Extended Essay

IB Physics

Title:

Investigating the effect of wire diameter on the tensile strength of wires of different material

Research Question:

Does an increase in diameter of a wire have the same degree of effect on the tensile strength of different materials?

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Table of contents

1. Introduction **2**
2. Background Science **3**
2.1 Load at break and Maximum Load 4
2.2 Young's Modulus 5
2.3 Hypothesis 6
3. Methods **7**
3.1 Preliminary Experiment 7
3.2 Variables 10
3.3 Experimental Procedure 12
3.4 Risk Assessment 13
4. Data **14**
4.1 Raw Data 14
4.2 Data Processing 18
4.2.1 Data 18
4.2.2 Uncertainties 19
4.3 Processed Data 20
4.4 Graph 24
5. Conclusion **28**
6. Evaluation **31**
Bibliography **34**

1. Introduction

Tensile testing is used to observe the axial stretching when a load is applied[1] on an object, so it can be said that tensile strength is the amount of load a material can withstand while stretching without fracturing. Tensile strength is applicable to many sectors in modern day society. Most prominently engineering[2], in civil engineering tensile tested wires can be seen in bridges and other large scale structures; an example of such bridges is seen in figure 1.

Figure 1 - A picture of the Golden Gate

The golden gate bridge uses twisted industrial strength wires; this is a common feature in other bridges around the world. As the safety of users when using a bridge is paramount to the engineers. Engineers need to make sure that the tensile strength of the wires used have enough resistance to withstand the unexpected but possible forces that can be exerted on a bridge. Such forces can range from extreme weather conditions to human activity such as innate synchronised walking. These can create an

adverse impact on structures if not taken account of so catastrophic effects are not induced on the users of the bridge or the bridge itself.

The importance and relevance of tensile strength in engineering led to the question: Will an increase in wire diameter of a wire lead to an increase in tensile strength and will the difference in tensile strength have the same degree of effect in different materials?

In this essay by means of first hand experimentation the hope is to find the effect of a change in diameter on the tensile strength of different materials.

2. Background Science

Tensile Strength being the load a material can support while stretching without fracturing is a relatively vague definition. This vague definition means that tensile strength can be quantified in various ways such as[1]:

- Load at break
- Maximum load
- Young's Modulus

Because of this there are different ways to determine whether the experiment is valid or not.

2.1 Load at break and Maximum Load

Load at Break

Load at break refers to the amount of force that is on the wire when it breaks[10]. The formula for this in the context of this experiment would be:

$$F = mg \tag{1}$$

F=Force (N)

Where m=mass measured in kilograms, g=gravitational acceleration measured in ms^{-2} , this is the standard formula for the force of gravity on an object.

Maximum Load

Maximum Load in the context of tensile strength of a wire would be the maximum amount of load that can be applied to a wire without the wire breaking or permanently deforming. This can be measured using stress as stress is known as the measure of an external force acting over the cross-sectional area of an object[2].

The formula for this is:

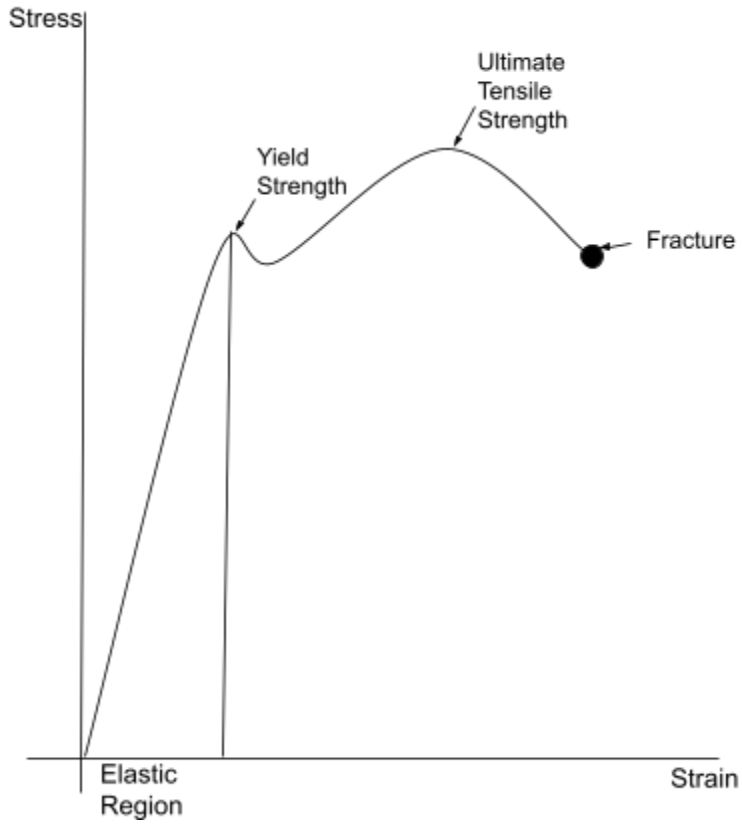
$$\sigma = F/A \tag{2}$$

σ = Stress

Where F = Force in N , and A = Area of cross-section in m^2.

This formula would be used to determine the stress on a material. Another way to measure maximum load would be the highest point of a stress strain diagram. Which idealistically would be as seen in figure 2 labelled 'Ultimate Tensile Stress'. But the shape of the stress strain diagram is dependent on the ductility of the material hence why the graph varies from object to object.

Figure 2 – A stress strain diagram



2.2 Young's Modulus

The graph in figure 2 can also be used to determine the Young's Modulus of an object. Young modulus is a measure of how easily a material stretches and deforms[4]. It can be calculated by finding the gradient of the straight line region (elastic region in figure 2) where hooke's law applies on a stress strain graph[6]. A higher young's Modulus of elasticity leads to a less elastic material which means that the material is stronger as a larger force is required to deform it. This method works because wires behave like springs in the elastic region of a stress strain graph. The gradient of the graph can be found by dividing the stress by the strain, with the strain[9] being the ratio between the deformation and original length of the object[3].

The formula can be derived from this as,

Using equation 2,

$$\sigma = \frac{F}{A} \tag{2}$$

$$\varepsilon = \frac{\delta}{L} \tag{3}$$

ε =Strain

Where δ =Extension (m) and L = Original length (m)

Young's Modulus = Stress/Strain

$$E = \frac{\sigma}{\varepsilon}$$

Substitute in Equation 2 and 3,

$$E = \frac{F/A}{\delta/L}$$

Simplified to,

$$E = \frac{FL}{A\delta}$$

So,

$$Young's\ Modulus = \frac{FL}{A\delta} \tag{4}$$

2.3 Hypothesis

The formula above can be used to discern the relationship between the area of cross-section and Young's Modulus:

$$E \propto \frac{1}{A}$$

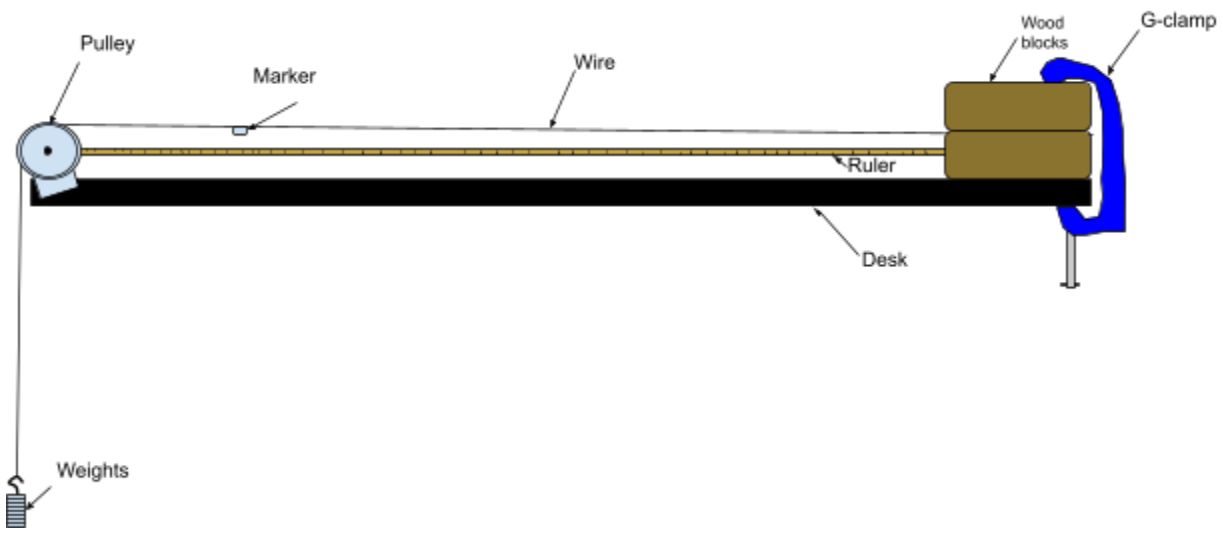
This shows that young’s modulus is inversely proportional to area. Which means as the cross-sectional area increases young's modulus will decrease. This experiment will test if young's modulus will actually decrease with different diameter wires and if the amount it decreases by will stay the same. As well as the other ways of finding tensile strength.

3. Methods

3.1 Preliminary Experiment

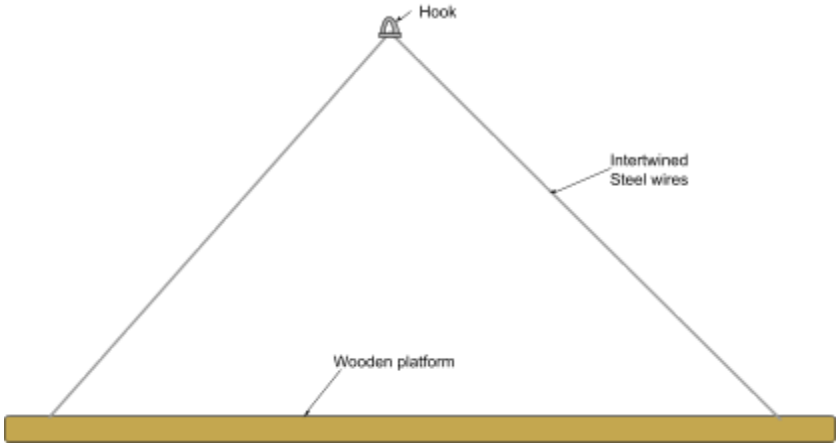
Initially, the length of a copper wire was taken with a metre ruler and markers were added to the wire so distance travelled by the marker could show the extension of the wire. Then the radius of the wire was taken with a calliper. The calliper did not allow for a suitable amount of precision so a micrometre was used instead. Making the results for the cross-sectional areas hence strain more accurate.

Figure 3 - Not to Scale diagram of experiment



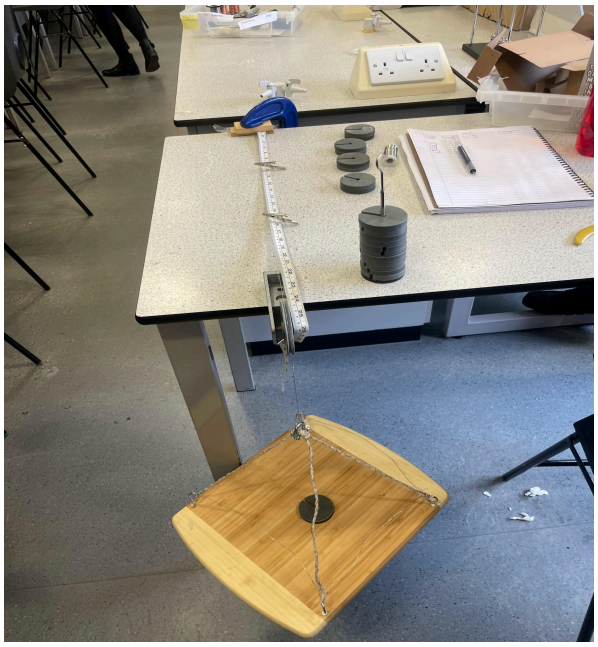
Initially, test runs were conducted using copper wire of 0.3mm diameter; the weights were added in 200g increments. The amount of weights needed exceeded the amount of weights that the weight hanger could hold so another weight hanger was attached to the previous hanger to add additional weights until the wire snapped. This way of loading weights was highly inefficient so a different type of weight hanger was made.

Figure 4 - Diagram of Improved weight Hanger



This new weight hanger in figure 4 was used as it was more efficient to load weights and it led to the new system as seen in figure 5. The new weight hanger is made with bamboo to make it as lightweight as possible to match the increments that weight is added. The intertwined steel wire is made so that the new weight hanger is stronger than the metal wire it's testing. So the wire being tested will fracture before the wire does.

Figure 5 - Picture of improved weight hanger



The new system allowed for the tensile strength of the stronger steel wire to be found as more weights could be added . The decision was made that when changing diameters the diameter should decrease as there was a limit to the amount of weights available. So in the final experiment 4 different wires were used: copper wire of 0.3mm diameter, steel wire of 0.3mm diameter, copper wire of 0.2mm diameter and steel wire of 0.2mm diameter.

3.2 Variables

Control Variables

Control Variable	Reason	Solution
Original length of wire	The length of wire used should stay the same as it affects the amount the wire extends as well as the tension distribution.	Length of the wire was measured to the same length of 1.45m.
Condition of wire	The condition of the wire was kept the same as only wires straight from the spool were used. This is because any weak points from wires of bad condition (dented or twisted) will lead to a degradation of the accuracy of the results.	The wire used was straight from the spool hence in as best a condition as possible.

Control Variable	Reason	Solution
Original position of the marker	The position of the marker was kept the same because of the difference in tension throughout the wire.	The marker was kept the same distance from the wooden block.
Temperature of the wire	Increased temperature will lead to decreased elasticity affecting the results.	Heating will occur due to stretching, so allowing time before taking reading as to not increase the temperature of the wire.

3.3 Experimental Procedure

A wire of length 1.45m is cut from a spool of wire. The wire is clamped down between wooden blocks so as to have the wires at the same height as the pulley wheel to best try to negate unwanted forces. The hook was then attached to the wire at a fixed length of 1.25m and the remaining wire was tightly wrapped around the hook to prevent slippage. After this the wire was placed on the pulley and a marker was put on the wire 40 cm from the wooden block. Weights are then added to the weight hanger In increments decided by the preliminary testing to be 200g for wires of 0.3mm and 100g for wires of 0.2mm. Each time a weight is added the extension should be measured after the wire leaves the flow state (the state in which the wire is extending). Once the load reaches 1200g for the wires of 0.3mm and 1300g for wires of 0.2mm then the hanger in figure 3 is replaced with the hanger in figure 4. Because the mass of the hanger in Figure 4 is 1400g. Weights are then to be added on top of the hanger and the extension measured until the wire fractures. This is done a total of 3 times for each wire.

3.4 Risk Assessment

This experiment is relatively safe but there are some risks.

Risk	Cause	Solution
Cuts	The thin wires and high tension on the wires can lead to some cuts if the experiment is not done carefully	Not touching the wires as they are very thin
Damaged floor/ Blunt force damage to foot	When the wire fractures the masses fall from a high height	Cardboard on the floor to cushion the fall and staying away from the fall zone
Eye damage	The snapping wire flares out and can cause eye damage	Goggles reduces the risk of eye damage

4. Data

4.1 Raw Data

Table 1: 0.3mm copper wire

Mass on weight hanger for copper wire of diameter 0.3mm (Kg) $\pm\ 2.8\%$	Position of marker from measured from the wooden block (m) $\pm\ 0.0005$			Averages	
	Attempt 1	Attempt 2	Attempt 3	Position of marker (m)	Change from original position (m)
0.0	0.400	0.400	0.400	0.4000	0.0000
0.2	0.400	0.400	0.400	0.4000	0.0000
0.4	0.400	0.401	0.401	0.4010	0.0010
0.6	0.403	0.402	0.403	0.4027	0.0027
0.8	0.404	0.402	0.404	0.4033	0.0033
1.0	0.405	0.404	0.405	0.4047	0.0047
1.2	0.406	0.407	0.406	0.4067	0.0067
1.4	0.408	0.413	0.409	0.4100	0.0100
1.6	0.413	0.425	0.418	0.4187	0.0187
1.8	0.429	0.431	0.428	0.4293	0.0293

Table 2: 0.3mm Steel wire

Mass on weight hanger for steel wire of diameter 0.3mm (Kg) $\pm 2.8\%$	Position of marker from measured from the wooden block (m) ± 0.0005			Average	
	Attempt 1	Attempt 2	Attempt 3	Position of marker (m)	Change from original position (m)
0.0	0.400	0.400	0.400	0.400	0.0000
0.2	0.400	0.400	0.400	0.4000	0.0000
0.4	0.400	0.400	0.400	0.4000	0.0000
0.6	0.402	0.400	0.400	0.4007	0.0007
0.8	0.403	0.400	0.400	0.4010	0.0010
1.0	0.403	0.400	0.400	0.4010	0.0010
1.2	0.403	0.400	0.400	0.4010	0.0010
1.4	0.403	0.400	0.401	0.4013	0.0013
1.6	0.403	0.400	0.401	0.4013	0.0013
1.8	0.403	0.401	0.401	0.4017	0.0017
2.0	0.404	0.401	0.401	0.4020	0.0020
2.2	0.404	0.401	0.404	0.4030	0.0030
2.4	0.405	0.401	0.405	0.4037	0.0037
2.6	0.409	0.402	0.410	0.4070	0.0070
2.8	0.413	0.405	0.415	0.4110	0.0110
3.0	0.419	0.410	0.425	0.4180	0.0180
3.2	0.429	0.419	0.445	0.4310	0.0310
3.4	x	0.439	x	0.4390	0.0390

Table 3: 0.2mm copper wire

Mass on weight hanger for copper wire of diameter 0.2mm (Kg) $\pm 2.8\%$	Position of marker from measured from the wooden block (m) ± 0.0005			Average	
	Attempt 1	Attempt 2	Attempt 3	Position of marker m	Change from original position m
0.0	0.400	0.400	0.400	0.4000	0.0000
0.1	0.400	0.400	0.400	0.4000	0.0000
0.2	0.401	0.401	0.401	0.4010	0.0010
0.3	0.402	0.401	0.401	0.4013	0.0013
0.4	0.403	0.402	0.402	0.4023	0.0023
0.5	0.405	0.405	0.406	0.4053	0.0053
0.6	0.410	0.415	0.412	0.4123	0.0123
0.7	0.427	0.417	x	0.4220	0.0220

Table 4:0.2mm Steel wire

Mass on weight hanger for steel wire of diameter 0.2mm (Kg) $\pm 2.8\%$	Position of marker from measured from the wooden block (m) ± 0.0005			Average	
	Attempt 1	Attempt 2	Attempt 3	Position of marker (m) ± 0.0005	Change from original position (m) ± 0.0005
0.0	0.400	0.400	0.400	0.4000	0.0000
0.1	0.400	0.400	0.400	0.4000	0.0000
0.2	0.400	0.400	0.400	0.4000	0.0000
0.3	0.400	0.400	0.400	0.4000	0.0000
0.4	0.400	0.401	0.403	0.4013	0.0013
0.5	0.400	0.401	0.404	0.4017	0.0017
0.6	0.401	0.401	0.405	0.4023	0.0023
0.7	0.401	0.402	0.405	0.4027	0.0027
0.8	0.401	0.403	0.405	0.4030	0.0030
0.9	0.401	0.404	0.405	0.4033	0.0033
1.0	0.401	0.404	0.406	0.4037	0.0037
1.1	0.401	0.407	0.406	0.4047	0.0047
1.2	0.401	0.407	0.407	0.4050	0.0050
1.3	0.402	0.409	0.407	0.4060	0.0060
1.4	0.406	0.411	0.409	0.4087	0.0087
1.5	0.410	0.414	0.411	0.4117	0.0117
1.6	0.410	0.414	0.414	0.4127	0.0127
1.7	0.413	0.425	0.420	0.4193	0.0193
1.8	0.423	0.428	0.426	0.4257	0.0257
1.9	0.427	0.433	0.429	0.4297	0.0297

4.2 Data Processing

4.2.1 Data

The load at break is found by locating the final point on the stress strain graph and then calculating the force at that point.

For copper wire of 0.3mm this is:

$$F = mg$$

$$F = 1.8 * 10$$

$$F = 18N$$

The Maximum Load will be determined by the highest point of the stress strain graph labelled as ultimate tensile strength in figure 2.

Young's modulus will be calculated by finding the gradient of the line of best fit of the elastic region of the stress strain Graph.

The strain was found by dividing the extension of the markers by the original length of the wire. When 4N of force is applied to copper of 0.3mm diameter it has a change in length of 0.001m so the strain is:

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

$$\varepsilon = \frac{0.0010}{1.25}$$

$$\varepsilon = 0.025$$

The stress was calculated by dividing the force applied by the cross-sectional area of the wire. So when 4N of force is applied to copper wire of 0.3mm diameter it has a stress of

$$\sigma = \frac{F}{A}$$

$$\sigma = \frac{4}{7.07 \times 10^{-8}}$$

$$\sigma = 5.7 \times 10^{7}$$

4.2.2 Uncertainties

To calculate the uncertainty of the force generated 7 different 100g masses were randomly sampled and the range was found to be 5.6g. So the uncertainty of the force generated would be 5.6/2 which is 2.8g which is $\pm\ 0.028N$. The diameter was measured with a micrometer with an uncertainty of $\pm 5 \times 10^{-7} m$. To find the area this is squared. So the uncertainty of the area is

$$\Delta A = 2 \times \frac{\Delta r}{r} \times A = 2 \times \frac{5\times10^{-7}}{3\times10^{-4}} \times (9 \times 10^{-8}) = 3 \times 10^{-10}.$$

So the percentage uncertainty of the stress value is:

$$\frac{\Delta\sigma}{\sigma} = \frac{3\times10^{-10}}{7.07\times10^{-8}} + \frac{0.028}{1} = 0.03224$$

$$Percentage\ Uncertainty\ of\ Stress\ = \frac{\Delta\sigma}{\sigma} \times 100 = 3.22\%$$

Strain is the ratio between extension and original length as these components were measured with the same instrument with an absolute uncertainty of 0.0001m.

So the percentage uncertainty of the strain value is

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{0.0005}{0.001} + \frac{0.0005}{0.4} = 0.50125$$

$$Percentage\ Uncertainty\ of\ Strain\ = \frac{\Delta\varepsilon}{\varepsilon} \times 100 = 50.1\%$$

The percentage uncertainty in the young's modulus would be

$$50.1\% + 3.22\% = 53.32\%$$

4.3 Processed Data

Table 1-Processed data for 0.3mm copper wire

Force (N)	Stress $(Nm^{-2})\ 10^7$ $\pm\ 3.22\%$	Strain on wire $\pm\ 50.1\%$
0	0	0
2	2.82	0
4	5.66	0.0008
6	8.49	0.00216
8	11.32	0.00264
10	14.15	0.00376
12	16.98	0.00536
14	19.81	0.008
16	22.64	0.01496
18	25.46	0.02344

Table 2- Processed data for 0.3mm Steel wire

Force (N)	Stress $(Nm^{-2})\ 10^{7}$ $\pm\ 3.22\%$	Strain on wire $\pm\ 50.1\%$
0	0.00	0
2	2.82	0
4	5.66	0
6	8.49	0.00056
8	11.32	0.00080
10	14.15	0.00080
12	16.98	0.00080
14	19.81	0.00104
16	22.64	0.00104
18	25.46	0.00136
20	28.29	0.00160
22	31.12	0.00240
24	33.95	0.00296
26	36.78	0.00560
28	39.61	0.00880
30	42.44	0.01440
32	45.27	0.02480
34	48.10	0.03120

Table 3-Processed data for 0.2mm Copper Wire

Force (N)	Stress $(Nm^{-2})\ 10^{7}$ $\pm\ 3.22\%$	Strain on wire $\pm\ 50.1\%$
0	0	0
1	3.18	0
2	6.37	0.00080
3	9.55	0.00104
4	12.73	0.00184
5	15.92	0.00424
6	19.10	0.00984
7	22.28	0.01760

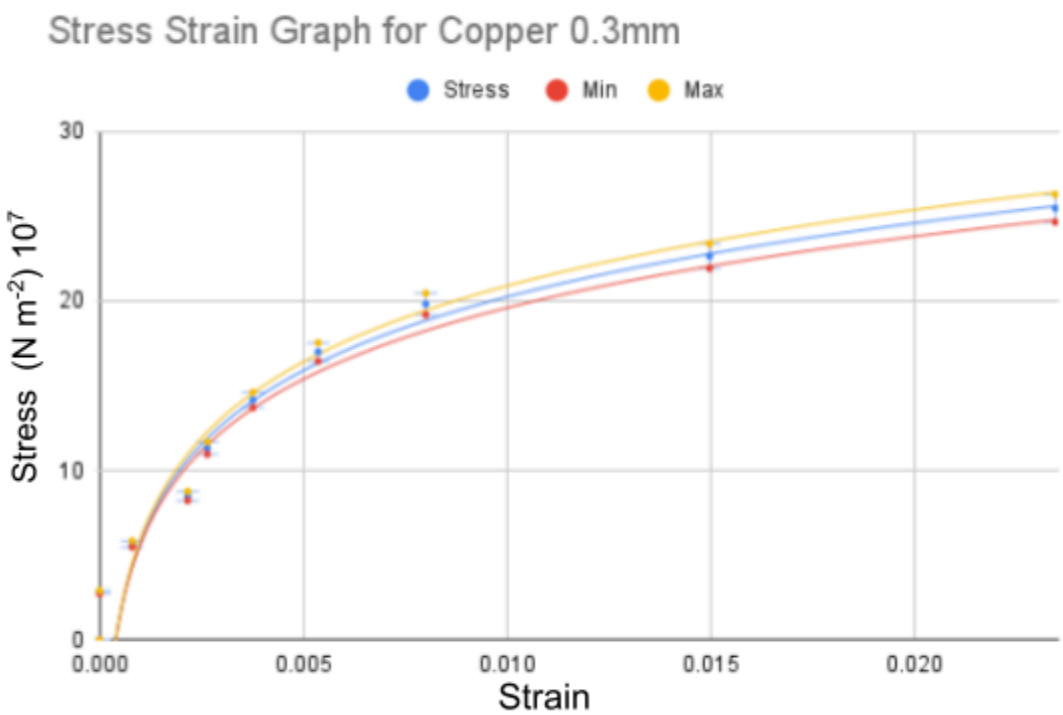
Table 4-The Stress Strain data for 0.2mm Steel Wire

Force (N)	Stress $(Nm^{-2})\ 10^{7}$ $\pm\ 3.22\%$	Strain on wire $\pm\ 50.1\%$
0	0	0
1	3.18	0
2	6.37	0
3	9.55	0
4	12.73	0.00104
5	15.92	0.00136
6	19.10	0.00184
7	22.28	0.00216
8	25.46	0.00240
9	28.65	0.00264
10	31.83	0.00296
11	35.01	0.00376
12	38.19	0.00400
13	41.38	0.00480
14	44.56	0.00696
15	47.75	0.00936
16	50.93	0.01016
17	54.11	0.01544
18	57.30	0.02056
19	60.48	0.02376

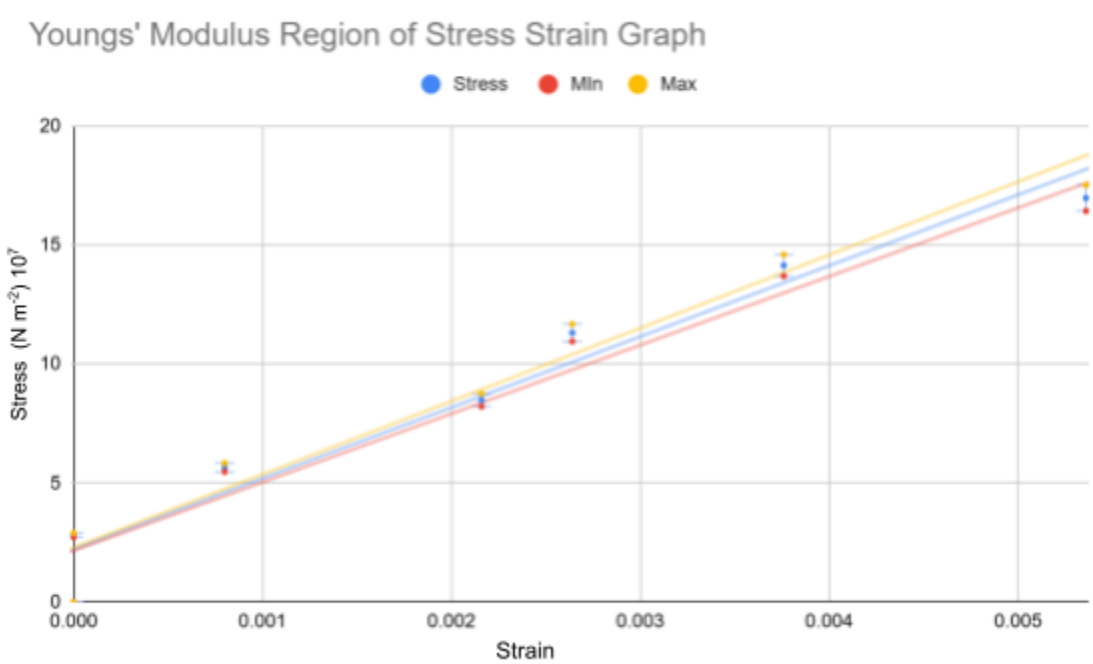
4.4 Graph

0.3mm Copper wire

Graph 1: The Stress Strain Graph for the Copper Wire of Diameter 0.3mm

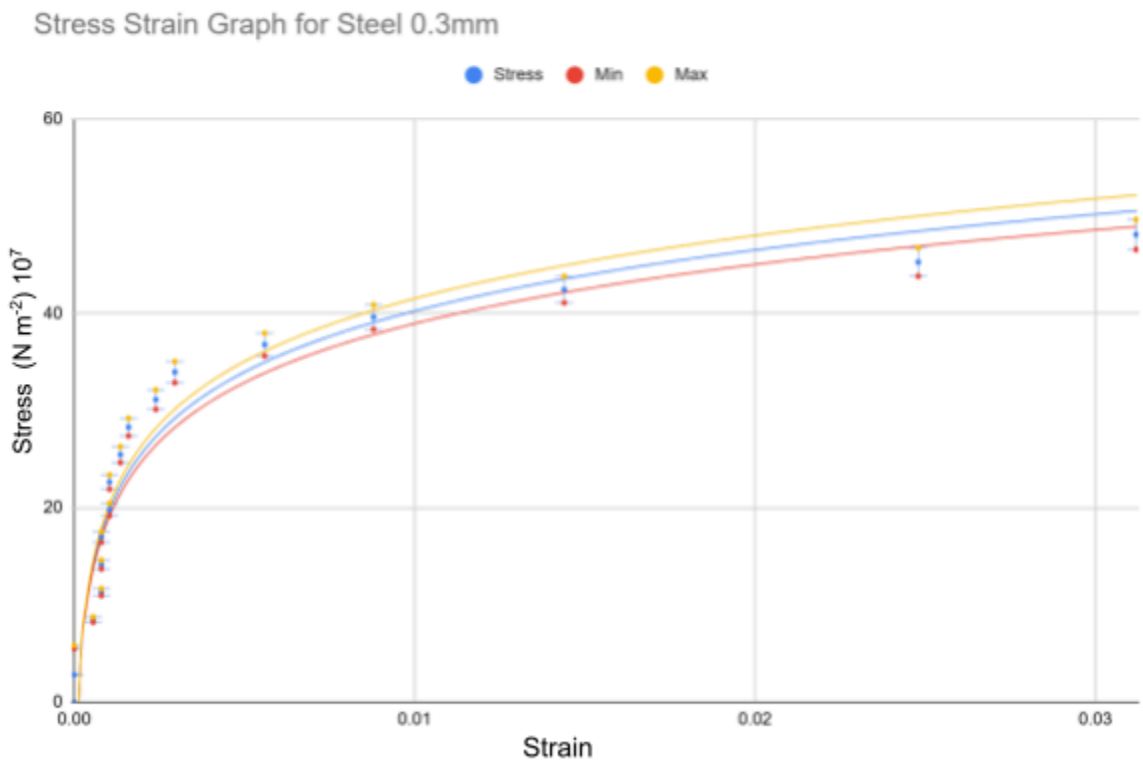


Graph 2: The Straight Line Region From The Stress Strain Graph of Copper of 0.3mm Diameter

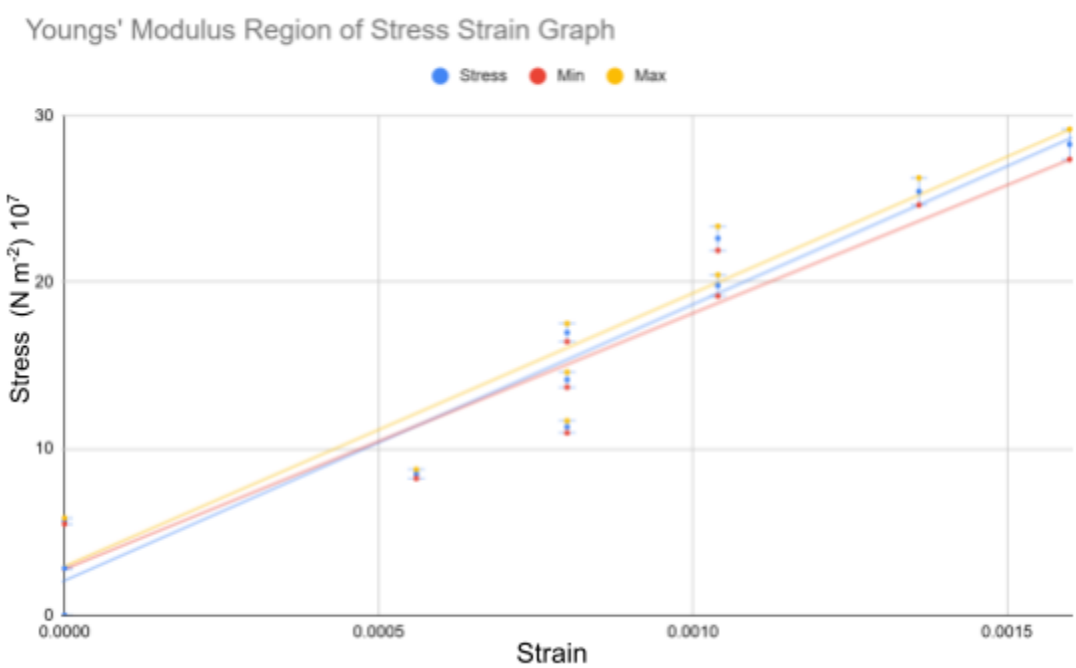


0.3mm Steel wire

Graph 1: The Stress Strain Graph for the Steel Wire of Diameter 0.3mm

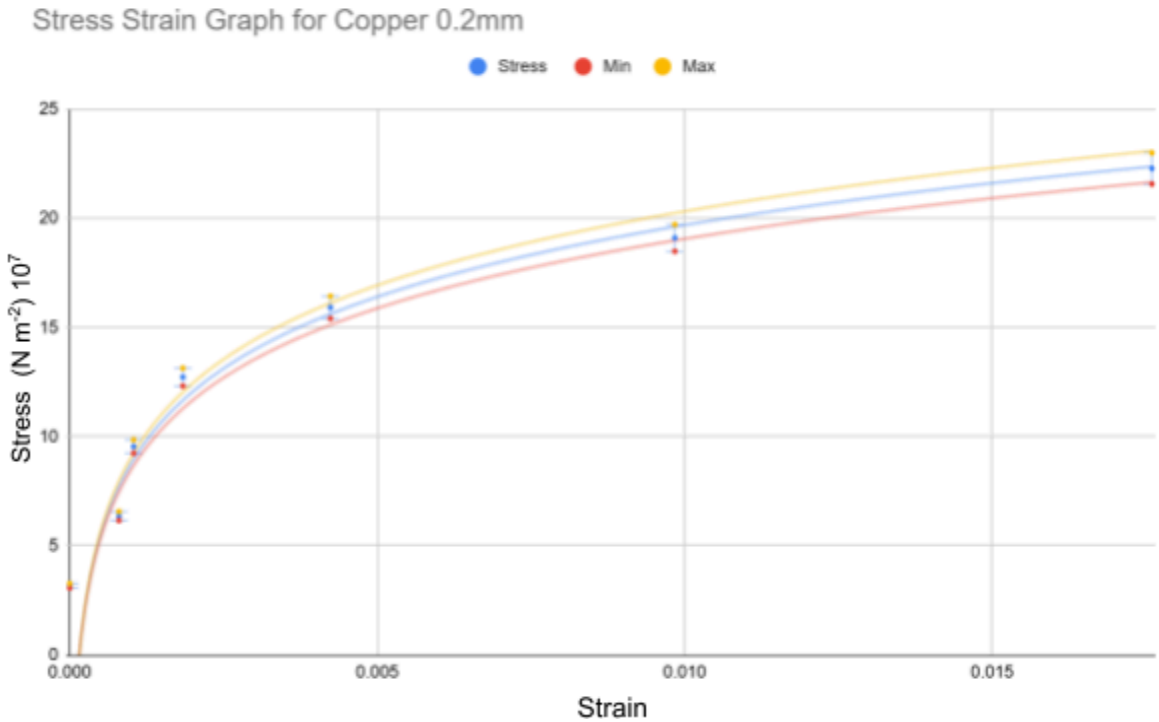


Graph 2: The Straight Line Region From The Stress Strain Graph of Steel of 0.3mm Diameter

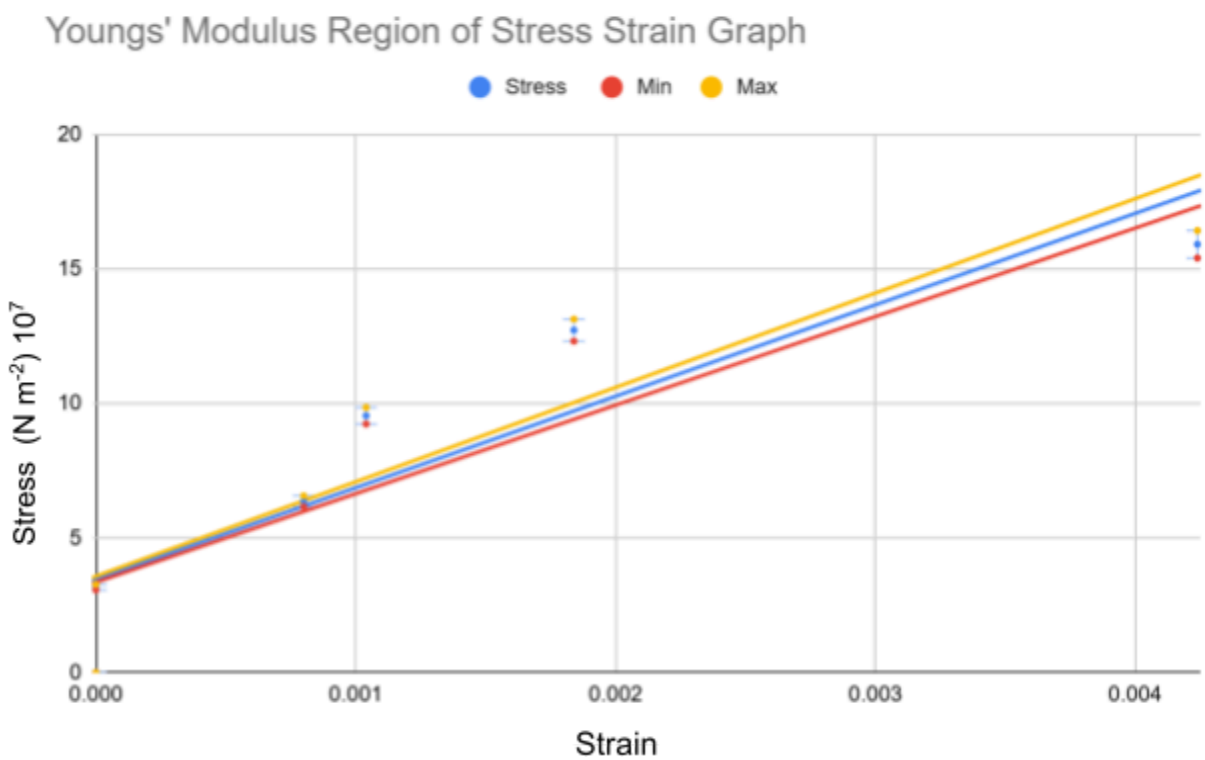


0.2mm Copper wire

Graph 1: The Stress Strain Graph for the Copper Wire of Diameter 0.2mm

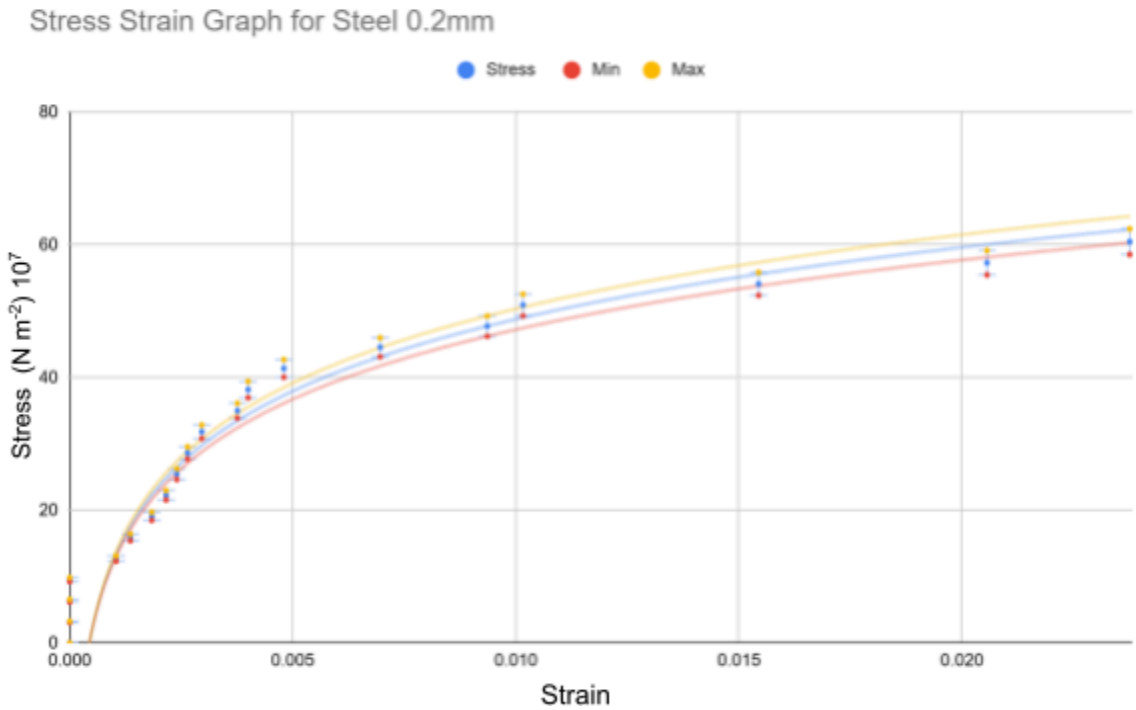


Graph 2: The Straight Line Region From The Stress Strain Graph of Copper of 0.2mm Diameter

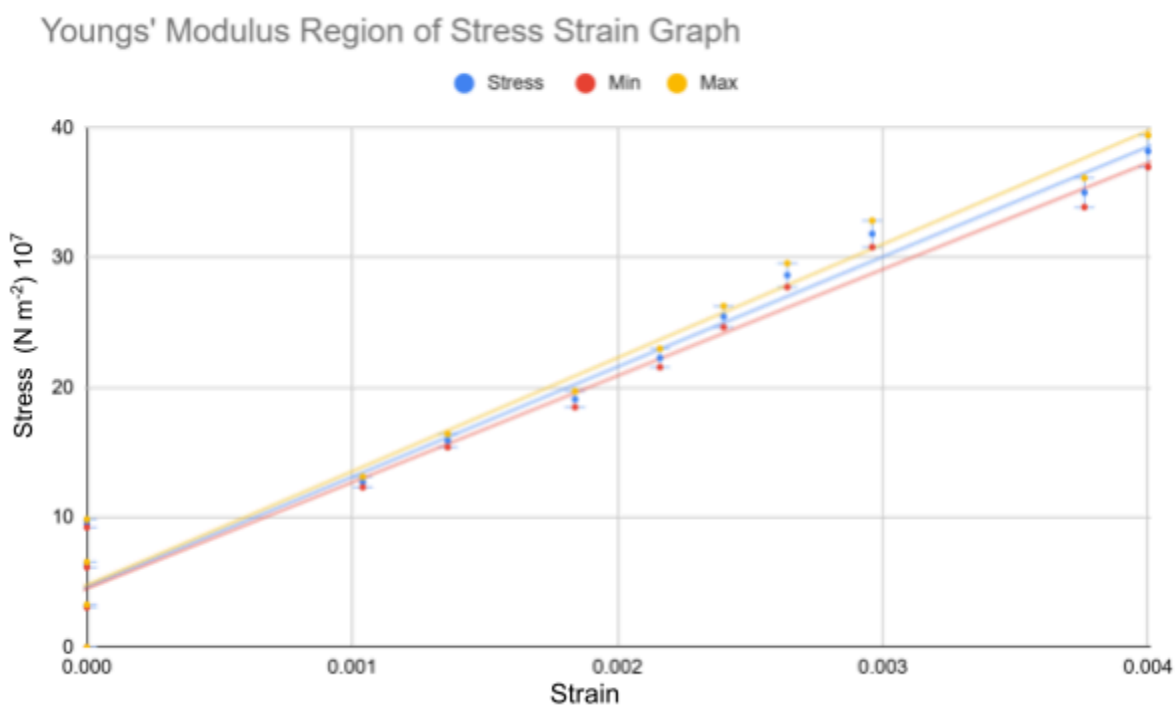


0.2mm steel wire

Graph 1: The Stress Strain Graph of Steel of 0.2mm diameter



Graph 2: The Straight line region from the Stress Strain Graph of Steel of 0.2mm diameter



5. Conclusion

Type of wire	Copper 0.3mm	Steel 0.3mm	Copper 0.2mm	Steel 0.2mm
Load at Break	18$\pm$ 0.5N	34$\pm$ 1N	8$\pm$ 0.2N	19$\pm$ 0.532N
Maximum load	198.1$\pm$ 5.5 MPA	424.4$\pm$ 11.9 MPA	159.2$\pm$ 4.5 MPA	413.8 $\pm$ 11.6 MPA
Young's modulus	70.8 $\pm$ 37.5 GPA	151.6 $\pm$ 80.3 GPA	69.18$\pm$ 36.7 GPA	122.4$\pm$ 64.9 GPA

As predicted, decreasing the area of the cross-section decreases the tensile strength. This is true for all three metrics of tensile Strength as well as for both materials used.

<u>Load at Break</u>

Load at break was initially at 18N for copper wire of 0.3mm but it decreased to 8N this is a 55.6% decrease. Whereas, the load at break for steel was originally 34N but it decreased to 19N this is a 44.2% decrease.This means that in regards to the load at break the load at break decreases when the wire diameter decreases but the amount that the value decreases varies from material to material. The reason for this could be the atom arrangement of the material As copper is a pure material and is only made with copper atoms in a regular arrangement. Whilst steel is an alloy which contains iron and carbon along with other elements this disrupts the regular structure of the steel atoms making it more rigid and less susceptible to extending.This could be why there is a high load at break and a smaller decrease when there is a change in wire diameter.

Maximum load

The Maximum Load of Copper at a diameter of 0.3mm was 198.1 MPA. This decreased to 159.2 MPA which is a 19.6% decrease. Steel on the other hand was initially at 424.4 MPA this decreased to 413.8 MPA when the diameter was changed; this is a 13.6% decrease. This maintains the trend of steel having a smaller decrease in tensile strength for the same decrease in diameter. The difference between the change in load at break was higher than the difference between maximum load. This is interpreted because the difference between the change of load of steel is 20% smaller than copper. But the difference between the change in maximum load of steel was only 8% lower than the change in maximum load of copper. The reason for this could be because of the way maximum load is calculated from the graph. As maximum load is the highest point of the graph without the wire's shape changing permanently a large portion of the graph is made redundant as a majority of the graph is inelastic deformation. Which could be why the difference between the two materials is smaller.

Young’s Modulus

The Young's Modulus of Copper at 0.3mm was calculated to be 70.8 GPA when the diameter decreases to 0.2mm the Young’s Modulus decreases to 69.1 GPA; this is a 2% decrease from the original 70.8 GPA. Steel however has a Young’s Modulus of 155.6 GPA which decreases to 122.4 GPa this is a 21% decrease in Tensile strength. This is a larger decrease than the decrease of copper. The results however do not correspond with common conventions of Young's modulus as the Young's Modulus of steel as being between 190 GPa and 210 GPa [5] the range was used as there are different variations

of steel. This invalidates Young's Modulus as the values found were significantly different from that already known. However, the calculation for Young's Modulus still showed that copper had a lower Young's Modulus than steel which means that steel has a lower elasticity than copper. This interpretation follows the general trend of steel being stronger than copper. That being said, Young's modulus is said to be constant[7] for materials no matter the form which makes the credibility of this result questionable. This was caused because of the large 50% uncertainty of the strain causing a majority of the 53% uncertainty of the young's modulus.

Summary

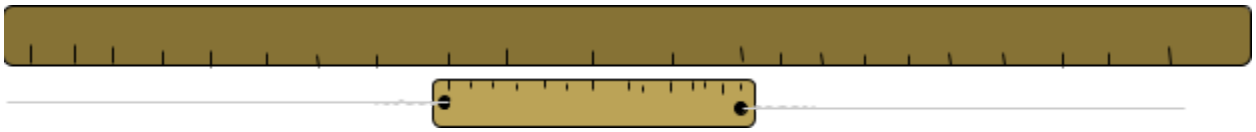
In regards to the question: Does an increase in diameter of a wire have the same degree of effect on the tensile strength of different materials? An increase in diameter will have an effect in some quantifications of tensile Strength such as load at break. But an increase in diameter may not have an effect on other quantifications of tensile strength that are constants for materials such as young's modulus. For the quantifications of tensile Strength that are affected by a change in diameter the effect of the change in diameter is to different degrees for different materials.

6. Evaluation

The experiment provided valid results for maximum load and load at break. It also gave the correct shape for the stress strain graph. This makes the experiment somewhat valid as it provided results that were not too far from generally accepted mechanical properties of the materials.

The method of using markers was inaccurate because the marker was attached to the wire using tape and a crocodile clip. This meant that whilst the marker was moving the tape might have been slipping as the wire is very thin and the adhesive strength of the tape was not enough to securely attach to the wire. The choice of using a metre ruler which goes up in 0.1mm was not the best choice for measuring such a small difference as well. This is because the marker would often be between millimetres and which would lead to inaccurate readings. This would be solved by using two devices: a ruler with holes at either end and a vernier calliper. These would be used in addition to the metre rule but with the ruler replacing the markers. The setup would be similar to the one seen in figure 6.

Figure 6



This would be a more accurate way of measuring the extension of the wire as there would be less chance of the wire moving and the marker not moving when compared to the tape. But this alone would not solve the accuracy problem. This is where the vernier calliper comes into play as it can be used to measure the change from the original position more accurately than the metre rule. The more accurate measurement of extension could lead to a more reliable value of Young's Modulus.

Another shortcoming of the methodology was the inaccuracy of the weights. Of the weights that were randomly sampled the range was found to be 2.8g. This amount stacked up as over 34 weights ended up being used. More accurately calibrated weights would decrease the uncertainty caused by the difference in mass from the wanted value.

Another improvement that could have been made to the experiment is smaller mass increments. Smaller mass increments would allow for more data points to be collected; this would allow for more accurate graphs. A more accurate graph is needed as the graph is a polynomial so more data points would lead to more accurate results when paired with better graphing software.

The final improvement that could be made to the experiment at this point would be to change the pulley used. The pulley used was metal and was very stiff. This led to uneven distribution of tension. A metal pulley will still need to be used to prevent the

wire from cutting into the pulley's wheel but a more lubricated wheel might make the distribution of tension more evenly distributed.

These would decrease the 53%

This essay could lead to further research based on these results as the decrease in quantifiers of tensile strength that changed was less than 66% this means that 3 wires of 0.2mm will theoretically have a higher maximum load and load at break than 2 wires of 0.3mm. This means that a research topic consequent of this essay could be to: Investigate the effect of amount of wires intertwined and the diameter of the wires intertwined on the maximum load and load at break of the intertwined wire. Another investigation that could be developed from this is: The degree of effect on tensile strength of wires of different diameters of alloys.

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Diagrams:
Figure 1:

https://unsplash.com/photos/the-golden-gate-bridge-towering-over-the-ocean-I14P8HJh9YU