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# Force Measurement using Strain Gauge

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**Abstract -** *Physics and mathematics can only take Engineering designs so far in real life. Experimentation of the design is a key factor when we talk about design reliability, quality and performance. To ensure that the testing and validation of our engineer's design does justice to the hard work and effort that is put into it, our team has come up with a reliable method to test the physical resilience to forces that a part can expect to experience in it's life. We propose to use strain gauges in specific formations on the designed prototype to understand it's behavior under stress.*

***Key Words***: Stress, Strain, Force, Strain Gauge, Validation, Arduino.

## 1. INTRODUCTION

The Mechanical Industry in USA alone has generated over $400 M in 2017. The mechanical industry is ever growing, coming up with new innovations to improve the vehicle performance, reliability and cost. To achieve this the Engineers always try to improve upon the previous designs. Maybe using a different material, approach or mechanism altogether if necessary. However, to go along with these design advancements, engineers need solid test and validation data. That can either provide evidence for or against their designs. Both of these results happen to be beneficial. The engineer will be able to improve the design with the help of this data.

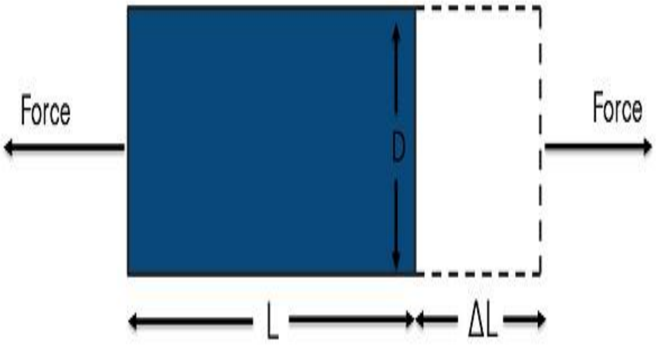
To help solve this problem, we came up with a systematic method to test parts for their resilience against different types of forces. Different forces can be measured by mounting strain gauges on the prototype part. The strain gauges can provide conclusive data to calculate the force that the part has undergone. This is done by the physical changes the strain gauge goes through due to the enormous stress.

In our project, we used multiple strain gauges in different configurations according to the requirement. We connected the output to an amplifier and then forward the signal to the microcontroller for data logging. The data can be then referred to for analysis and validation.

## 2. LITERATURE REVIEW

### What is strain?

In mechanical testing and measurement, you need to understand how an object reacts to various forces. The amount of deformation a material experiences due to an applied force is called strain. Strain is defined as the ratio of the change in length of a material to the original, unaffected length, as shown in Figure 1. Strain can be positive (tensile), due to elongation, or negative (compressive), due to contraction. When a material is compressed in one direction, the tendency to expand in the other two directions perpendicular to this force is known as the Poisson effect. Poisson's ratio (v), is the measure of this effect and is defined as the negative ratio of strain in the transverse direction to the strain in the axial direction. Although dimensionless, strain is sometimes expressed in units such as in./in. or mm/mm. In practice, the magnitude of measured strain is very small, so it is often expressed as microstrain (με), which is ε x 10-6.



$$\varepsilon = \frac{\Delta L}{L}$$

**Figure 1.** Strain is the ratio of the change in length of a material to the original, unaffected length.

The four different types of strain are axial, bending, shear, and torsional. Axial and bending strain are the most common (see Figure 2). Axial strain measures how a material stretches or compresses as a result of a linear force in the horizontal direction. Bending strain measures a stretch on one side of a material and the contraction on the opposite side due to the linear force applied in the vertical direction. Shear strain measures the amount of deformation that occurs from a linear force with components in both the horizontal and vertical directions. Torsional strain measures a circular force with components in both the vertical and horizontal directions.

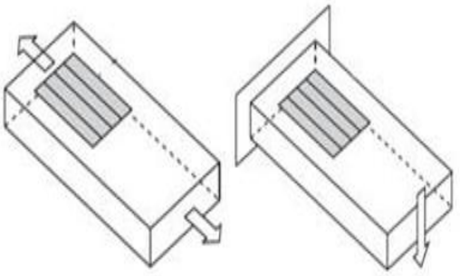


**Figure 2.** Axial strain measures how a material stretches or pulls apart. Bending strain measures a stretch on one side and a contraction on the other side.

### How do you measure strain?

You can measure strain using several methods, but the most common is with a strain gage. A strain gage's electrical resistance varies in proportion to the amount of strain in the device. The most widely used strain gage is the bonded metallic strain gage. The metallic strain gage consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction. The grid is bonded to a thin backing called the carrier, which is attached directly to the test specimen. Therefore, the strain experienced by the test specimen is transferred directly to the strain gage, which responds with a linear change in electrical resistance.

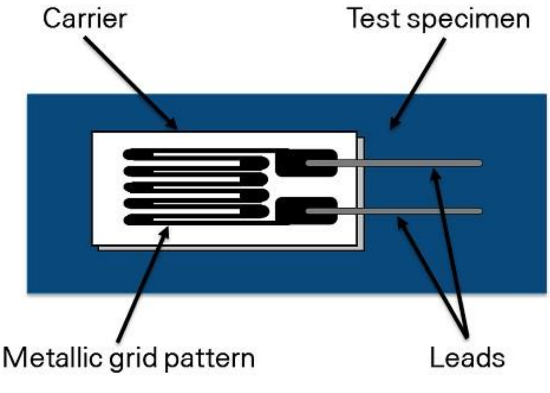


**Figure 3.** The electrical resistance of metallic grid changes in proportion to the amount of strain experienced by the test specimen.

A fundamental parameter of the strain gage is its sensitivity to strain, expressed quantitatively as the gage factor (GF). GF is the ratio of the fractional change in electrical resistance to the fractional change in length, or strain:

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon}$$

The GF for metallic strain gages is usually around 2. You can obtain the actual GF of a particular strain gage from the sensor vendor or sensor documentation.

In practice, strain measurements rarely involve quantities larger than a few millistrain (e x 10-3). Therefore, to measure the strain, you have to accurately measure very small changes in resistance. For example, suppose a test specimen undergoes a strain of 500 me. A strain gage with a GF of 2 exhibits a change in electrical resistance of only 2 (500 x 10-6) = 0.1%. For a 120 Ω gage, this is a change of only 0.12 Ω.

To measure such small changes in resistance, strain gage configurations are based on the concept of a Wheatstone bridge. The general Wheatstone bridge, illustrated in Figure 4, is a network of four resistive arms with an excitation voltage, VEX, that is applied across the bridge.

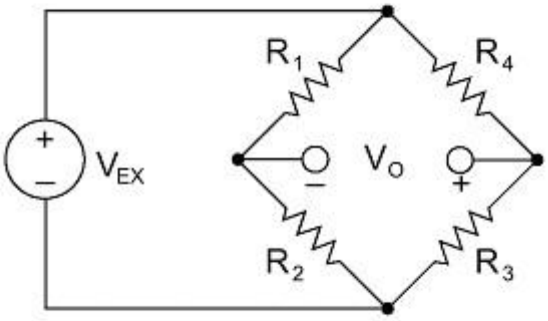


**Figure 4.** Strain gages are configured in Wheatstone bridge circuits to detect small changes in resistance.

The Wheatstone bridge is the electrical equivalent of two parallel voltage divider circuits. R1 and R2 compose one voltage divider circuit, and R4 and R3 compose the second voltage divider circuit. The output of a Wheatstone bridge, Vo, is measured between the middle nodes of the two voltage dividers.

$$V_O = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + 2}\right] * V_{EX}$$

From this equation, you can see that when R1 /R2 = R4 /R3, the voltage output VO is zero. Under these conditions, the bridge is said to be balanced. Any change in resistance in any arm of the bridge results in a nonzero output voltage. Therefore, if you replace R4 in Figure 4 with an active strain gage, any changes in the strain gage resistance unbalance the bridge and produce a nonzero output voltage that is a function of strain.

### Types of strain gages

The three types of strain gage configurations, quarter-, half-, and full-bridge, are determined by the number of active elements in the Wheatstone bridge, the orientation of the strain gages, and the type of strain being measured.

### Quarter-Bridge Strain Gage

### Configuration Type I

Measures axial or bending strain

Requires a passive quarter-bridge completion resistor known as a dummy resistor

Requires half-bridge completion resistors to complete the Wheatstone bridge

R4 is an active strain gage measuring the tensile strain (+ε)

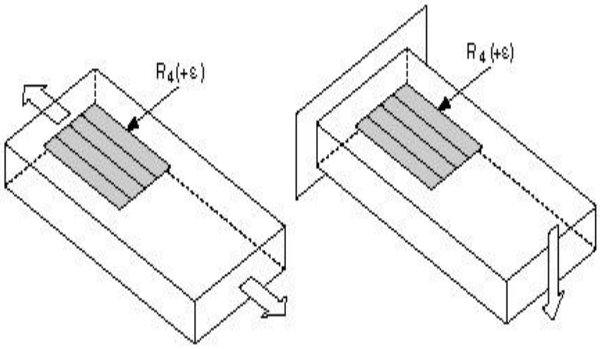


**Figure 5.** Quarter-Bridge Strain Gage Configurations

### Configuration Type II

Ideally, the resistance of the strain gage should change only in response to applied strain. However, strain gage material, as well as the specimen material to which the gage is applied, also responds to changes in temperature. The quarter-bridge strain gage configuration type II helps further minimize the effect of temperature by using two strain gages in the bridge. As shown in Figure 6, typically one strain gage (R4) is active and a second strain gage(R3) is mounted in close thermal contact, but not bonded to the specimen and placed transverse to the principal axis of strain. Therefore, the strain has little effect on this dummy gage, but any temperature changes affect both gages in the same way. Because the temperature changes are identical in the two strain gages, the ratio of their resistance does not change, the output voltage (Vo) does not change, and the effects of temperature are minimized.

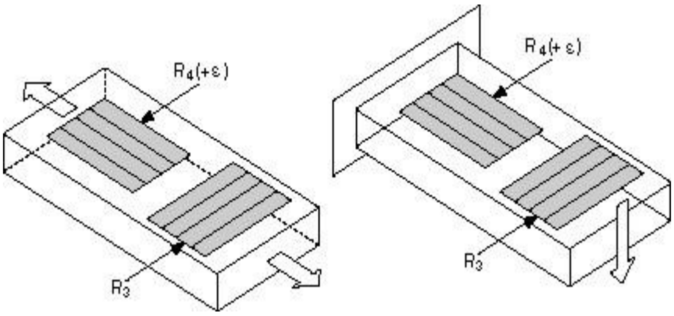


**Figure 6.** Dummy strain gages eliminate effects of temperature on the strain measurement.

### Half-Bridge Strain Gauge

You can double the bridge's sensitivity to strain by making both strain gages active in a half-bridge configuration.

### Configuration Type I

Measures axial or bending strain

Requires half-bridge completion resistors to complete the Wheatstone bridge

R4 is an active strain gage measuring the tensile strain (+ε)

R3 is an active strain gage compensating for Poisson's effect (-νε)

This configuration is commonly confused with the quarter-bridge type II configuration, but type I has an active R3 element that is bonded to the strain specimen.

### Configuration Type II

Measures bending strain only

Requires half-bridge completion resistors to complete the Wheatstone bridge

R4 is an active strain gage measuring the tensile strain (+ε)

R3 is an active strain gage measuring the compressive strain (-ε)

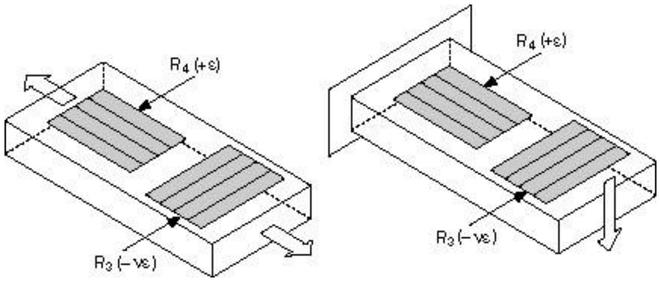
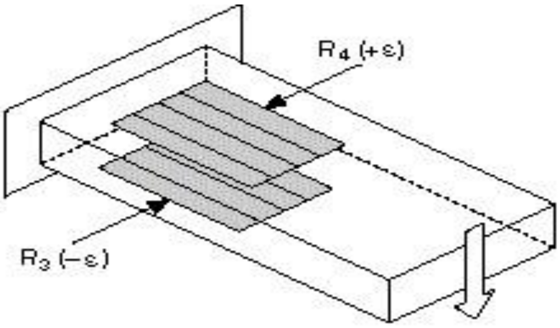


**Figure 7.** Configuration I - Bending Strain Only



**Figure, 8.** Configuration II - Bending Strain Only(Half-Bridge Strain Gauge)

**Full-Bridge Strain Gauge**

A full-bridge strain gage configuration has four active strain gages and is available in three different types. Types 1 and 2 measure bending strain and type 3 measures axial strain. Only types 2 and 3 compensate for the Poisson effect, but all three types minimize the effects of temperature.

**Configuration Type I**

Highly sensitive to bending strain only

R1 and R3 are active strain gages measuring compressive strain (−e)

R2 and R4 are active strain gages measuring tensile strain (+e)

**Configuration Type II**

Sensitive to bending strain only

R1 is an active strain gage measuring the compressive Poisson effect (−ve)

R2 is an active strain gage measuring the tensile Poisson effect (+ve)

R3 is an active strain gage measuring the compressive strain (−e)

R4 is an active strain gage measuring the tensile strain (+e)

**Configuration Type III**

Measures axial strain

R1 and R3 are active strain gages measuring the compressive Poisson effect (−ve). R2 and R4 are active strain gages measuring the tensile strain (+e).

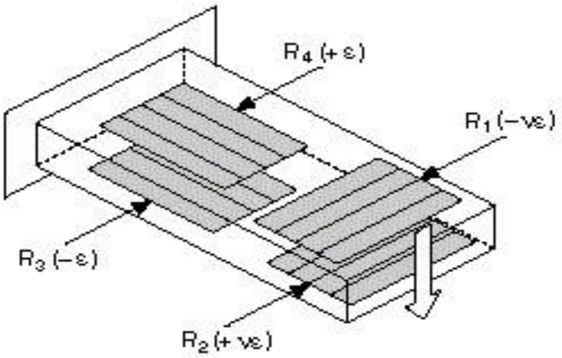


**Figure 9.** Configuration I - Only Bending Strain

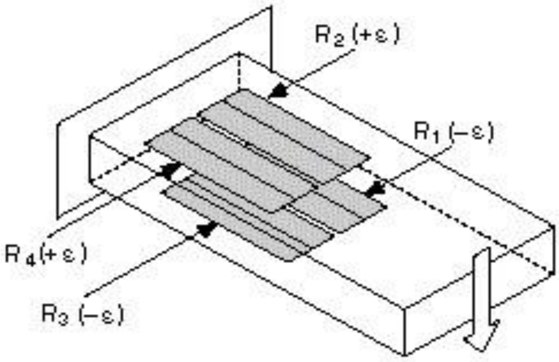


**Figure 10.** Configuration II - Only Bending strain

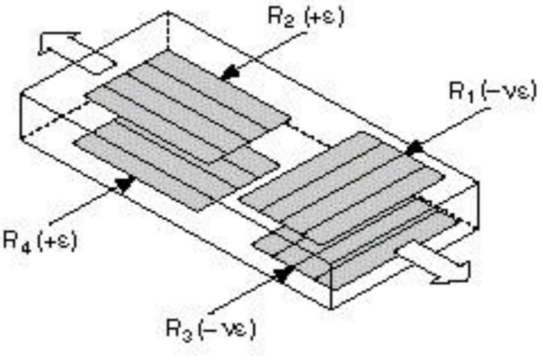


**Figure 11.** Configuration III - Only Axial Strain (Full-Bridge Strain Gage Configurations) [1]

### Calculations for Quarter Bridge

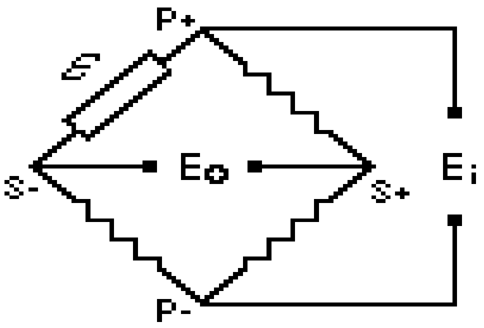


**Figure 12.** Quarter Bridge Circuit Diagram

$$\frac{E_0}{E_i} = \frac{F\varepsilon}{4 + 2F\varepsilon}$$

This single longitudinal gage configuration will respond to bending loads but is unaffected by torsional loads if the gage is mounted on the centerline. Care must be taken with how the load is applied, because transducers utilizing this configuration will also respond to any axial loads that may be present. Since this configuration produces a small amount of nonlinearity (approximately 0.1% for each 1000 microstrain) and is sensitive to changes in temperature, the following "half-bridge" configuration is generally preferred. When a half bridge cannot be used, the sensitivity to temperature for a single active gage configuration can be minimized by using the proper self-temperature-compensated strain gage and by zero-balancing before the load is applied.

### Calculations for Half Bridge

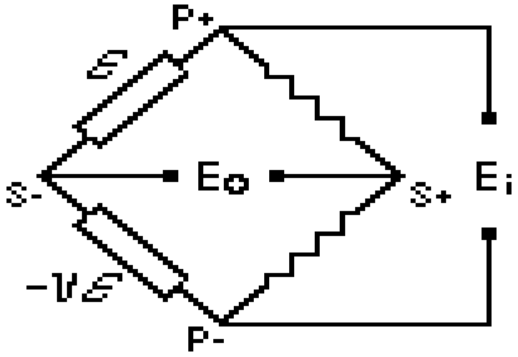


**Figure 13.** Half Bridge Circuit Diagram

$$\frac{E_0}{E_i} = \frac{F\varepsilon\left(1 + \nu\right)}{4 + 2F\varepsilon\left(1 - \nu\right)}$$

Because the longitudinal gage and the transverse "Poisson" gage are in adjacent arms, the resistance changes of thermal origins will be cancelled in this version when both active gages and the specimen experience like changes in temperature. The bridge output is increased by a factor of approximately (1+v) and the nonlinearity is reduced to approximately [ (1-v)/100] % per each 1000 microstrain of longitudinal strain.

### Calculations for Full Bridge

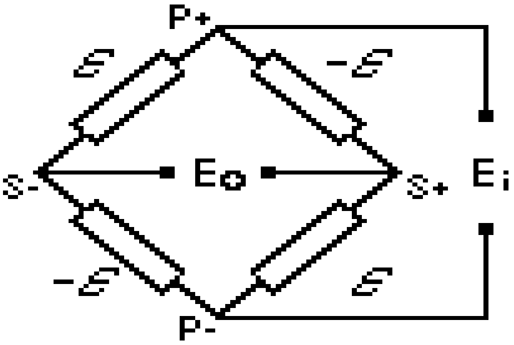


**Figure 14.** Full Bridge Circuit Diagram

$$\frac{E_o}{E_i} = F\varepsilon$$

This four-gage version is the most popular bending beam configuration. The linear bridge output is twice that of the preceding half-bridge version. Note that the two gages on the top surface are in opposite arms of the Wheatstone bridge, as are the two gages on the bottom surface.[2]

### How do I choose the right strain gauge?

Once you have decided the type of strain you intend to measure (axial or bending), other considerations include sensitivity, cost, and operating conditions. For the same strain gauge, changing the bridge configuration can improve its sensitivity to strain. For example, the full-bridge type I configuration is four times more sensitive than the quarter-bridge type I configuration. However, full-bridge type I requires three more strain gauges than quarter-bridge type I. It also requires access to both sides of the gauged structure. Additionally, full-bridge strain gauges are significantly more expensive than half-bridge and quarter-bridge gauges.

### Grid Width

Using a wider grid, if not limited by the installation site, improves heat dissipation and enhances strain gauge stability. However, if the test specimen has severe strain gradients perpendicular to the primary axis of strain, consider using a narrow grid to minimize error from the effect of shear strain and Poisson strain.

### Nominal Gauge Resistance

Nominal gauge resistance is the resistance of a strain gauge in an unstrained position. You can obtain the nominal gauge resistance of a particular gauge from the sensor vendor or sensor documentation. The most common nominal resistance values of commercial strain gauges are 120 Ω, 350 Ω, and 1,000 Ω. Consider a higher nominal resistance to reduce the amount of heat generated by the excitation voltage. Higher nominal resistance also helps reduce signal variations caused by lead-wire changes in resistance due to temperature fluctuations.

### Temperature Compensation

Ideally, strain gauge resistance should change in response to strain only. However, a strain gauge's resistivity and sensitivity also change with temperature, which leads to measurement errors. Strain gauge manufacturers attempt to minimize sensitivity to temperature by processing the gauge material to compensate for the thermal expansion of the specimen material for which the gauge is intended. These temperature-compensated bridge configurations are more immune to temperature effects. Also consider using a configuration type that helps compensate for the effects of temperature fluctuations.

### Installation

Installing strain gauges can take a significant amount of time and resources, and the amount varies greatly depending on the bridge configuration. The number of bonded gauges, number of wires, and mounting location all can affect the level of effort required for installation. Certain bridge configurations even require gauge installation on opposite sides of a structure, which can be difficult or even impossible. Quarter-bridge type I is the simplest because it requires only one gauge installation and two or three wires.

### Signal conditioning for strain gages

Strain gage measurements are complex and several factors can affect measurement performance. Therefore, you need to properly select and use the bridge, signal conditioning, wiring, and DAQ components to generate reliable measurements. For example, resistance tolerances and strain induced by the application of the gage generate some initial offset voltage when no strain is applied. Similarly, long lead wires can add resistance to the arm of the bridge, which adds an offset error and desensitizes the output of the bridge. To ensure accurate strain measurements, consider the following:

**Bridge completion to complete the required circuitry for quarter- and half-bridge strain gages.**

**Excitation to power the Wheatstone bridge circuitry.**

**Remote sensing to compensate for errors in excitation voltage from long lead wires.**

**Amplification to increase measurement resolution and improve signal-to-noise ratio.**

**Filtering to remove external, high-frequency noise.**

**Offset nulling to balance the bridge to output 0 V when no strain is applied.**

**Shunt calibration to verify the output of the bridge to a known, expected value.[1]**

## 3. METHODOLOGY

### 3.1. STRAIN GAUGE

We used strain gauge in a whetstone configuration to measure change in strain of the prototype part. As force is applied on the part, strain gauge undergoes deformation. The resistance of strain gauge changes. This change is converted into corresponding change in voltage. This voltage is the fed to the HX711 voltage amplifier.

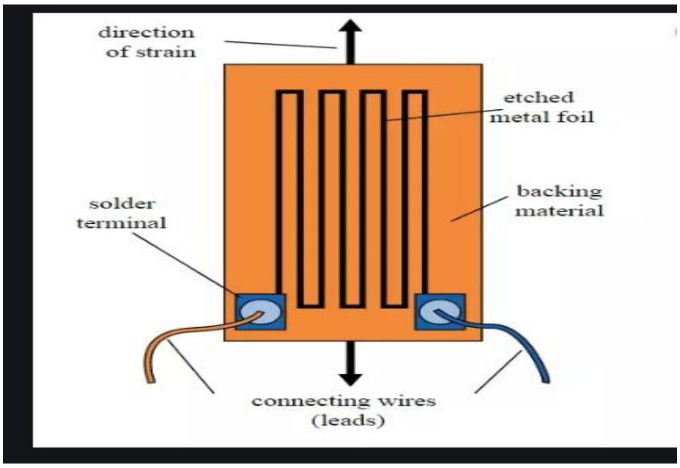


**Figure 15.** Strain Gauge Diagram

### 3.2. HX711 amplifier

HX711 is a voltage amplifier module. It works on op-amp technology. It also has an in-built 24-bit ADC which provides better resolution.

The change in voltage due to stain gauges is very small and cannot be directly measure by micro controller. Hence, we used HX711 module to amplify change in voltage from micro volt to milli volt. So that the micro controller can identify this data.

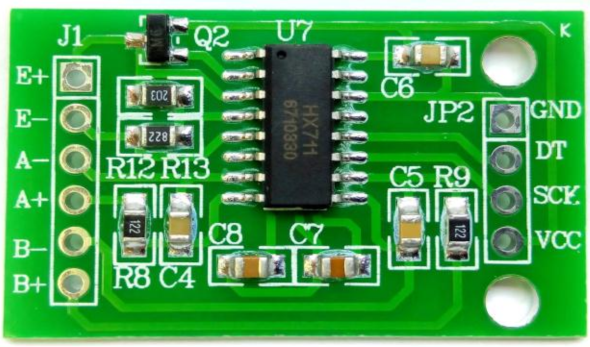


**Figure 16.** HX711 Module

## 3.3. MICRO-CONTROLLER

We have used Arduino nano as microcontroller. Output from hx711 module was fed to Arduino. We used the voltages along with the previously mentioned formulae to find strain, stress and force on prototype.

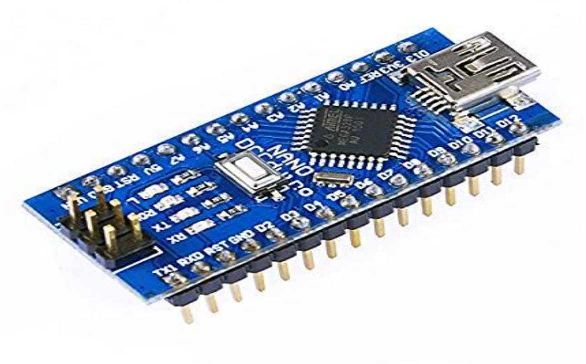


**Figure 17.** Arduino Nano

## 4. RESULT

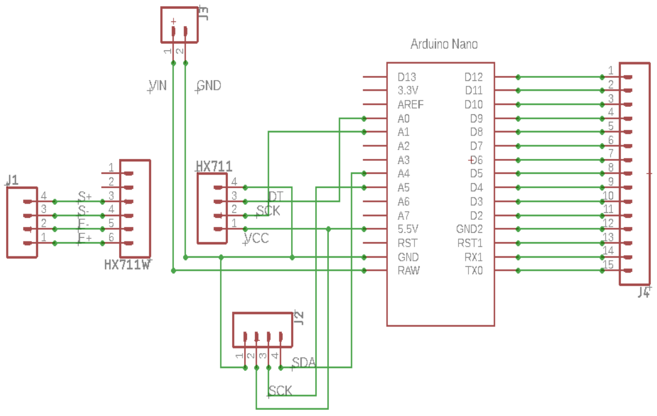
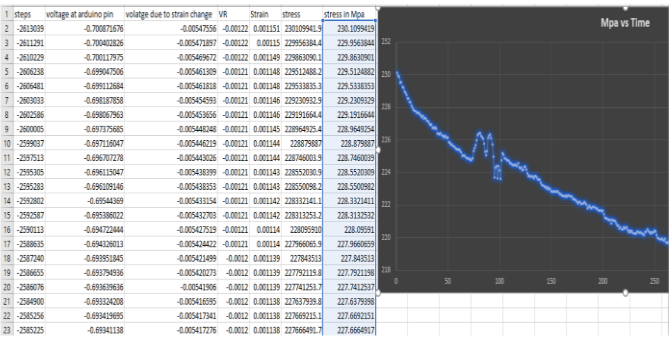
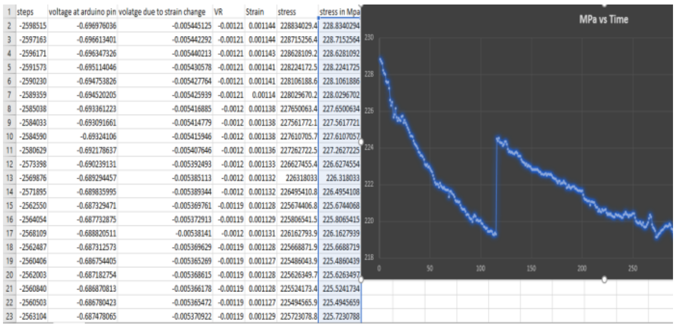


**Figure 18.** Project Schematic



| | steps | voltage at arduino pin | volatge due to strain change | VR | Strain | stress | stress in Mpa |
|---|---|---|---|---|---|---|---|
| 2 | -2613039 | -0.700871676 | -0.00547556 | -0.00122 | 0.001151 | 230109941.9 | 230.1099419 |
| 3 | -2611291 | -0.700402826 | -0.005471897 | -0.00122 | 0.00115 | 229956384.4 | 229.9563844 |
| 4 | -2610229 | -0.700117975 | -0.005469672 | -0.00122 | 0.001149 | 229863090.1 | 229.8630901 |
| 5 | -2606238 | -0.699047506 | -0.005461309 | -0.00121 | 0.001148 | 229512488.2 | 229.5124882 |
| 6 | -2606481 | -0.699112684 | -0.005461818 | -0.00121 | 0.001148 | 229533835.3 | 229.5338353 |
| 7 | -2603033 | -0.698187858 | -0.005454593 | -0.00121 | 0.001146 | 229230932.9 | 229.2309329 |
| 8 | -2602586 | -0.698067963 | -0.005453656 | -0.00121 | 0.001146 | 229191664.4 | 229.1916644 |
| 9 | -2600005 | -0.697375685 | -0.005448248 | -0.00121 | 0.001145 | 228964925.4 | 228.9649254 |
| 10 | -2599037 | -0.697116047 | -0.005446219 | -0.00121 | 0.001144 | 228879887 | 228.879887 |
| 11 | -2597513 | -0.696707278 | -0.005443026 | -0.00121 | 0.001144 | 228746003.9 | 228.7460039 |
| 12 | -2595305 | -0.696115047 | -0.005438399 | -0.00121 | 0.001143 | 228552030.9 | 228.5520309 |
| 13 | -2595283 | -0.696109146 | -0.005438353 | -0.00121 | 0.001143 | 228550098.2 | 228.5500982 |
| 14 | -2592802 | -0.69544369 | -0.005433154 | -0.00121 | 0.001142 | 228332141.1 | 228.3321411 |
| 15 | -2592587 | -0.695386022 | -0.005432703 | -0.00121 | 0.001142 | 228313253.2 | 228.3132532 |
| 16 | -2590113 | -0.694722444 | -0.005427519 | -0.00121 | 0.00114 | 228095910 | 228.09591 |
| 17 | -2588635 | -0.694326013 | -0.005424422 | -0.00121 | 0.00114 | 227966065.9 | 227.9660659 |
| 18 | -2587240 | -0.693951845 | -0.005421499 | -0.0012 | 0.001139 | 227843513 | 227.843513 |
| 19 | -2586655 | -0.693794936 | -0.005420273 | -0.0012 | 0.001139 | 227792119.8 | 227.7921198 |
| 20 | -2586076 | -0.693639636 | -0.00541906 | -0.0012 | 0.001139 | 227741253.7 | 227.7412537 |
| 21 | -2584900 | -0.693324208 | -0.005416595 | -0.0012 | 0.001138 | 227637939.8 | 227.6379398 |
| 22 | -2585256 | -0.693419695 | -0.005417341 | -0.0012 | 0.001138 | 227669215.1 | 227.6692151 |
| 23 | -2585225 | -0.69341138 | -0.005417276 | -0.0012 | 0.001138 | 227666491.7 | 227.6664917 |

**Figure 19.** Output of Experiment 1 with Graphical analysis using MS Excel



| | steps | voltage at arduino pin | volatge due to strain change | VR | Strain | stress | stress in Mpa |
|---|---|---|---|---|---|---|---|
| 2 | -2598515 | -0.696976036 | -0.005445125 | -0.00121 | 0.001144 | 228834029.4 | 228.8340294 |
| 3 | -2597163 | -0.696613401 | -0.005442292 | -0.00121 | 0.001144 | 228715256.4 | 228.7152564 |
| 4 | -2596171 | -0.696347326 | -0.005440213 | -0.00121 | 0.001143 | 228628109.2 | 228.6281092 |
| 5 | -2591573 | -0.695114046 | -0.005430578 | -0.00121 | 0.001141 | 228224172.5 | 228.2241725 |
| 6 | -2590230 | -0.694753826 | -0.005427764 | -0.00121 | 0.001141 | 228106188.6 | 228.1061886 |
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| 12 | -2573398 | -0.690239131 | -0.005392493 | -0.0012 | 0.001133 | 226627455.4 | 226.6274554 |
| 13 | -2569876 | -0.689294457 | -0.005385113 | -0.0012 | 0.001132 | 226318033 | 226.318033 |
| 14 | -2571895 | -0.689835995 | -0.005389344 | -0.0012 | 0.001132 | 226495410.8 | 226.4954108 |
| 15 | -2562550 | -0.687329471 | -0.005369761 | -0.00119 | 0.001128 | 225674406.8 | 225.6744068 |
| 16 | -2564054 | -0.687732875 | -0.005372913 | -0.00119 | 0.001129 | 225806541.5 | 225.8065415 |
| 17 | -2568109 | -0.688820511 | -0.00538141 | -0.0012 | 0.001131 | 226162793.9 | 226.1627939 |
| 18 | -2562487 | -0.687312573 | -0.005369629 | -0.00119 | 0.001128 | 225668871.9 | 225.6688719 |
| 19 | -2560406 | -0.686754405 | -0.005365269 | -0.00119 | 0.001127 | 225486043.9 | 225.4860439 |
| 20 | -2562003 | -0.687182754 | -0.005368615 | -0.00119 | 0.001128 | 225626349.7 | 225.6263497 |
| 21 | -2560840 | -0.686870813 | -0.005366178 | -0.00119 | 0.001128 | 225524173.4 | 225.5241734 |
| 22 | -2560503 | -0.686780423 | -0.005365472 | -0.00119 | 0.001127 | 225494565.9 | 225.4945659 |
| 23 | -2563104 | -0.687478065 | -0.005370922 | -0.00119 | 0.001129 | 225723078.8 | 225.7230788 |

**Figure 20.** Output of Experiment 2 with Graphical analysis using MS Excel

The voltage readings from the microcontroller are fed into a MS Excel sheet. We calculated the strain, stress and force corresponding to every reading. After plotting a force v/s time graph of this data, it was really easy to identify the sudden increase in force when instantaneous force is applied on the prototype model.

## 5. CONCLUSIONS

The problem we undertook in this project, was to make an easy to use, effective and easily replicable project for students and people without any electronics background. To accomplish this feat, we encountered many adversaries. To be able to choose the best way to measure the forces on the prototype we had to learn a lot about force dynamics. Then to make sure that the system is simple enough for everybody to use it to it's full potential. Due to the perseverance and determination of the team, we were able to simplify the system into a few pieces, without compromising the performance. The system has a lot of applications for design of different types, sizes, materials and mechanisms. It possesses enormous potential for large scale use.

## REFERENCES

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## BIOGRAPHIES

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