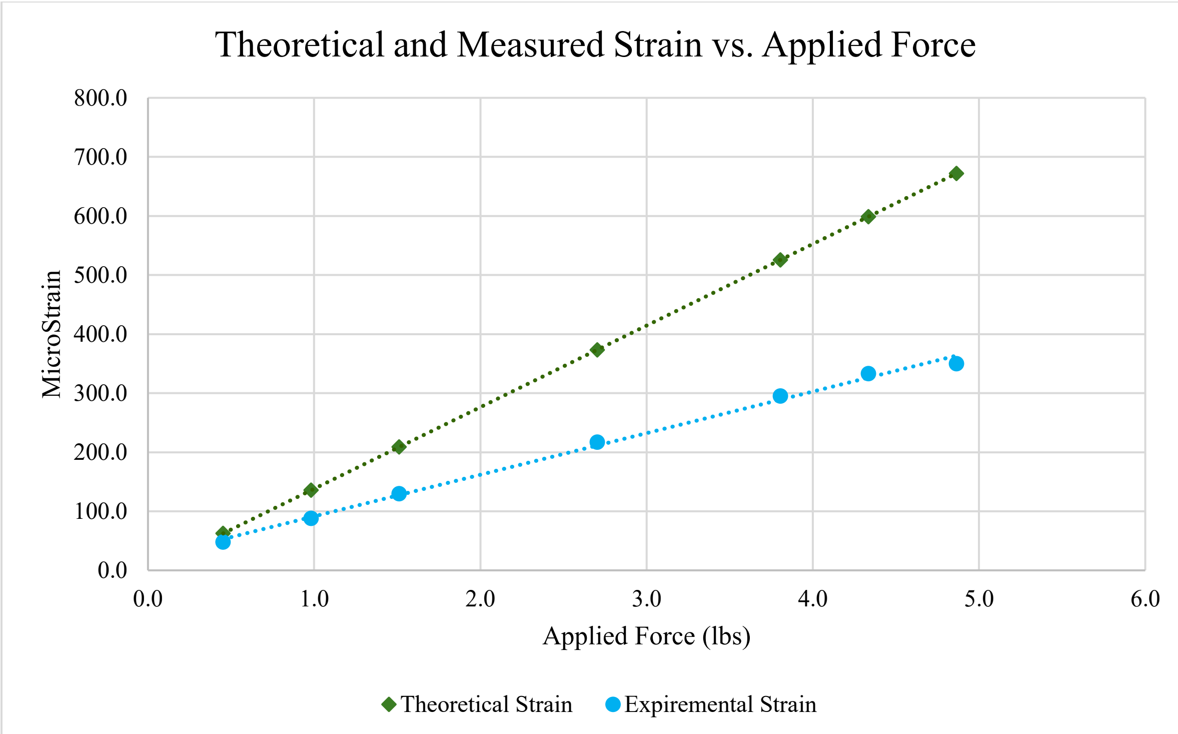


*Figure 7: Theoretical and Measured strain vs. Applied Forces*

Both graphs have been made and surprisingly and comparing the data, it's visible that the data is far from what was expected. The points that we have for the theoretical calculations are all linear and follow the perfect trend that we expected. The error that is most visible is in the modulus of elasticity. For the case shown in both figure 5 and 6, the modulus of elasticity that we found was lower than the ideal one for steel. This is seen in both the strain and stress values as points set up in a line but not as steep as the theoretical ones. A few possible sources of why this error could have occurred are measurements. Although the dial indicator got zeroed out, there was still a slight deflection present in the gage before starting the experiment, this could very well influence the values found in the measured modulus of elasticity equation. The next measurements would be the measurement from the base to the dial indicator and the measurement from the base to the load. It was unclear whether the measurement from the base to the load should be taken from the base to the center of the load, to the start of the load, or to the end of the load. In this case, the measurement from the base to the start of the load was taken but that could not have been the most accurate position for the modulus of elasticity. The reason for the measurement of the dial indicator slightly to the base being slightly off is the increments for which the value was recorded at. A tape measure was used that had increments in 1/16-inch increments and when recording values as such precision, a guess had to be made. Both values are input variables for the deflection equation so they could have also been a factor in the calculation for the modulus of elasticity.

Apart from the error in measurement for the measured stress and strain values, a measurement for the theoretical stress values were taken too. This measurement was for the moment of the force that was applied to the beam. It was from the road to the center of the strain gage. Once again, it may not have been the most accurate due to the tools that were being used which affect the stress values that are calculated, and along with the stress values, the strain values get affected too. It's not reasonable to question the load that was applied because that was measured independently with the most reliability from the scale that was given in the experiment. Overall, all possible errors suggested come from values that were measured throughout the experiment. To resolve errors like this, multiple trials may need to be done to get the most accuracy as well using more accurate instruments for the moment and deflection equations.

## Conclusion/References

There is a clear relationship between the electrical resistance and mechanical deformations, further supporting the principles of strain measurements. Using a quarter Wheatstone bridge in the strain gage allowed for measurable changes in voltage that corresponded with the strain generated by the beam under the applied forces. Using Hooke's Law, the theoretical results can be calculated to have a valid comparison to the experimental data. Though the theoretical data and the experimental data both exhibit similar linear trends as the applied force increased, there's a noticeable stray in experimental data points from what was theoretically expected. This deviation from the theoretical may be the result of human error while setting up the experiment. Despite this, the experimental data still shows a proportional trend between the applied load, stress, and strain. This retains some validity that the strain gage can reflect material behavior under elastic loading conditions with some accuracy.

## Appendix/Questions

*Table 1: Full table of theoretical and measured values for Stress and Strain*

| | **Applied load (Kg)** | **Beam Deflection (in)** | **Surface Micro Strain** | **Applied Force (lbs)** | **Moment (lb-in)** | **Theoretical Stress(lb/in^2)** | **Theoretical Strain (με)** | **Youngs Modulus (psi)** | **Experimental Stress (psi)** |
|---|---|---|---|---|---|---|---|---|---|
| Hanger | 0.205 | 0.1052 | 48 | 0.452 | 8.311 | 1905.7 | 62.5 | 22107594 | 1090.2 |
| 1 | 0.445 | 0.2260 | 88 | 0.982 | 18.041 | 4136.7 | 135.6 | 22338548 | 1998.7 |
| 2 | 0.685 | 0.3455 | 130 | 1.511 | 27.772 | 6367.8 | 208.8 | 22492922 | 2952.6 |
| 3 | 1.225 | 0.6090 | 217 | 2.703 | 49.665 | 11387.7 | 373.4 | 22820342 | 4928.6 |
| 4 | 1.725 | 0.8690 | 295 | 3.806 | 69.936 | 16035.7 | 525.8 | 22520223 | 6700.2 |
| 5 | 1.965 | 0.9850 | 333 | 4.336 | 79.666 | 18266.7 | 598.9 | 22632352 | 7563.3 |
| 6 | 2.205 | 1.0390 | 350 | 4.865 | 89.396 | 20497.8 | 672.1 | 24076669 | 7949.4 |

### Sample Calculations – Theoretical Stress and Strain (hanger)

$$Moment\ (M) = Force(F) * Distance\ from\ load\ to\ gage(D)$$

$$M = 18.375 * 0.0452 \approx 8.3\ lbs - in$$

*A conversion from kg to lbs was made to get the force of: $Force = Kg * 0.0685218 \frac{slugs}{Kg} * 32.2 \frac{ft}{s^2}$

$$Moment\ of\ inertia(I) = \frac{base\ (b) * height^3(h)}{12} = \frac{0.9898 * 0.1626^3}{12} \approx 0.000354\ in^4$$

$$Stress\ (\sigma_{theoretical}) = \frac{Moment\ (M) * Distance\ from\ center\ to\ point\ of\ interest\ (C)}{Moment\ of\ inertia\ (I)}$$

$$= \frac{M * \frac{h}{2}}{I} = \frac{8.3 * \frac{0.1626}{2}}{0.000354} \approx 1905.7\ \frac{lbs}{in^2}$$

$$Strain(\varepsilon_{theoretical}) = \frac{Stress(\sigma_{theoretical})}{Modulus\ of\ elasticity\ (E_{theoretical})} * 10^6 = \frac{1905.7}{30500000} * 10^6 \approx 62.5\ \mu\varepsilon$$

### Sample Calculations – Measured Stress and Strain (hanger)

$$Strain(\varepsilon_{measured}) = 48\ \mu\varepsilon$$

$$Modulus\ of\ elasticity(E) = \frac{Force(P) * Distance\ from\ dial\ indicator\ to\ base(x^2)}{6 * Deflection(\delta) * Moment\ of\ interia(I)}$$

$$* (3 * Distance\ from\ base\ to\ load(L) - Distance\ from\ dial\ indicator\ to\ base(x))$$

$$E_{measured} = \frac{0.452 * (14.875)^2}{6 * 0.1052 * 0.000354} \approx 22.1 * 10^6\ psi$$

*This was done for all measured modulus of elasticities, and an average was taken to find the stress for each strain value

$$E_{measured,average} = 22712664\ psi$$

$$Stress(\sigma_{measured}) = Modulus\ of\ Elasticity\left(E_{measured,average}\right) * Strain(\varepsilon_{measured})$$

$$\sigma_{measured} = 22712664 * 0.000048 \approx 1090.2\ psi$$