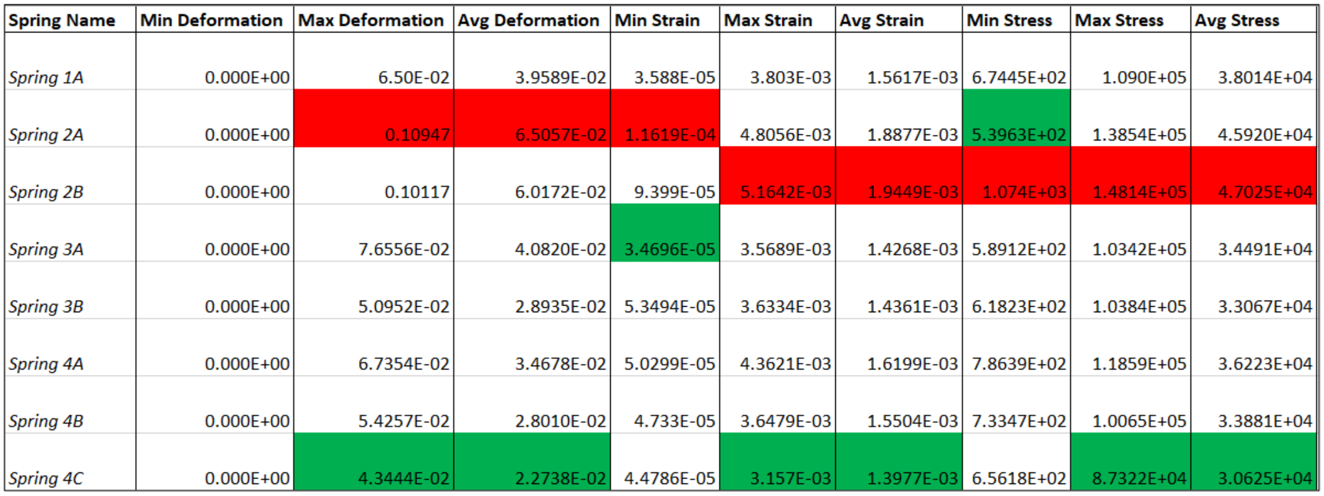
Results and Analysis

ANSYS Simulations

The ANSYS simulations are split into three main sections based on the material used: structural steel, 1095 steel (annealed), or 5160 steel (hardened and tempered). In the tables below, values that are highlighted in red are the highest values in the column, while those highlighted green are the lowest values in their respective columns.

The first set of analyses were done using structural steel. Springs from Series 2 consistently performed the worst (had the highest values), while Spring 4C performed the best in most categories. Interestingly, Spring 2A performed the best when it came to minimum stress despite doing poorly in other columns.

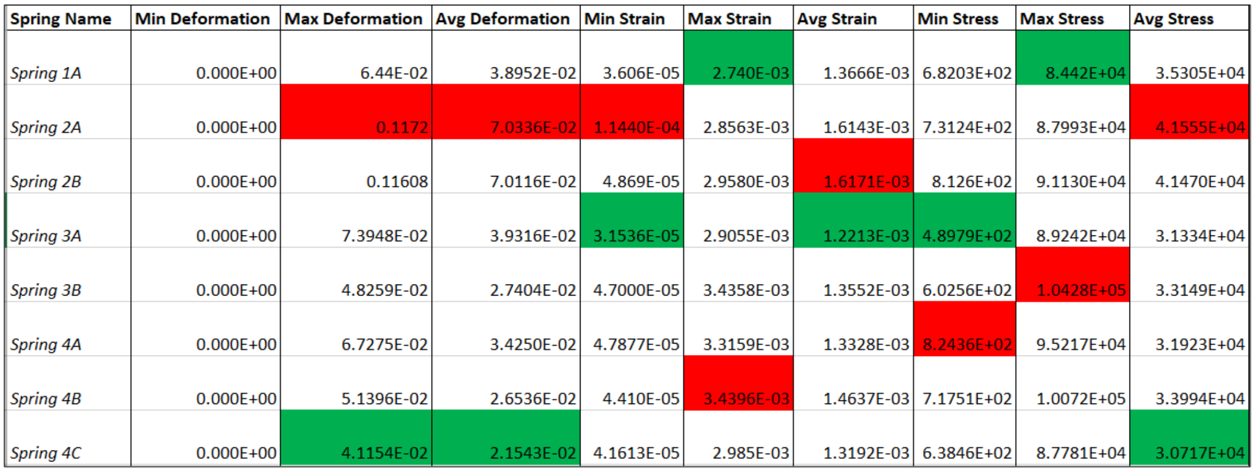
Table 1: Structural Steel Analysis Values for Spring Designs



Spring Name	Min Deformation	Max Deformation	Avg Deformation	Min Strain	Max Strain	Avg Strain	Min Stress	Max Stress	Avg Stress
Spring 1A	0.000E+00	6.50E-02	3.9589E-02	3.588E-05	3.803E-03	1.5617E-03	6.7445E+02	1.090E+05	3.8014E+04
Spring 2A	0.000E+00	0.10947	6.5057E-02	1.1619E-04	4.8056E-03	1.8877E-03	5.3963E+02	1.3854E+05	4.5920E+04
Spring 2B	0.000E+00	0.10117	6.0172E-02	9.399E-05	5.1642E-03	1.9449E-03	1.074E+03	1.4814E+05	4.7025E+04
Spring 3A	0.000E+00	7.6556E-02	4.0820E-02	3.4696E-05	3.5689E-03	1.4268E-03	5.8912E+02	1.0342E+05	3.4491E+04
Spring 3B	0.000E+00	5.0952E-02	2.8935E-02	5.3494E-05	3.6334E-03	1.4361E-03	6.1823E+02	1.0384E+05	3.3067E+04
Spring 4A	0.000E+00	6.7354E-02	3.4678E-02	5.0299E-05	4.3621E-03	1.6199E-03	7.8639E+02	1.1859E+05	3.6223E+04
Spring 4B	0.000E+00	5.4257E-02	2.8010E-02	4.733E-05	3.6479E-03	1.5504E-03	7.3347E+02	1.0065E+05	3.3881E+04
Spring 4C	0.000E+00	4.3444E-02	2.2738E-02	4.4786E-05	3.157E-03	1.3977E-03	6.5618E+02	8.7322E+04	3.0625E+04

The next set of analyses were done using 1095 steel (annealed). These are more closely related to the original spring because they are based in a real material that is used to manufacture the springs. Interestingly, these trends did not match those in structural steel or 5160 steel. Spring 2A continued to perform poorly. Both Spring 1A and Spring 3A performed well in 1095 steel. While Spring 4C also performed well, Springs 4A and 4B didn’t do well when it came to stress, suggesting that the larger radii of Spring 4C reduced the stress. This was confirmed by graphing the average values for stress, deformation, and strain throughout Series 4. As we can see in **Figure 1**, the values for each spring decreased as the radii increased (from Spring 4A to Spring 4C).

Table 2: Annealed 1095 Steel Analysis Values for Spring Designs



Spring Name	Min Deformation	Max Deformation	Avg Deformation	Min Strain	Max Strain	Avg Strain	Min Stress	Max Stress	Avg Stress
Spring 1A	0.000E+00	6.44E-02	3.8952E-02	3.606E-05	2.740E-03	1.3666E-03	6.8203E+02	8.442E+04	3.5305E+04
Spring 2A	0.000E+00	0.1172	7.0336E-02	1.1440E-04	2.8563E-03	1.6143E-03	7.3124E+02	8.7993E+04	4.1555E+04
Spring 2B	0.000E+00	0.11608	7.0116E-02	4.869E-05	2.9580E-03	1.6171E-03	8.126E+02	9.1130E+04	4.1470E+04
Spring 3A	0.000E+00	7.3948E-02	3.9316E-02	3.1536E-05	2.9055E-03	1.2213E-03	4.8979E+02	8.9242E+04	3.1334E+04
Spring 3B	0.000E+00	4.8259E-02	2.7404E-02	4.7000E-05	3.4358E-03	1.3552E-03	6.0256E+02	1.0428E+05	3.3149E+04
Spring 4A	0.000E+00	6.7275E-02	3.4250E-02	4.7877E-05	3.3159E-03	1.3328E-03	8.2436E+02	9.5217E+04	3.1923E+04
Spring 4B	0.000E+00	5.1396E-02	2.6536E-02	4.410E-05	3.4396E-03	1.4637E-03	7.1751E+02	1.0072E+05	3.3994E+04
Spring 4C	0.000E+00	4.1154E-02	2.1543E-02	4.1613E-05	2.985E-03	1.3192E-03	6.3846E+02	8.7781E+04	3.0717E+04

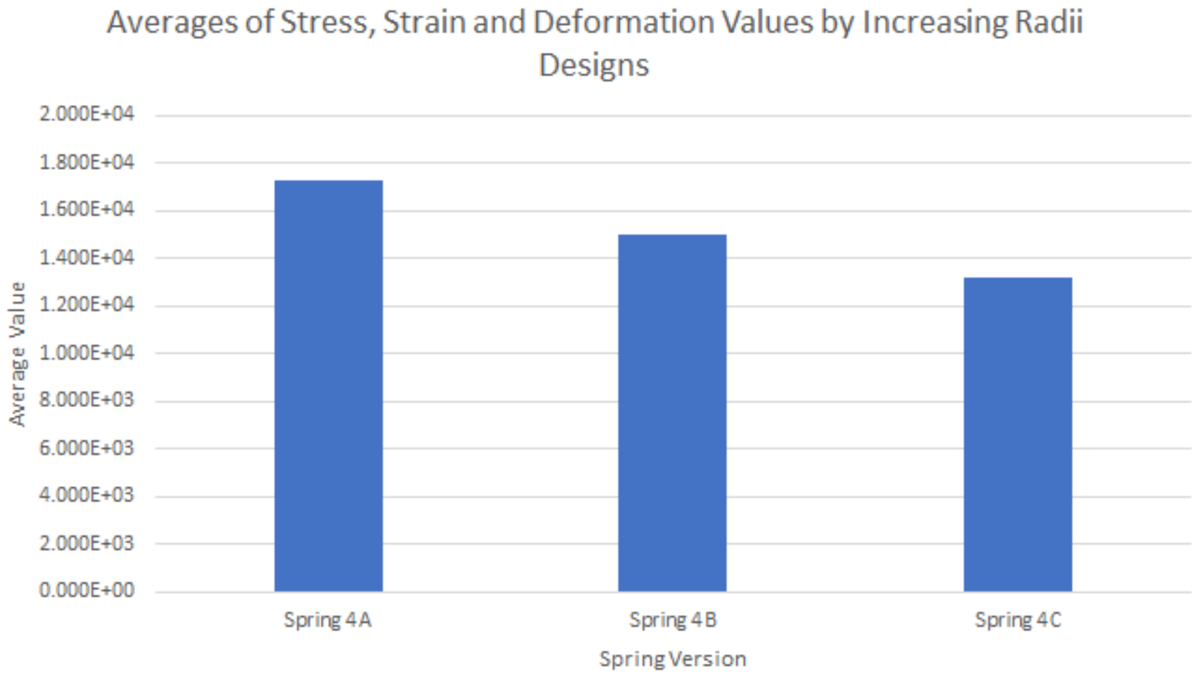
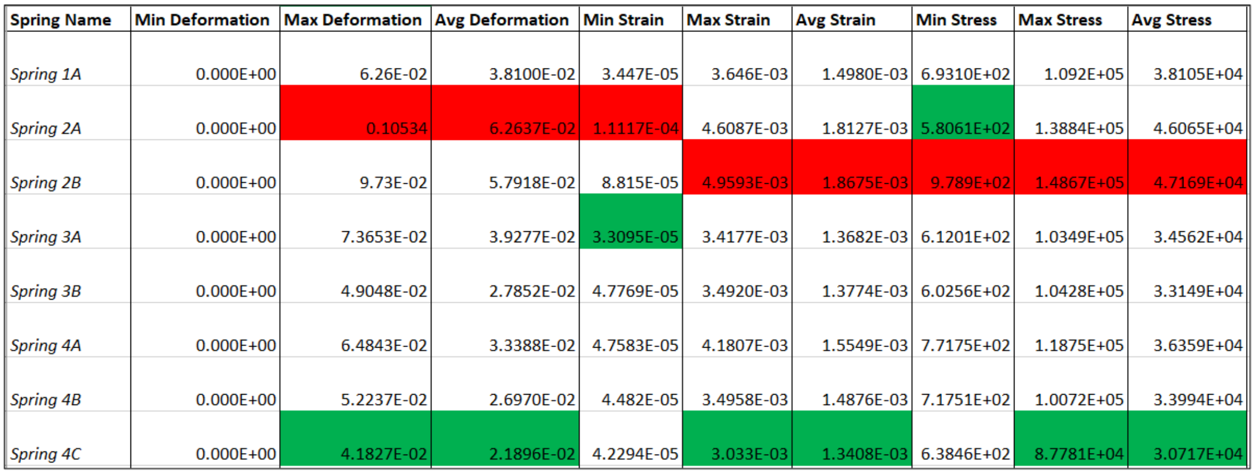


Figure 1: Graph of Averages of Stress, Strain and Deformation Values for Series 4 (increasing radii)

The final set of analyses were done using 5160 steel. The trends from this table completely matched structural steel, though the values were different. The springs from Series 2 continued to perform poorly, and Spring 4C continued to perform well.

Table 3: Hardened and Tempered 5160 Steel Analysis Values for Spring Designs



Spring Name	Min Deformation	Max Deformation	Avg Deformation	Min Strain	Max Strain	Avg Strain	Min Stress	Max Stress	Avg Stress
Spring 1A	0.000E+00	6.26E-02	3.8100E-02	3.447E-05	3.646E-03	1.4980E-03	6.9310E+02	1.092E+05	3.8105E+04
Spring 2A	0.000E+00	0.10534	6.2637E-02	1.1117E-04	4.6087E-03	1.8127E-03	5.8061E+02	1.3884E+05	4.6065E+04
Spring 2B	0.000E+00	9.73E-02	5.7918E-02	8.815E-05	4.9593E-03	1.8675E-03	9.789E+02	1.4867E+05	4.7169E+04
Spring 3A	0.000E+00	7.3653E-02	3.9277E-02	3.3095E-05	3.4177E-03	1.3682E-03	6.1201E+02	1.0349E+05	3.4562E+04
Spring 3B	0.000E+00	4.9048E-02	2.7852E-02	4.7769E-05	3.4920E-03	1.3774E-03	6.0256E+02	1.0428E+05	3.3149E+04
Spring 4A	0.000E+00	6.4843E-02	3.3388E-02	4.7583E-05	4.1807E-03	1.5549E-03	7.7175E+02	1.1875E+05	3.6359E+04
Spring 4B	0.000E+00	5.2237E-02	2.6970E-02	4.482E-05	3.4958E-03	1.4876E-03	7.1751E+02	1.0072E+05	3.3994E+04
Spring 4C	0.000E+00	4.1827E-02	2.1896E-02	4.2294E-05	3.033E-03	1.3408E-03	6.3846E+02	8.7781E+04	3.0717E+04

I noticed some interesting results when I compared the average values from 1095 steel to 5160 steel. The purpose of this comparison was to see the strengths and weaknesses of the different materials. The results were very clear. You can see in **Figure 2** that the average deformation for 1095 steel is much higher than 5160 steel. This makes sense, as the 5160 steel used was hardened. For strain, the opposite occurred as seen in **Figure 3**; 1095 steel had much lower average strain than 5160 steel. A full set of comparisons can be seen in the appendix (**Figure 30**). The results of these comparisons show that 1095 steel has lower strain and stress values, while using 5160 steel can help improve the spring's deformation value.

By comparing the maximum and minimum values from the 1095 and 5160 tables by indicating which values are the lowest (**Table 4**: Comparison of extremes of 1095 steel and 5160 steel), there is again a trend of high deformation values from 1095 while 5160 performs poorly in stress and strain. Minimum deformation values were removed from this comparison, as all were zeroes.

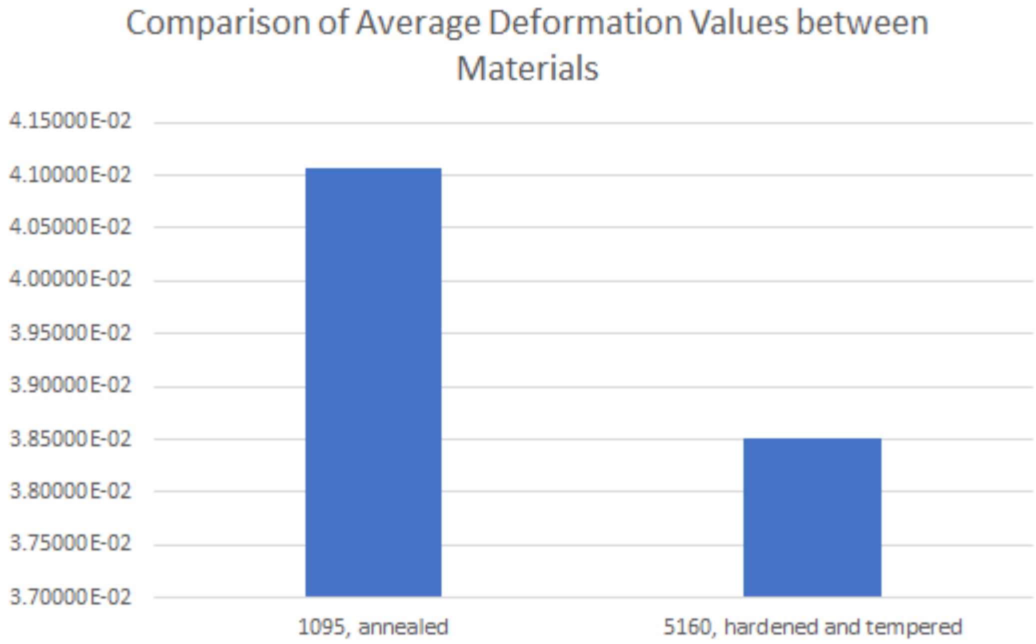


Figure 2: Graph comparing average deformation values between 1095 steel and 5160 steel

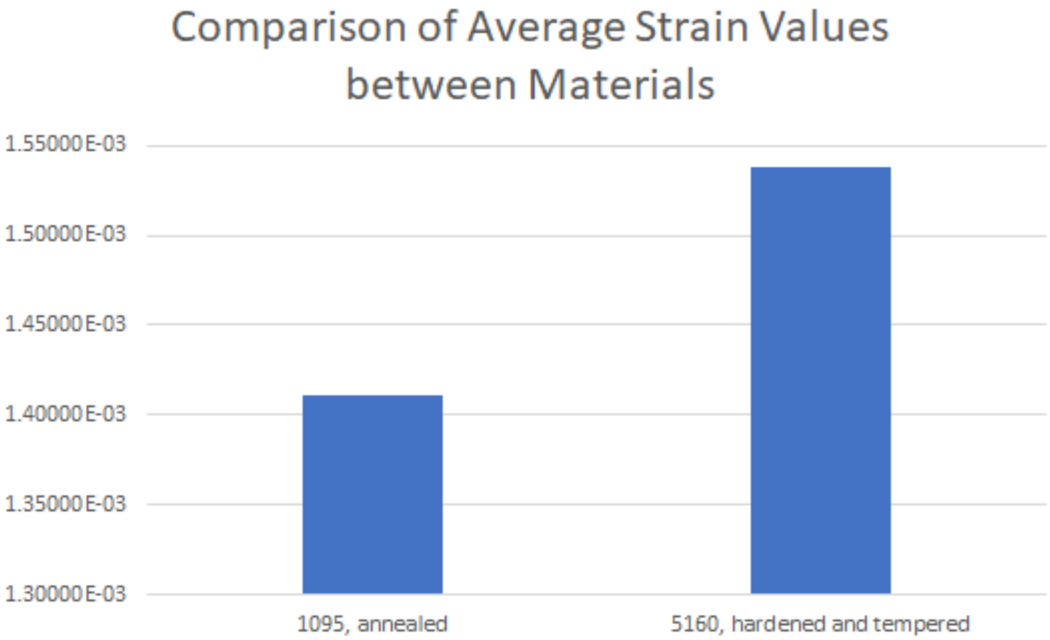
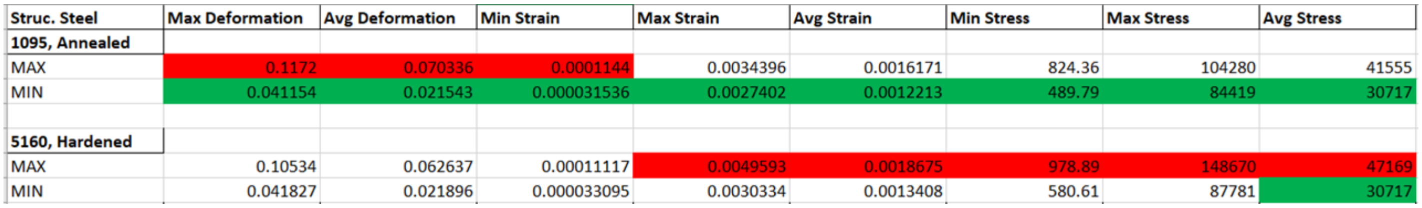


Figure 3: Graph comparing average strain values between 1095 steel and 5160 steel

Table 4: Comparison of extremes of 1095 steel and 5160 steel

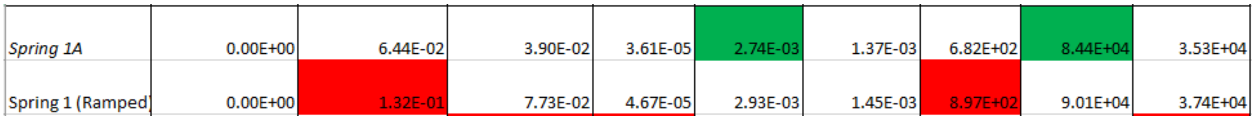


Struc. Steel	Max Deformation	Avg Deformation	Min Strain	Max Strain	Avg Strain	Min Stress	Max Stress	Avg Stress
1095, Annealed								
MAX	0.1172	0.070336	0.0001144	0.0034396	0.0016171	824.36	104280	41555
MIN	0.041154	0.021543	0.000031536	0.0027402	0.0012213	489.79	84419	30717
5160, Hardened								
MAX	0.10534	0.062637	0.00011117	0.0049593	0.0018675	978.89	148670	47169
MIN	0.041827	0.021896	0.000033095	0.0030334	0.0013408	580.61	87781	30717

Based on the results outlined above, the spring design that is eventually chosen should be based on values from the material that is used. While the 1095 steel deforms more, it has lower stress values, which is what we're interested in reducing. Therefore, it is recommended to use annealed 1095 steel unless a better material is presented in the future. If 1095 annealed steel is used, Spring 3A would be a good option. But if 5160 hardened steel is used, it would be best to use Spring 4C. Some sources of error in these analyses are the lack of surface coatings (versus the actual spring design), and possible variations due to the simplified mesh (model).

In addition to analyzing the new designs, I also analyzed the spring when it is placed in other positions within the guitar (i.e. other notches on the clamp). Seen below, the values for the angled spring were higher in all categories compared to the spring when it's in the center notch.

Table 5: Comparing results from the component force study to results from the original spring

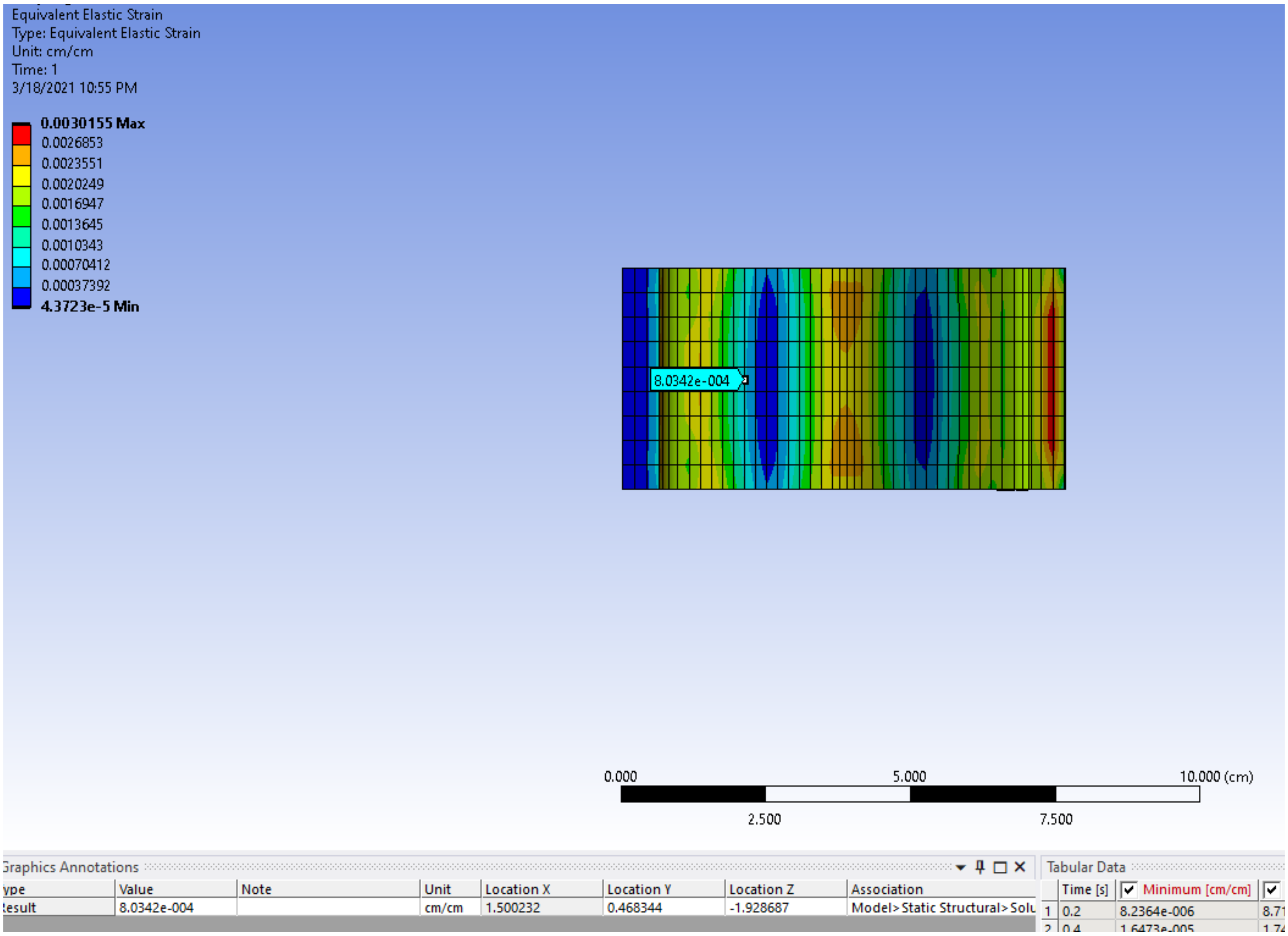


Spring 1A	0.00E+00	6.44E-02	3.90E-02	3.61E-05	2.74E-03	1.37E-03	6.82E+02	8.44E+04	3.53E+04
Spring 1 (Ramped)	0.00E+00	1.32E-01	7.73E-02	4.67E-05	2.93E-03	1.45E-03	8.97E+02	9.01E+04	3.74E+04

Lab Test Results

To confirm the ANSYS results, I had to have two analyses: simulating the part in ANSYS and measuring the strain in the lab. In **Figure 4**, we can see that at 2.5 centimeters from the edge of the spring, the strain is 8.0342E-4. To convert this to microstrains, we need to multiply it by 10^6. Therefore, the microstrains that we expect in the lab test are 803.42 (unitless).

In the lab test (**Figure 5**), we ended up getting two plateaus of data, one around 500 and one around 800 microstrains. The one around 500 is most likely due to the guitar bridge not being balanced and fully tightened, so we are going to focus on the 800 range of values (**Figure 6**). We can clearly see that the values oscillate about 800 microstrains and using Excel we can see that the average of that range of values is 799.2565 microstrains (**Table 6**: Calibrated microstrain of the spring while clamped in the guitar). This is very close to our theoretical results, with a percent error of 0.52%. Possible sources of error are the simulation being off due to the difference in surface coatings (the simulation uses pure zinc while the actual spring uses zinc-nickel alloy), and the strain gage not being exactly at 2.5 cm from the edge. However, because of how close these values are to each other, we can conclude that our ANSYS results roughly match those found in the lab.



Equivalent Elastic Strain
Type: Equivalent Elastic Strain
Unit: cm/cm
Time: 1
3/18/2021 10:55 PM

Graphics Annotations

ype	Value	Note	Unit	Location X	Location Y	Location Z	Association
esult	8.0342e-004		cm/cm	1.500232	0.468344	-1.928687	Model> Static Structural> Solu

Tabular Data

	Time [s]	☑ Minimum [cm/cm]	☑
1	0.2	8.2364e-006	8.71
2	0.4	1.6473e-005	1.74

Figure 4: Results from the ANSYS study to imitate actual spring values

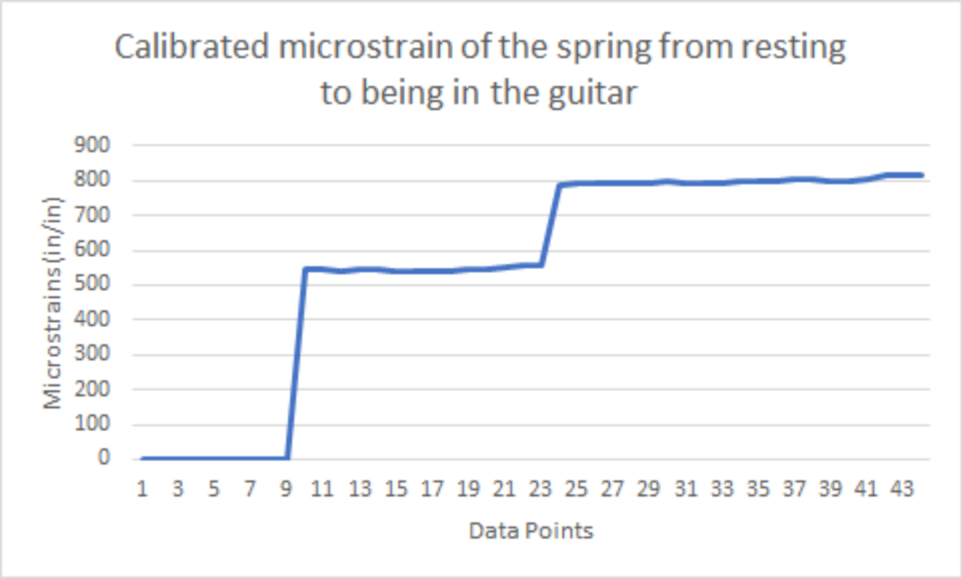


Figure 5: Graph of the calibrated microstrain of the spring from resting state to being clamped in the guitar

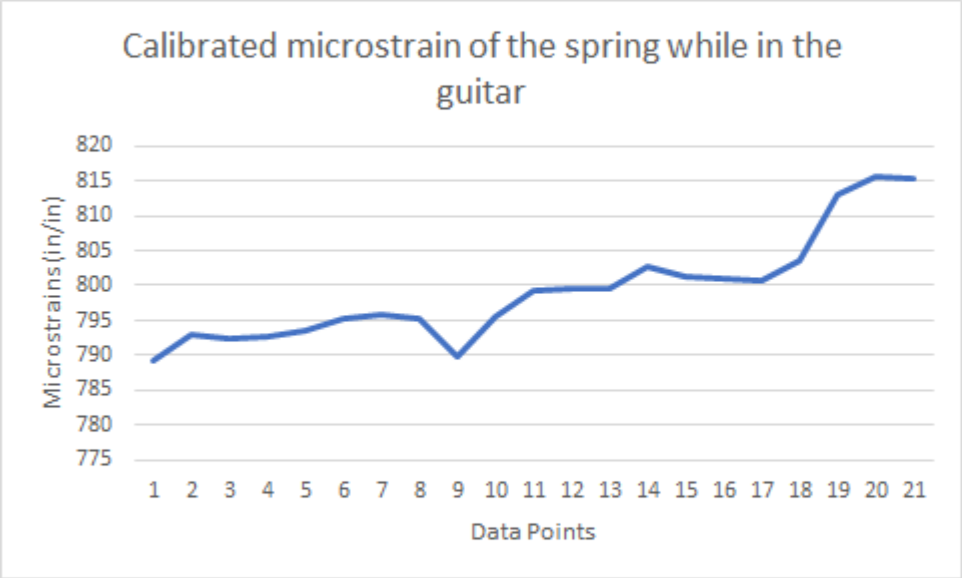


Figure 6: Graph of calibrated microstrain experienced by the spring while clamped in the guitar

Conclusions

Like most projects, this one was full of problems and things that could have gone better. For those going forward, I recommend you do not use a remote desktop to run ANSYS, as there can be errors that are based solely on the computer. Instead, use the computer lab in Higgins Laboratory. I also recommend that you do not use LabView for future studies with strain gages. Instead, use an Arduino program. An Arduino strain gage module found online would make connecting to the strain gage much easier. These values could be recorded onto an SD card, which there are also Arduino modules for.

There are also plenty of items that still need to be worked on. These are merely suggestions to teams that use this project in the future:

Do a scanning electron microscope analysis of the broken spring. There are possible patterns where the springs break in the same spot. While I didn’t get to use the SEM this term, it could be useful to see how the original spring design has failed, and whether there’s a pattern.

There is still room to grow for new spring designs. New teams should continue to create and test new spring designs. A concern was raised in this project about whether new spring designs would deform enough to hit the boundaries of the cavity, so future teams should also test whether those springs hit the boundary of the guitar. This could be done by increasing the force to see how much input force it takes to hit the boundaries. The probe tool in ANSYS is a great way to see how the spring’s positions have changed.

When a spring design is selected to go forward with, teams should use fatigue analysis with S-N curves to quantify how many cycles the spring will take until failure. Maximum stress can easily be found in ANSYS. Future teams should also use modal and dynamic structural analysis in the final analyses of the spring. For their fatigue analysis, teams should determine how much force a guitarist applies to the spring and use this value to get a realistic stress value. This will make their data more accurate.

Quantifying the resistance of the eventual spring design could be important from a marketing perspective. Professor Manzo suggested using low, medium, and hard to describe how much the spring resists being deformed by the guitarist. This could be done by testing the deformation value in ANSYS, then testing the real-life value using a force gage and a spring.

Finally, when teams have completed all necessary steps, they should design a manufacturing process for the spring. From my research, I recommend that teams anneal the steel prior to manufacturing using a heat treatment oven. In lieu of this, teams can heat up the steel, then allow it to cool slowly in a folded piece of ceramic fiber blanket. I would recommend that teams attempt to continue to use a Zinc-Nickel alloy for coating, and top that off with trivalent chromate coating for protection against corrosion.

Appendix

Appendix A: Diagrams and Information

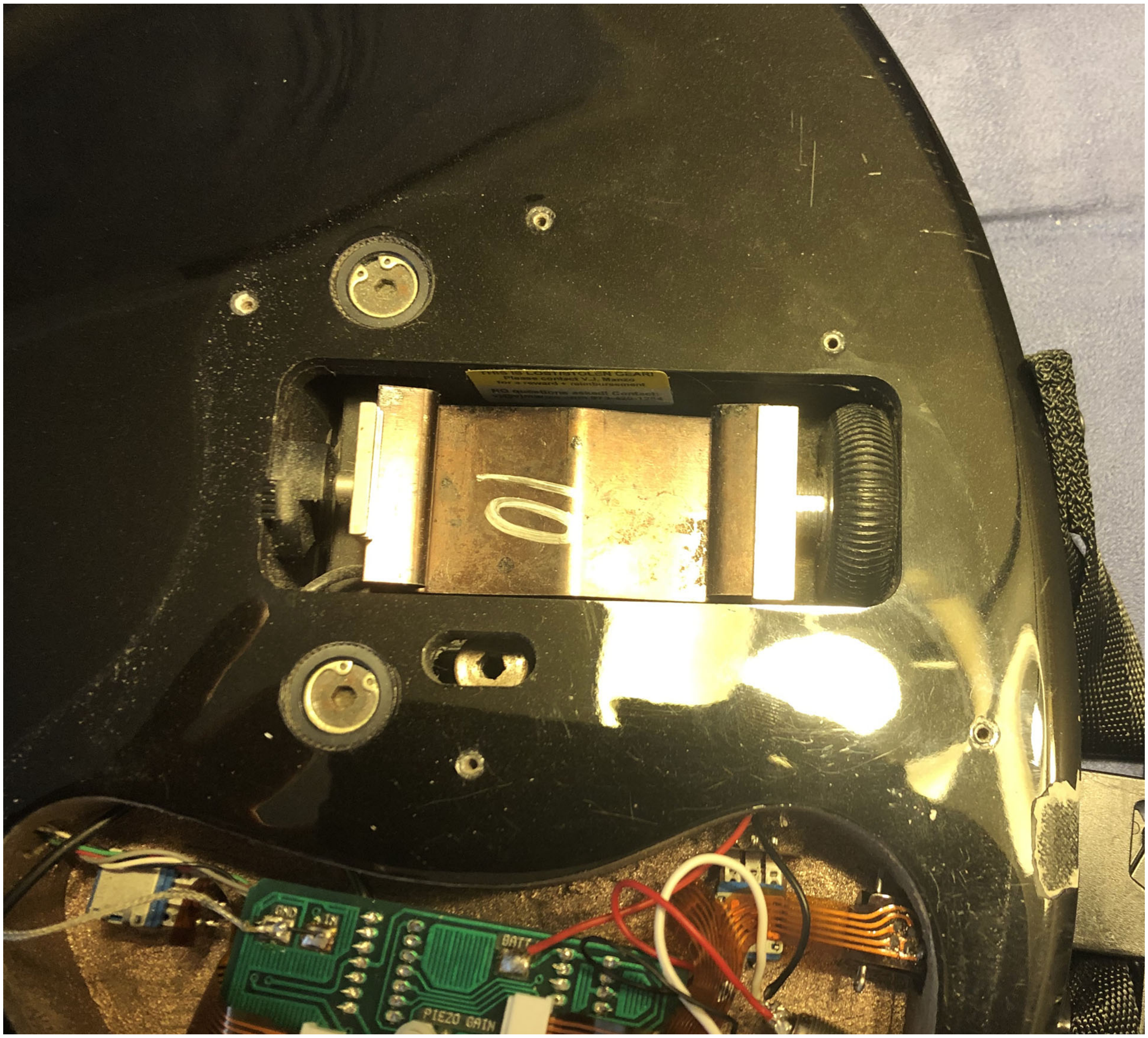
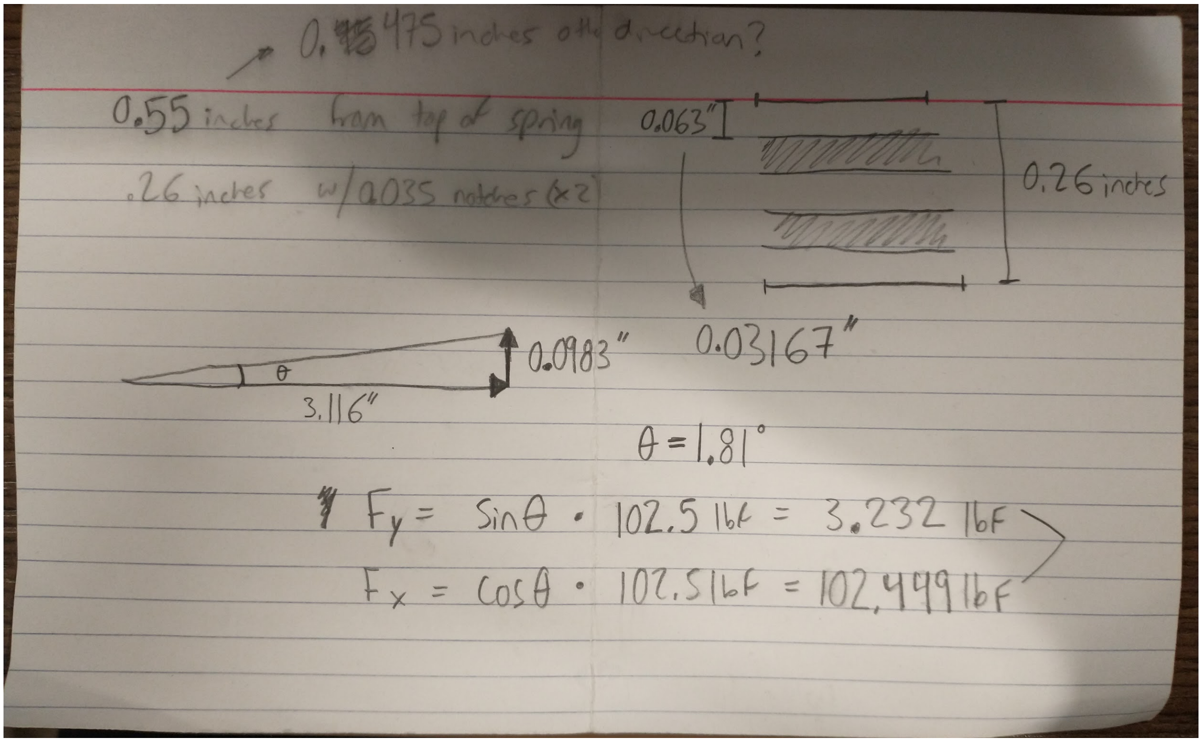


Figure 7: Image of the spring in the guitar, taken by Professor Manzo



0.475 inches other direction?

0.55 inches from top of spring

.26 inches w/ 0.035 notches (x2)

$\theta = 1.81^\circ$

$F_y = \sin\theta \cdot 102.5\ \text{lbf} = 3.232\ \text{lbf}$

$F_x = \cos\theta \cdot 102.5\ \text{lbf} = 102.449\ \text{lbf}$

Figure 8: Calculations for the components of force while the spring is clamped at an angle

Appendix B: Spring Designs

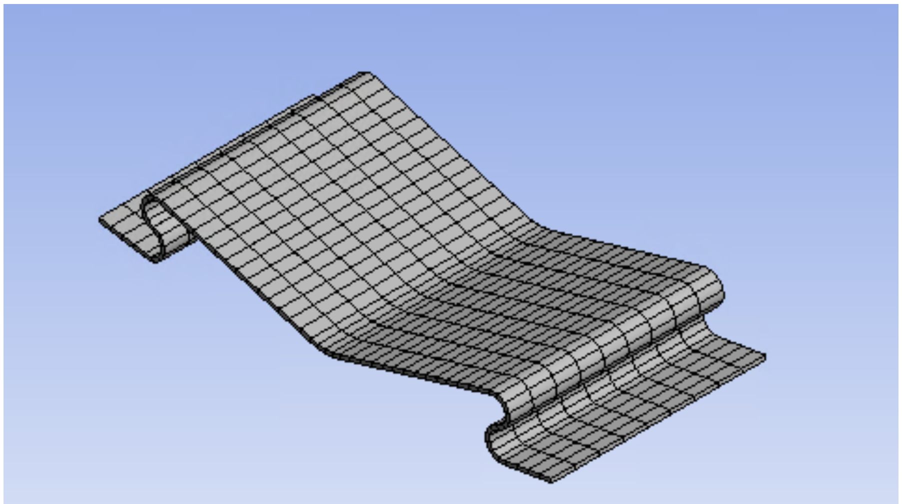


Figure 9: Spring 1A - Original spring design

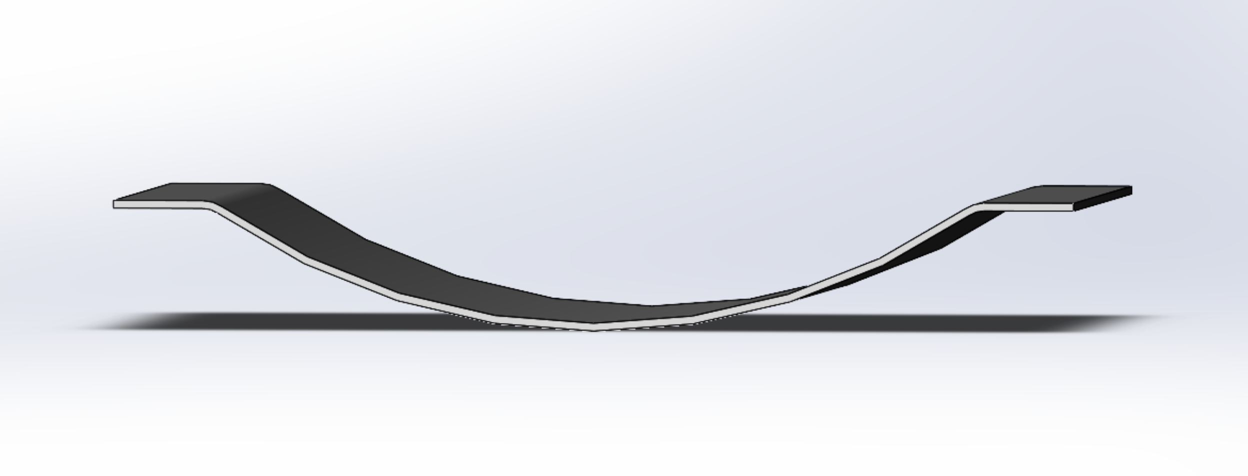


Figure 10: Spring 2A

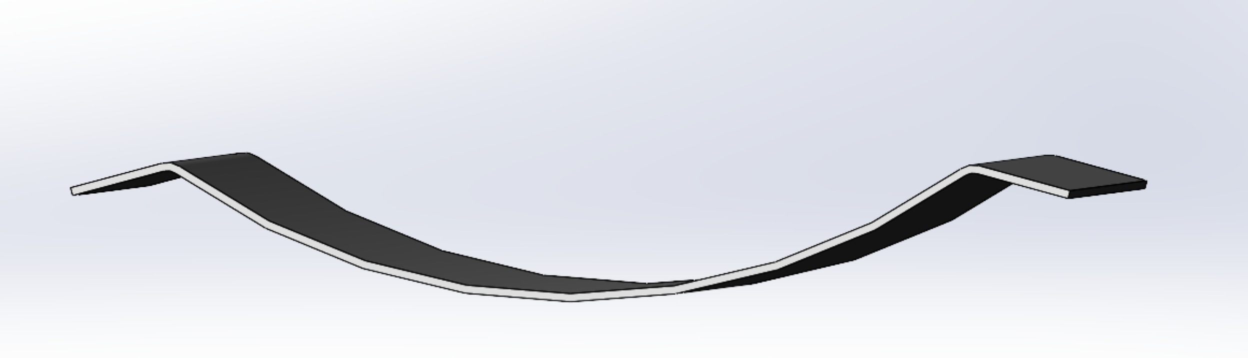


Figure 11: Spring 2B

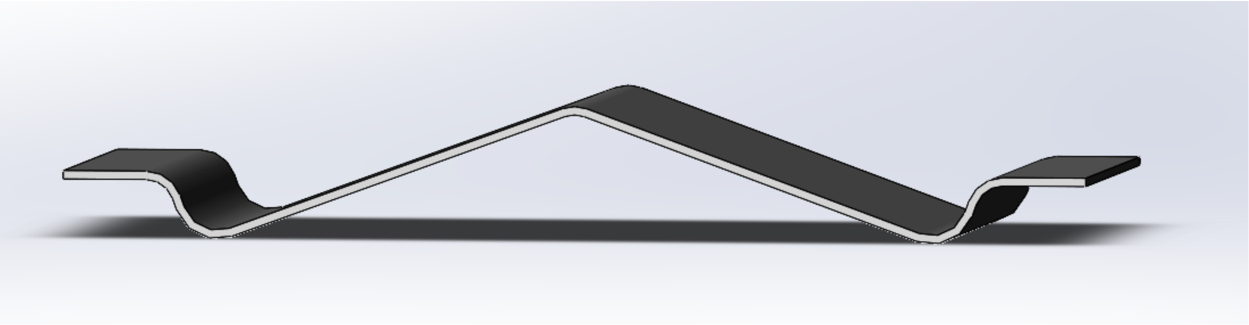


Figure 12: Spring 3A

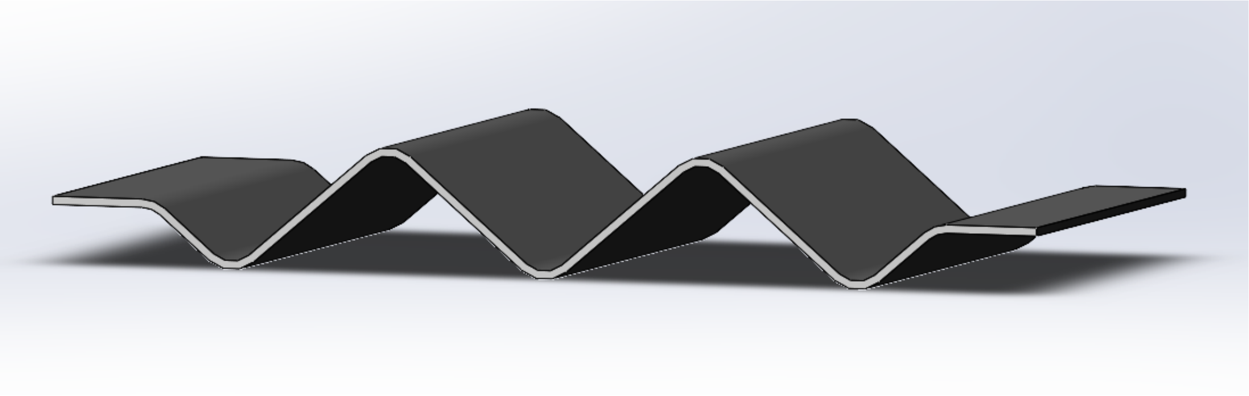


Figure 13: Spring 3B

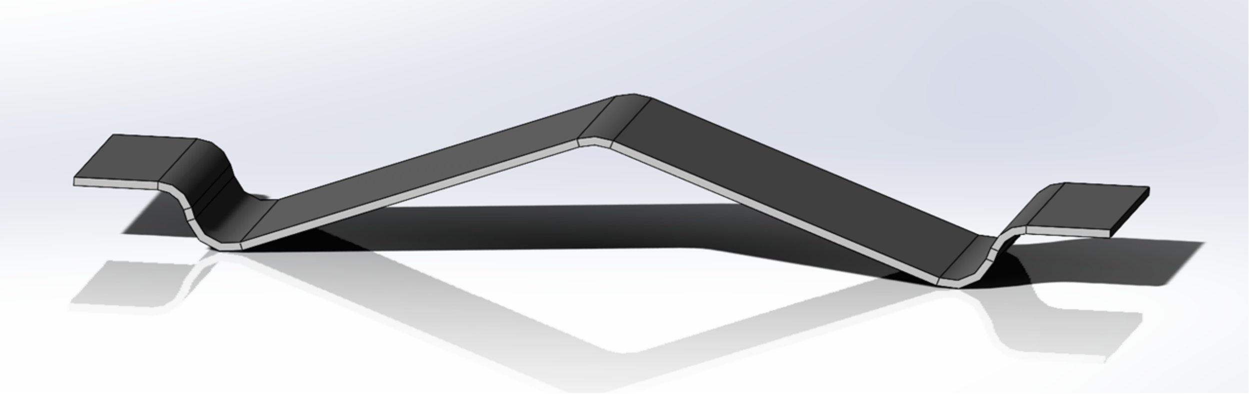


Figure 14: Spring 3C

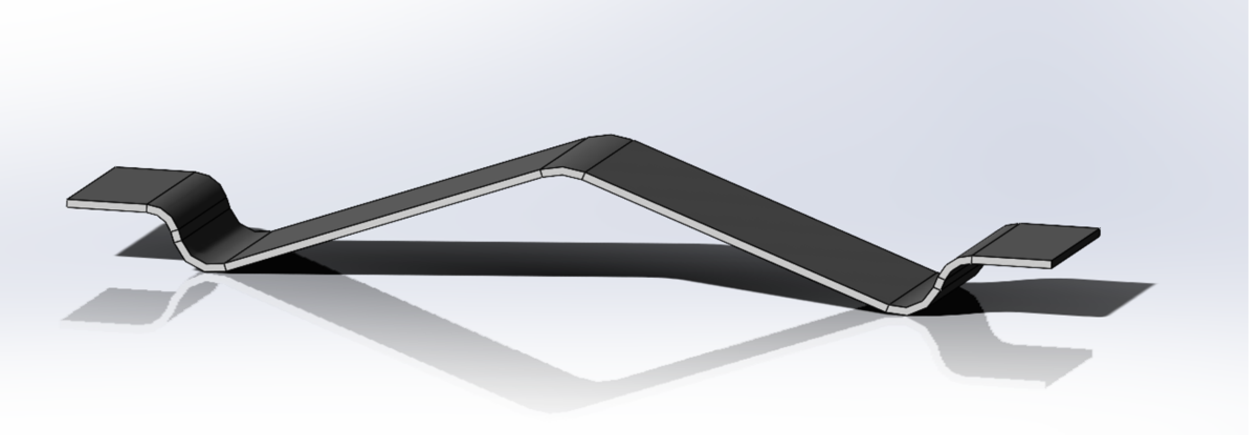


Figure 15: Spring 3D

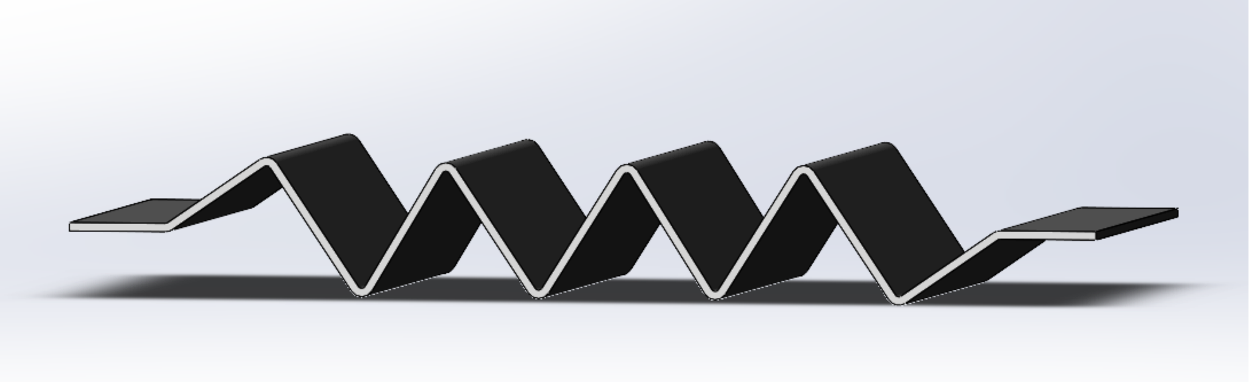


Figure 16: Spring 4A

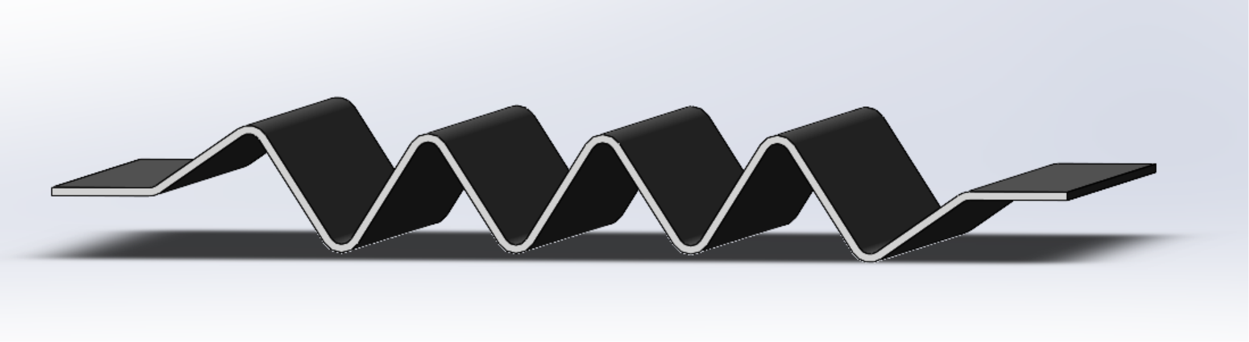


Figure 17: Spring 4B

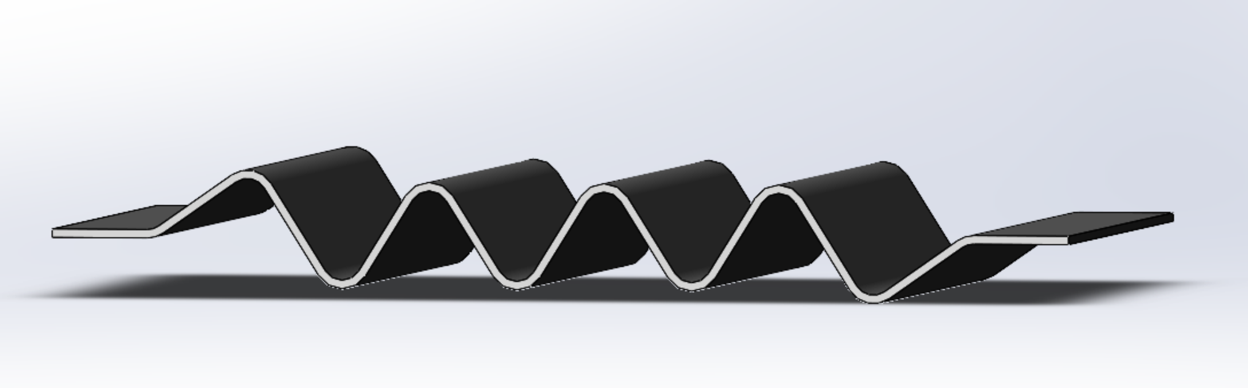


Figure 18: Spring 4C

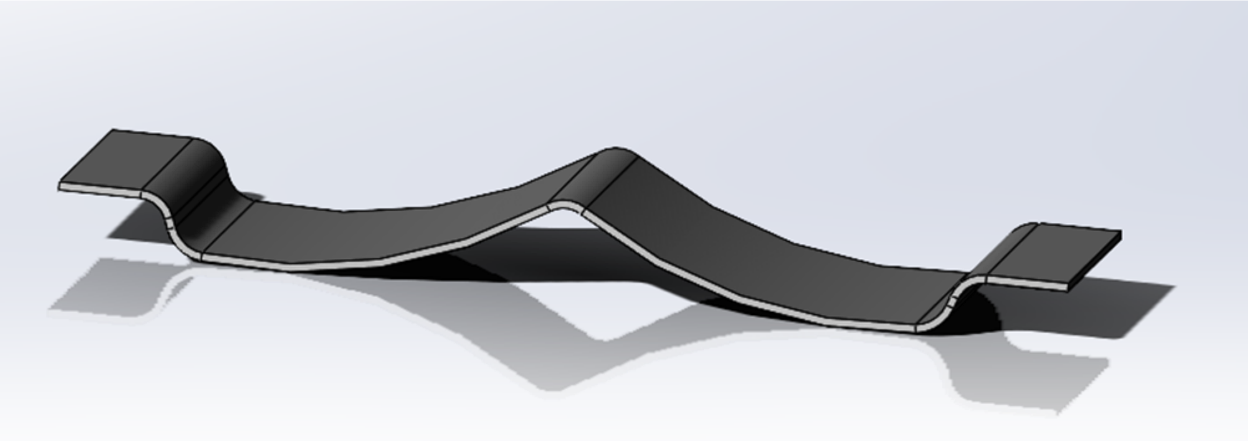


Figure 19: Spring 5A

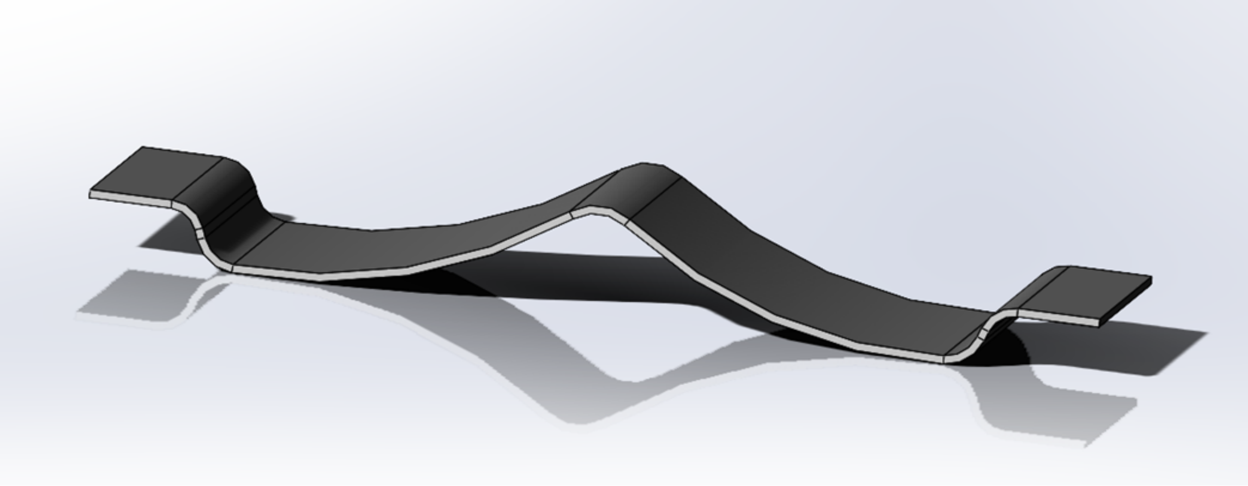


Figure 20: Spring 5B

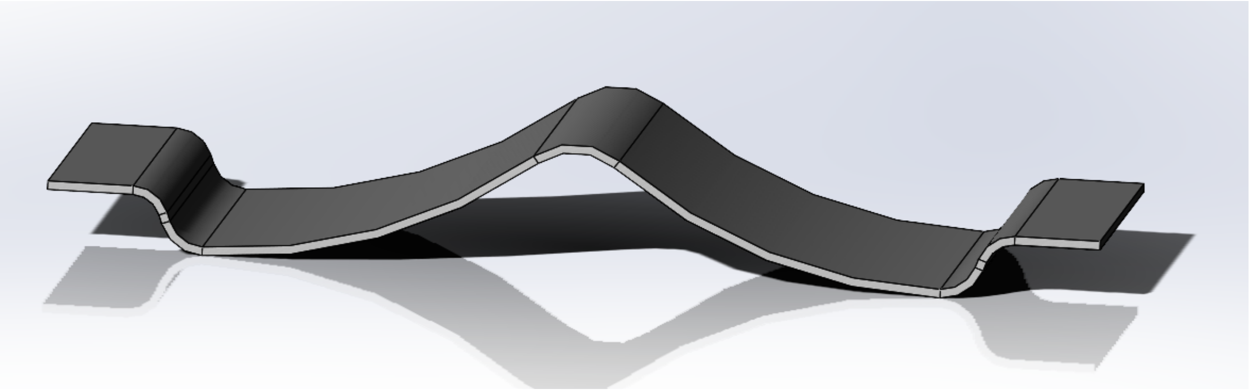
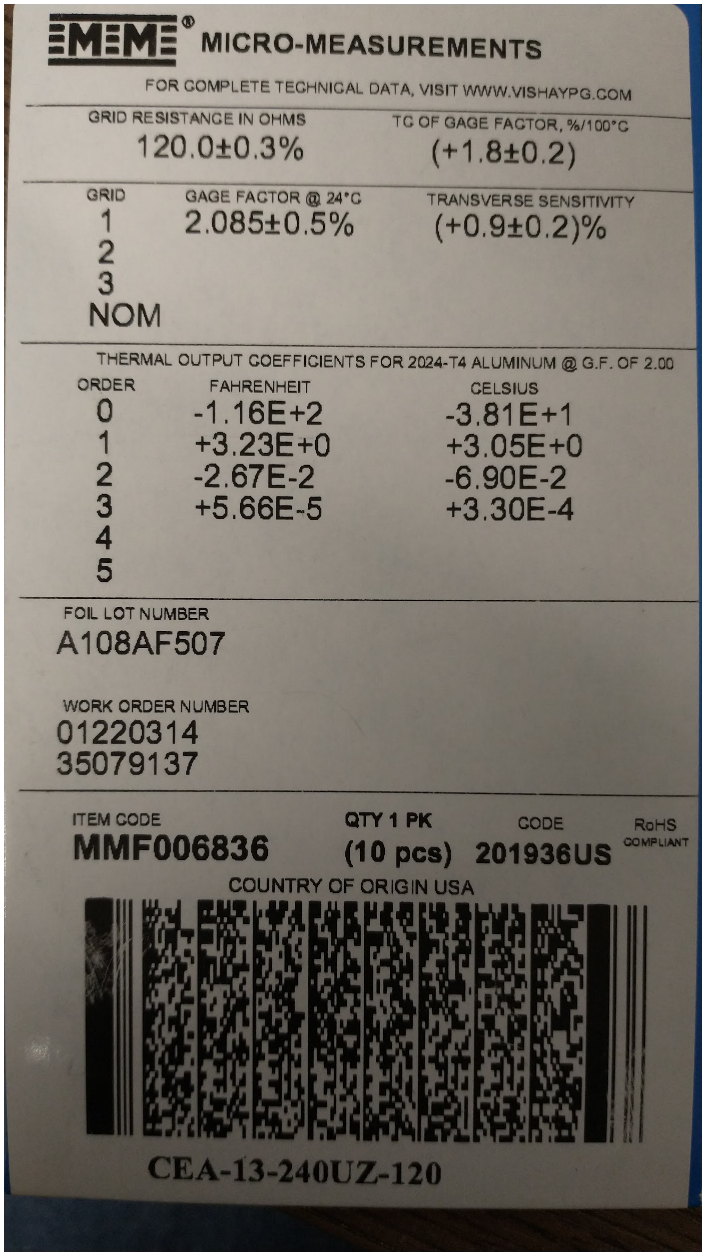


Figure 21: Spring 5C

Appendix C: Laboratory Setup



MICRO-MEASUREMENTS

FOR COMPLETE TECHNICAL DATA, VISIT WWW.VISHAYPG.COM

GRID RESISTANCE IN OHMS	TC OF GAGE FACTOR, %/100°C
120.0±0.3%	(+1.8±0.2)

GRID	GAGE FACTOR @ 24°C	TRANSVERSE SENSITIVITY
1	2.085±0.5%	(+0.9±0.2)%
2		
3		
NOM		

THERMAL OUTPUT COEFFICIENTS FOR 2024-T4 ALUMINUM @ G.F. OF 2.00

ORDER	FAHRENHEIT	CELSIUS
0	-1.16E+2	-3.81E+1
1	+3.23E+0	+3.05E+0
2	-2.67E-2	-6.90E-2
3	+5.66E-5	+3.30E-4
4		
5		

FOIL LOT NUMBER
A108AF507

WORK ORDER NUMBER
01220314
35079137

ITEM CODE	QTY 1 PK	CODE	RoHS COMPLIANT
MMF006836	**(10 pcs)**	**201936US**	

COUNTRY OF ORIGIN USA

CEA-13-240UZ-120

Figure 22: Specifications for the strain gage

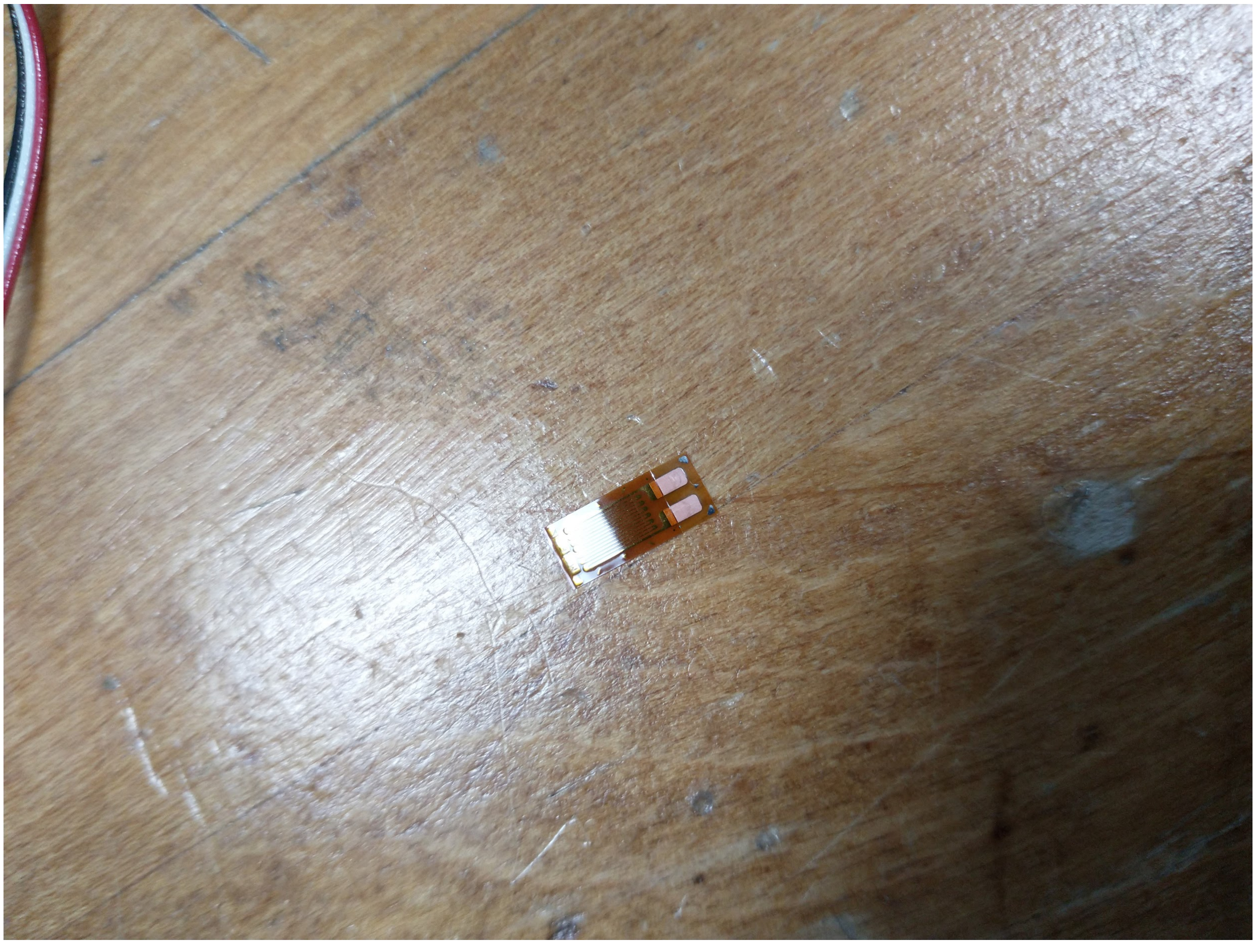


Figure 23: Lay the strain gage out on the table

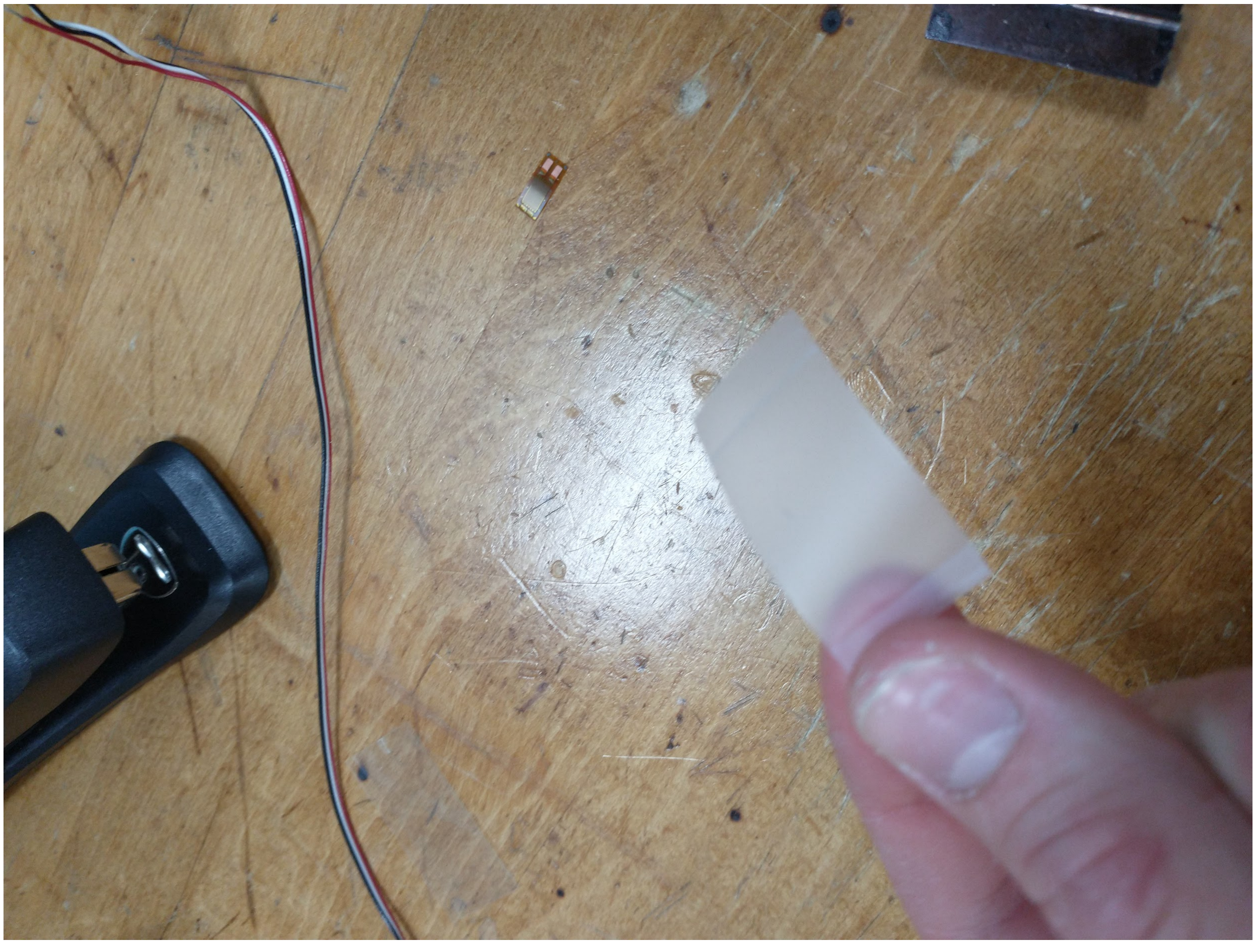


Figure 24: Fold one end of the scotch tape over

Figure 25: Strain gage attached with tape to the spring

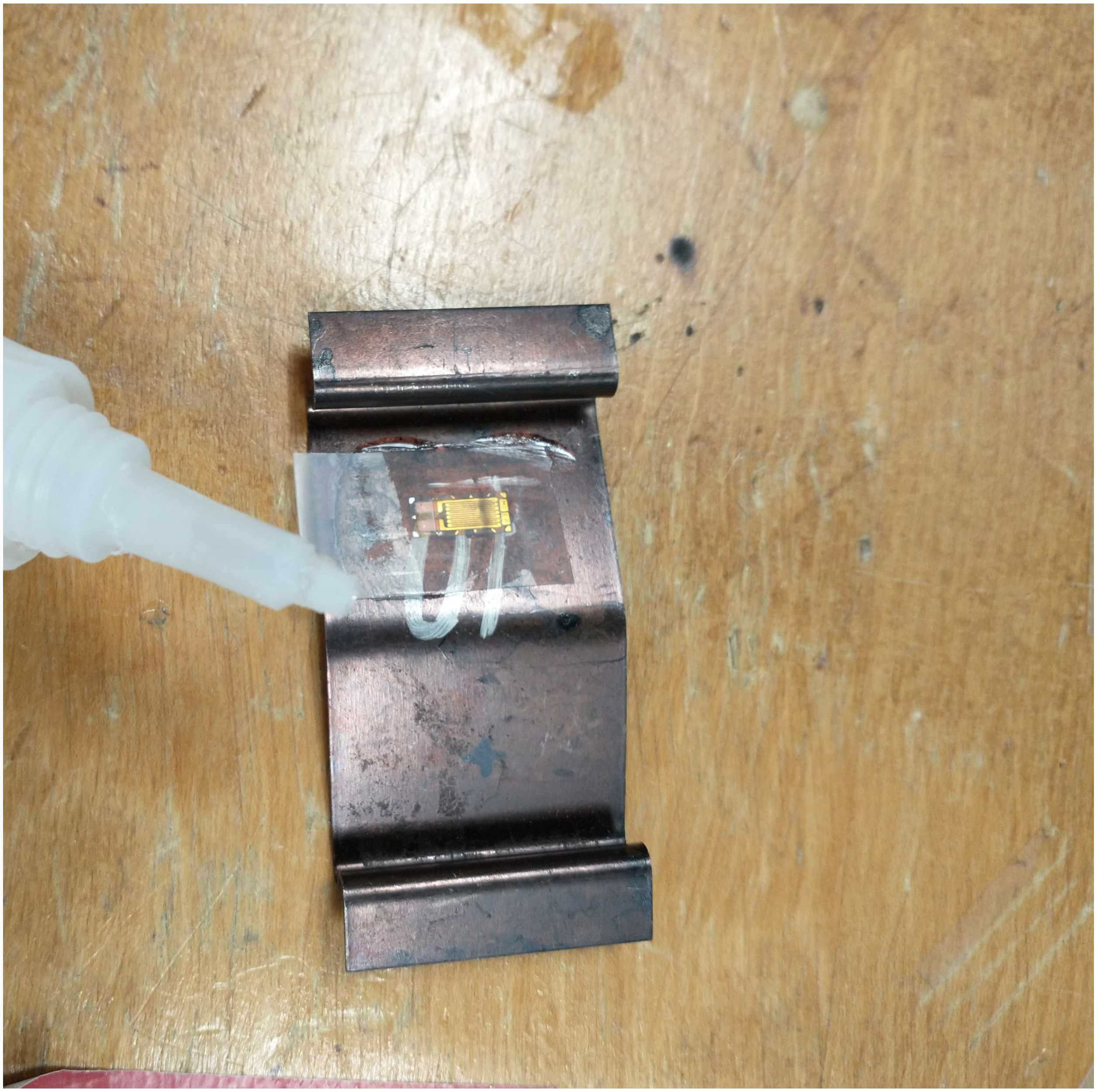


Figure 26: Gluing the strain gage onto the spring

Figure 27: Both strain gages glued to the spring

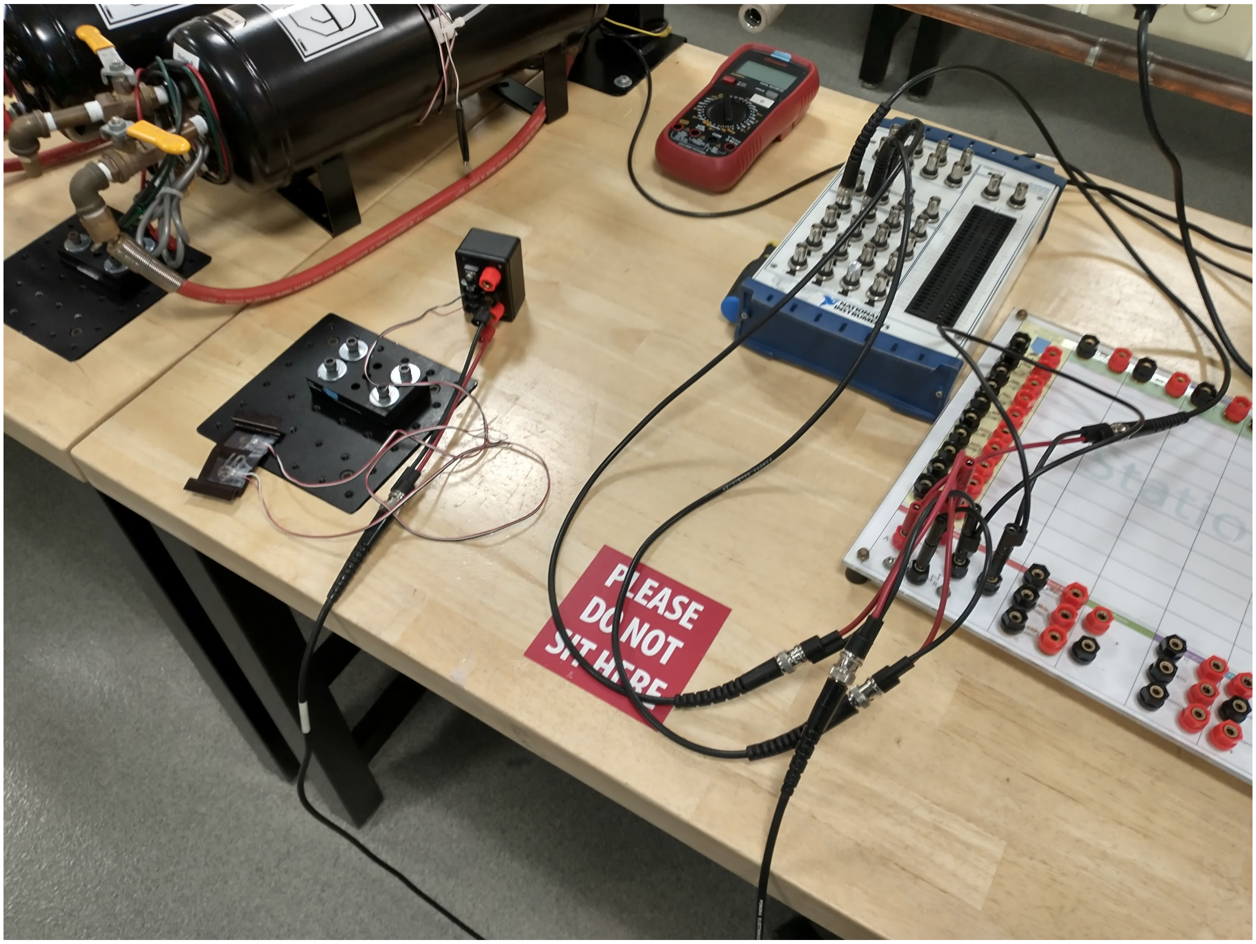


Figure 28: Set up for LabView software using a Wheatstone bridge

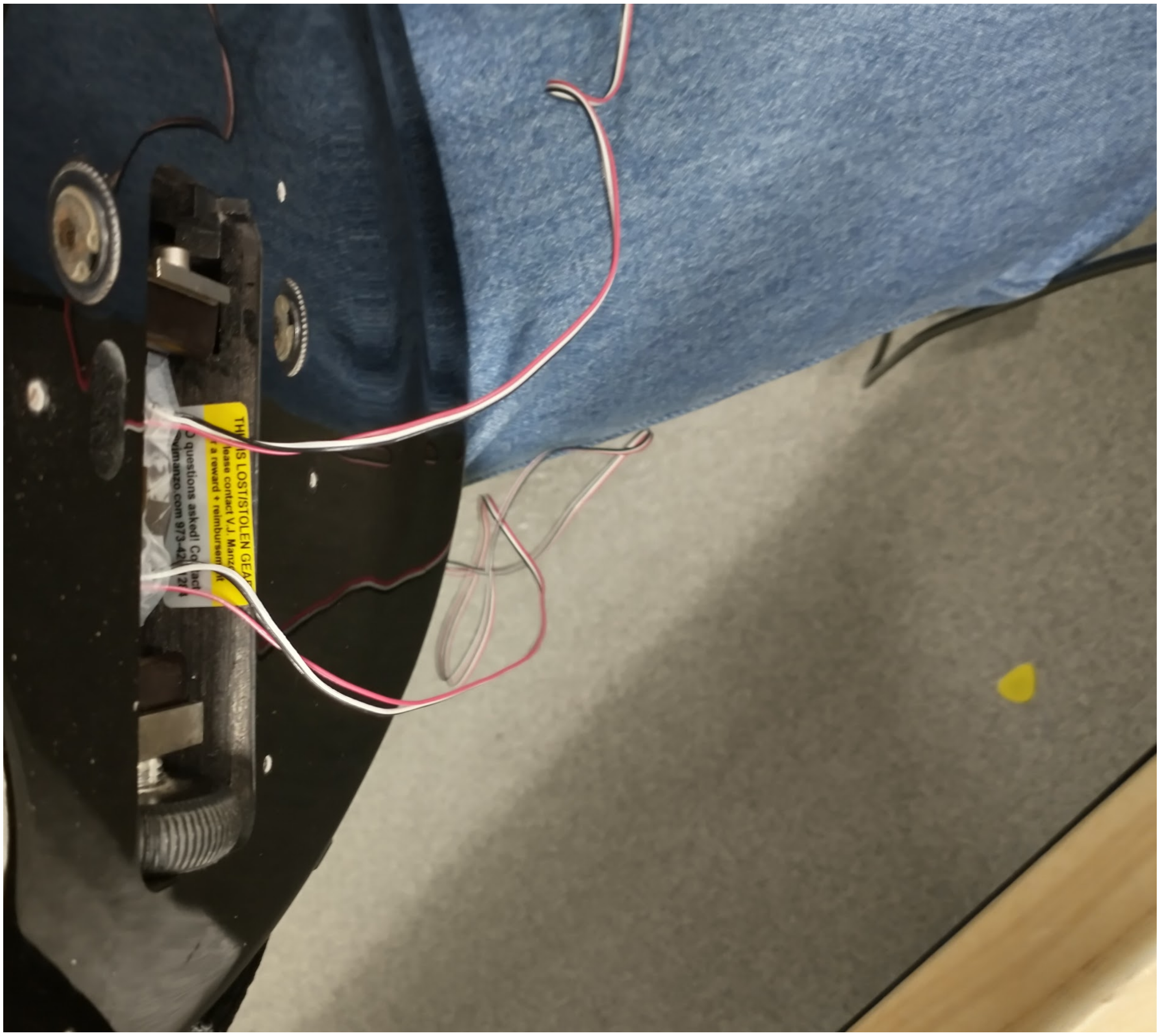


Figure 29: Guitar with the test spring inside

Appendix D: Tables and Charts

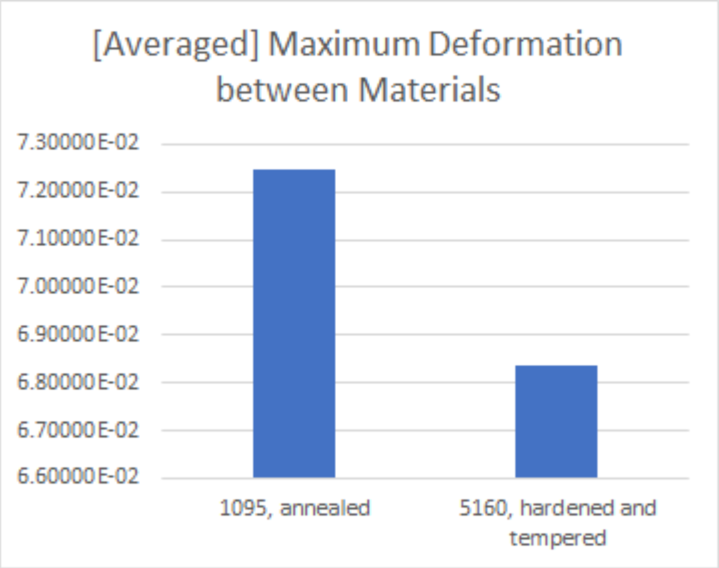


Figure 30: Graph comparing averaged maximum deformation values between 1095 steel and 5160 steel

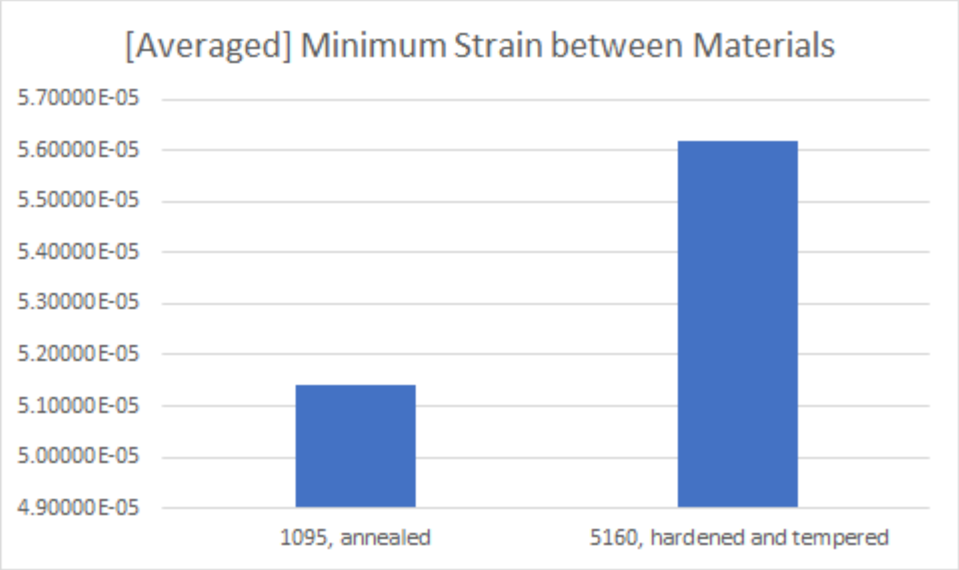


Figure 31: Graph comparing averaged minimum strain values between 1095 steel and 5160 steel

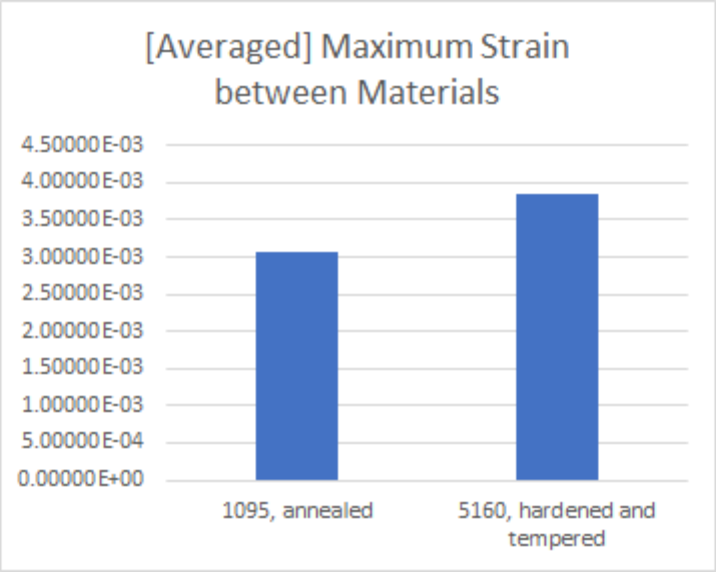


Figure 32: Graph comparing averaged maximum strain values between 1095 steel and 5160 steel

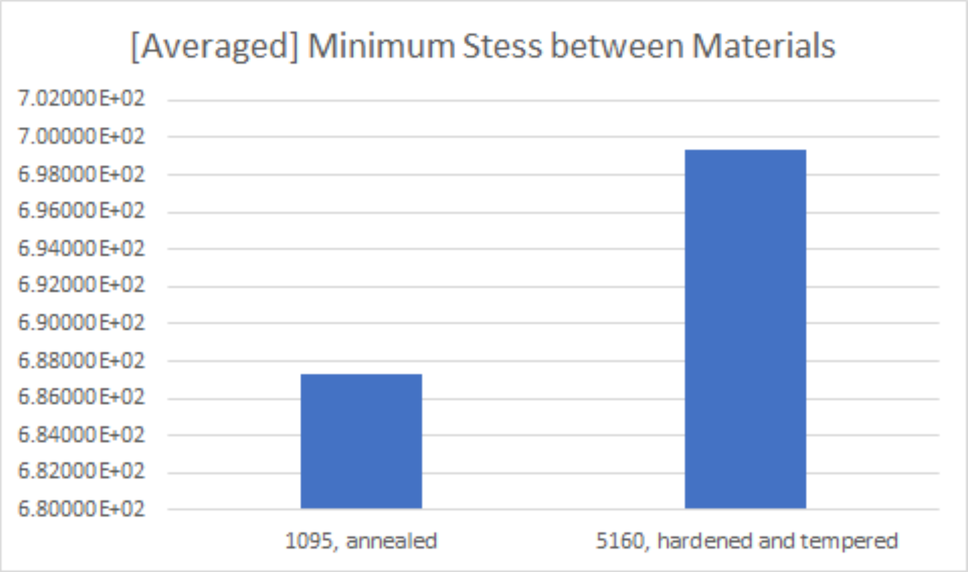


Figure 33: Graph comparing averaged minimum stress values between 1095 steel and 5160 steel

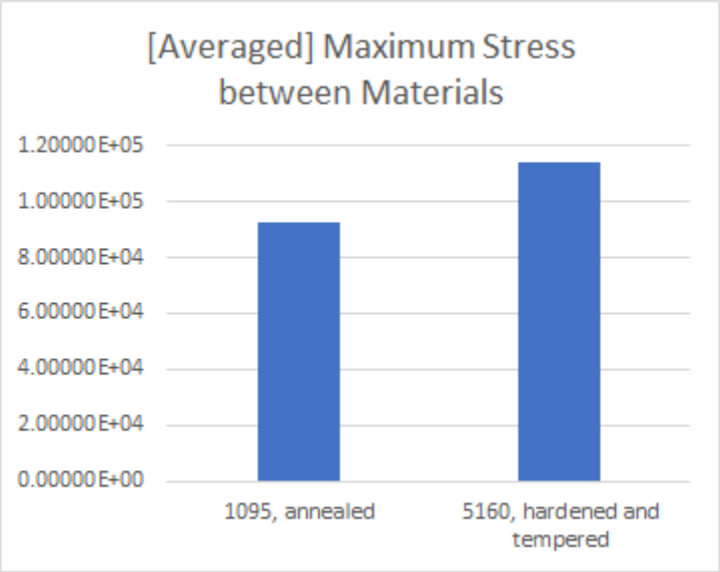


Figure 34: Graph comparing averaged maximum stress values between 1095 steel and 5160 steel

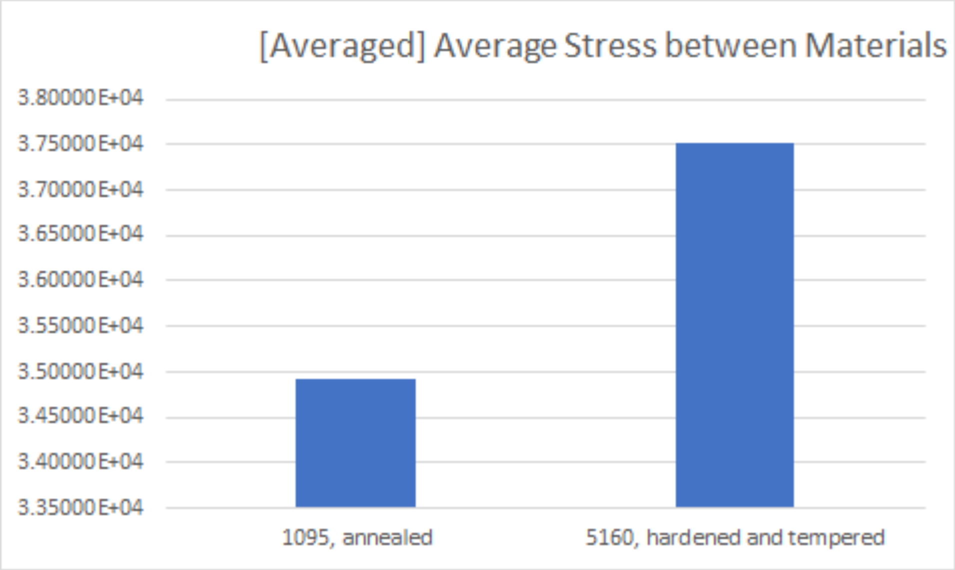
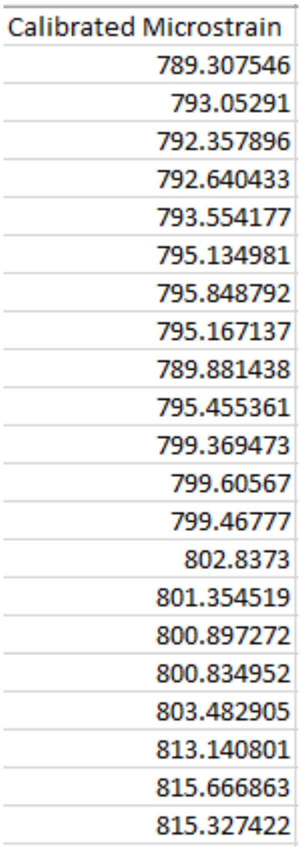


Figure 35: Graph comparing averaged average stress values between 1095 steel and 5160 steel

Table 6: Calibrated microstrain of the spring while clamped in the guitar



Calibrated Microstrain
789.307546
793.05291
792.357896
792.640433
793.554177
795.134981
795.848792
795.167137
789.881438
795.455361
799.369473
799.60567
799.46777
802.8373
801.354519
800.897272
800.834952
803.482905
813.140801
815.666863
815.327422