Washington University in St. Louis

MEMS 205 Mechanics and Materials Science Laboratory

Lab 4: Tensile and Flexure Testing with Statistical Analysis

Section: Group D (Tuesday 12 PM)

Lab Instructor: Dr. Sellers

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We hereby certify that the lab report herein is our original academic work, completed in accordance with the McKelvey School of Engineering and Undergraduate Student academic integrity policies, and submitted to fulfill the requirements of this assignment.

Matthew Donaldson	Team Leader	Matt D
Isaac Sasser	Data Acquisition Manager	Isaac Sasser
Andrew Brown	Test Engineer	Andrew Brown
Aidan Murphy	Quality Control Engineer	Aidan Murphy

Abstract

Through the instruction of Amazon Air, we were tasked with testing material properties for drones. We determined the elastic modulus, yield stress and ultimate stress of several different metals, plastics, and the max load, elastic modulus, and flexural strength glass. For the metals and plastics, we used a tensile machine and TW essential application software to measure the stress and strain of the specimen. Each specimen was a dog bone shape. The glass was broken up into groups, one unscratched, one scratched horizontally and one the other vertically. Then a four-point flexure machine was used on each specimen to measure the force applied and the displacement of the specimen. From the tensile test, it was apparent that the plastics had a wide range for the elastic modulus and were not similar to published data. In our data, we found that nylon, PETG, and PLA had an elastic modulus of 0.553 GPa, 1.30 GPa, 3.07 Gpa respectively. The metals elastic modulus were more consistent with published data, for steel, aluminum and copper they were 266 GPa, 63.2 GPa, and 85.4 GPa respectively. As the glass broke we noticed that the glass with no scratches had significantly higher max load, flexure strength, and elastic modulus than the glass with the scratches. Using Chi-squared analysis we found that the average max load, flexure strength and elastic modulus for unscratched glass were 56.70 N, 947.37 MPa, 93.25 GPa. From the two groups with different scratch orientations, we noticed that the horizontal scratches caused the glass to have a lower max load, flexure strength, and elastic modulus.

Introduction

Amazon Air Prime has tasked us to provide a summary of the material properties of the materials to be used in the construction of their delivery drone prototype. Accordingly, we use an MTS universal tester to determine the elastic modulus, yield stress, yield strain, ultimate stress, ultimate strain, and percent elongation of 1018 steel, 6061 aluminum, 110 copper, and Teflon, as well as 3D printed Nylon, PLA, and PETG. For glass, which is highly brittle, we determine the elastic modulus, maximum load, and (ultimate) flexure strength.

The MTS universal tester uses a movable crosshead, mounted between two posts, to apply a force to a material. Computer software connected to the universal tester records both the force and the displacement caused by the force. The universal tester can be tooled to perform a tension test or a flexure test. In a flexure test, a thin rectangle of the subject material is flexed between supports until it fails (Fig. 1). In a tension test, a dog bone shaped sample of the subject material (Fig. 2), is stretched between two clamps (Fig. 1), which are attached to the universal tester, until the dogbone fails.

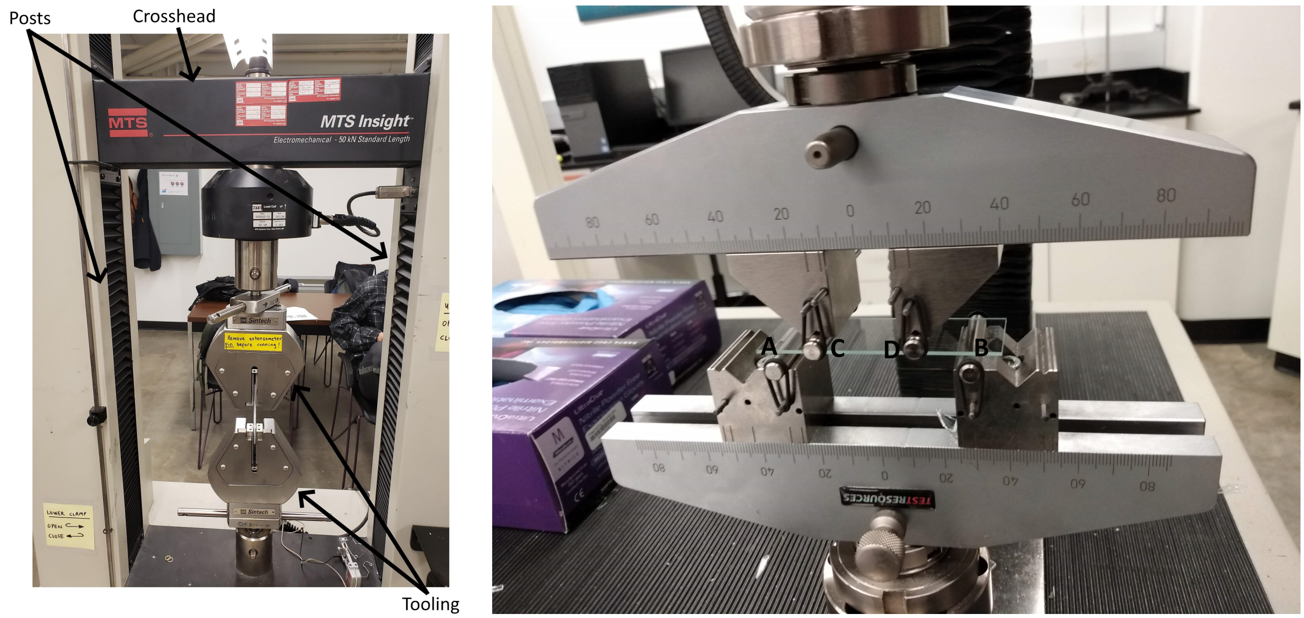

Fig 1. The flexure testing machine with tensile test tooling (left) and four-point bending tool with contact points labeled A-D (right).

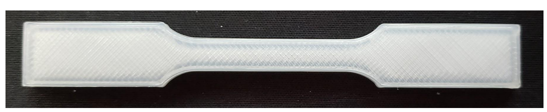

Fig. 2 Sample specimen for the tensile testing machine.

For the more ductile materials, everything but glass, we determine their properties by generating a stress-strain curve. The curve plots stress as a function of strain, with strain on the abscissa and the stress of the corresponding load on the ordinate. Stress is defined as the force per cross-sectional area, where the cross-sectional area is the area that supports the applied force [1]. As the material is stressed, the cross-sectional area changes. Stress measurements based on this changing area are called true stress [1]. However, it is very difficult to measure a changing cross-sectional area, so it is most common to calculate stress based on the original area of the material. Stress calculated in this manner is called engineering stress. Most material properties are determined from engineering stress [1], so our stress-strain curves use engineering stress.

Tension Test

During a tension test, the applied force is parallel to the face of the corresponding cross-sectional area, resulting in uniform stress across this area. Therefore, engineering stress is given by [1]:

$$\sigma = \frac{P}{A_o} \tag{1}$$

σ is engineering stress, *P* is the load applied to the specimen, and A_o is the initial cross-sectional area of the specimen normal to the applied force. When calculating strain for a tensile test, we again recognize that the relevant cross-sectional area is parallel with the applied load and that the stress is generally uniform across the material. Therefore, the engineering strain of a tensile test is given by [1]:

$$\epsilon = \frac{l_i - l_o}{l_o} \tag{2}$$

ϵ is the strain, l_i is the instantaneous length of the specimen, and l_o is the initial length of the specimen. The elastic modulus is the slope of the stress-strain curve during the linear elastic phase of the deformation of a material, relating stress to strain in terms of Hooke's law by $\sigma = E\epsilon$ [1]. E is the elastic modulus, and functions as the constant of proportionality. The elastic modulus determined from the stress-strain curve during the linear elastic region with the expression:

$$E = \frac{\sigma}{\epsilon} \tag{3}$$

Yield stress, σ_y, is the point on the stress-strain curve above which the material will experience plastic deformation. Plastic deformation begins when the curve becomes non-linear. However, it is often very difficult to determine when the curve makes this transition. As a result, we define the yield point as the value on the stress axis intersected by a line drawn from 0.002 strain and parallel to the linear elastic region of the curve [1]. Yield strain, ϵ_y, is the point on the strain axis beyond which the material will deform plastically [2]. This means yield strain is simply the point on the strain axis that corresponds to the yield stress on the stress axis.

The ultimate tensile strength of a material is "the maximum engineering stress, in tension, that may be sustained without fracture" [3]. Therefore, the ultimate stress is simply the maximum on the engineering stress-strain curve, and the ultimate strain is the strain that corresponds to the ultimate stress. Percent elongation is simply “the percentage of plastic strain at fracture” [1], given by:

$$\%EL = \frac{l_f - l_o}{l_o} \times 100 \tag{4}$$

$\%EL$ is percent elongation and l_f is the length of the specimen at fracture, and l_o is the initial length of the specimen. However, no matter the initial length of a specimen, after the specimen experiences ultimate strain, much of the yielding occurs in the necking region [1]. The shorter the initial specimen, the greater is the portion of %EL caused by necking. Therefore, we report the initial length of the specimen to provide context for %EL values [1].

Flexure Test

Glass is tested with a flexure test because it is a ceramic [4] and ceramics can only withstand approximately 0.1% elongation before they fail [1]. This makes it very difficult to grip and pull glass, as required by the tensile test without causing it to shatter. It also means that if the jaws of the tensile tester are not perfectly in line, the specimen will fail from bending stress, which is difficult to calculate from the tensile test orientation. The flexure test neither requires clamps to grip the specimen nor perfect alignment between top and bottom supports, so it is optimal for use with glass.

The high brittleness of glass means that it will generally fail during elastic deformation [1]. Therefore, it is not necessary to generate a full stress-strain curve for glass. Ultimate flexural strength is the maximum stress experienced by the sample when it fails. Elastic modulus is the slope of the linear elastic region of the stress-strain curve. Because we know that the glass fails during this region elastic modulus is simply:

$$E = \frac{\sigma_{fs}}{\epsilon_{fs}} \tag{5}$$

σ_{fs} is the ultimate flexural strength and ϵ_{fs} is the strain that corresponds to the ultimate flexural strength. During a flexure test, the applied force is normal to the corresponding cross-sectional area. This causes the material to bend, putting the top of the specimen under compression and the bottom under tension [1]. We use a four-point bending flexure test, resulting in maximum and uniform tensile stress on the bottom of the specimen between points C and D

(Fig. 1). Therefore, at the load which causes failure, the ultimate flexural strength, [5], is given by:

$$\sigma_{fs} = \frac{3P_u L}{4bd^2} \tag{6}$$

L is the distance between A and B (Fig. 1), *b* is the width of the specimen, and *d* is the thickness between the faces of the specimen. The strain that corresponds to the physical location of the stress and to the ultimate flexural strength, [5], is given by the following equation, where *D* is the maximum deflection at the center of the beam.

$$\epsilon_{fs} = 4.36\frac{Dd}{L^2} \tag{7}$$

Surface Treatment

The surface treatment of a material affects its material properties. When loaded, a material will fail at the point of highest stress and this point is normally on the material's surface. Therefore, anything processing that causes stress concentrations on a material's surface is expected to weaken the material [6]. We test with the flexure test by comparing smooth glass with glass that has been lightly sanded on the bottom face. By sanding the bottom, we introduce stress concentrations to the glass surface at the location of highest stress. We also test the effect of the direction of sanding by sanding one group of specimens in the direction parallel with the shorter dimension of the bottom face and another group in the direction parallel to the longest dimension of the bottom face. We refer to the directions as "horizontal" and "vertical," respectively. The flexure test causes the glass to fail in the horizontal direction from a crack that begins at its surface. Horizontal failure implies that any surface crack that leads to failure must propagate horizontally across the specimen's surface. Horizontal scratches will add uniform stress concentrations in the horizontal directions, making it easy for surface cracks to propagate horizontally. Therefore, horizontal sanding should lead to failure under lighter loads than should vertical sanding. Any sanding, horizontal or vertical, should lead to failure under lighter loads than should unsanded glass.

3D Printed Materials

The materials properties reported for the 3D printed materials cannot be generalized to any application of these materials. The orientation of the load relative to the direction of printing affects the way the material responds to the load [7]. Therefore, the values we determine are only applicable to samples printed with the exact same settings as our samples.

Experimental Methods

The purpose of this experiment was to determine the material properties of several different materials shown in Table 1 and the equipment used for each test is shown in Table 2. A tensile test was done on the metals and plastics to measure the force and displacement of the materials. The tensile machine, shown in Fig. 1 and 3, and the TW essentials application software were used for this section. We took note of the maximum force that the machine can handle, displayed on the attached load cell, to ensure the machine is operating safely. First, the material was attached to the upper clamp of the machine. Then the clamp was lowered so that the bottom clamp could be attached to the specimen. It is important after this step to then put the material in slight tension in order to ensure that there is no wiggling in the joints. This slight tension will also depend on the material that is being tested, putting more tension on metals (about 100 N) and less tension on the plastics (about 10 N). Also, after every step, we re-zeroed the load and crosshead. Next, the extensometer was attached to the material between the clamps and the zeroing pin was removed. Once the extensometer was attached, again, we zeroed the load, crosshead, and extensometer. It was important to remember to change the testing rate depending on the material (Table 3). When we ran the test if the displacement goes beyond 10mm, we took off the extensometer and continued testing. This ensured that the extensometer would not break.

Next, was the flexure test. For this test, three groups of the glass slides were tested with one of the groups having uniform horizontal scratches and the other having uniform vertical scratch marks on them from 180 grit paper. We then placed one glass slide at a time onto the mount. It was important to note the orientation of the scratches during the test compared to the way the specimen was placed. Once the specimen is mounted a constant load is applied to the glass until failure. We made sure that there was no preload before starting the test but the tip was just above the specimen. Before every test, the load and displacement were zeroed. While handling the broken specimen we used nitrile gloves to pick up the broken pieces of glass. We then disposed of them in the broken glass disposal bin.

Table 1 Material quantity and dimensions in the lab

Material	Amount	Length (in)	Width (in)	Thickness(in)
1018 Steel	1	4.003	0.253	0.123
6061 Aluminum	1	4.000	0.252	0.127
110 Copper	1	4.003	0.251	0.125
Teflon	1	4.012	0.248	0.128
Nylon	2	3.962 3.964	0.260 0.255	0.125 0.125
PLA	3	4.013 4.002 4.011	0.271 0.259 0.278	0.118 0.120 0.121
PETG	3	4.005 3.988 3.990	0.269 0.251 0.281	0.124 0.130 0.118
Glass	30	-	24.900(mm)	1.040(mm)

Table 2 Equipment list

Equipment	Serial number	Description
MTS Insight (Tensile Machine)	10268472	Model #: 634115 Max Load: 50 kN
MTS Systems (Flexure Machine)	85565	Model #: 27-00077 Max Load: 30 kN

Table 3 Testing rate of each specimen

Material	Testing rate (mm/s)
All Metals	0.8
PLA and PETG	0.1
Teflon and Nylon	2

Results and Discussion

When determining the properties of glass using the flexure test, we used the chi-squared distribution and a 95% confidence interval to determine a range for the expected value of elastic modulus, max loading, and flexural strength. The chi-squared analysis gave the team a range of standard deviations for the population (all samples) using the calculated standard deviation from the data. The underlying assumption of the chi-squared confidence interval is that the data is normally distributed. Meaning that the variation in the properties of glass is normally distributed and in our case with a chi-squared distribution.

When looking at the data from the test there are important points about how the data was analyzed that should be noted. First, Fig 4 below shows the data from the undamaged glass trials.

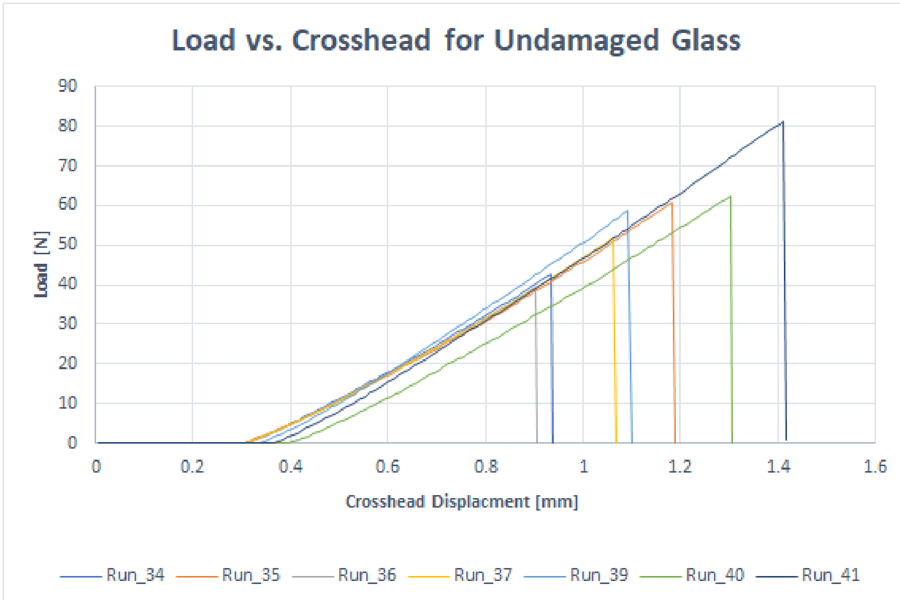

Fig. 3 **Load vs crosshead (displacement) of the flexure test for undamaged glass. The breakpoint of the glass is clearly seen by the sharp peak in the load. In addition, this graph shows no plastic deformation, meaning the region up until the break is linear**

The data in Fig. 3 was nearly continuous so it was plotted as lines instead of markers. The only exception to this is the final point after the break where the load jumps back down to zero or negative in a one-time step. It is important to note that the entire region of the graph is linear, aside from the noise at the start. This linearity implies that Eq. 6 and Eq. 7 can be used to determine the flexural strength and strain respectively. With both of these calculated in the elastic region Eq. 5 can be used to determine the elastic modulus.

This noise comes from the fact that the test was started without a preload, so the crosshead was not touching the sample at the start of the test. Thus, we see an increase in crosshead but not load. To find the true displacement then, the noise at the beginning must be subtracted from the crosshead at fracture to gain the displacement at fracture.

Undamaged glass

The chi-squared analysis of the 95% confidence interval for the undamaged glass is as follows, where σ in each of these confidence intervals represents standard deviations.

Max Load: $11.0012 \leq \sigma \leq 18.5589$ [N]

Flexural Strength: $183.8250 \leq \sigma \leq 310.1099$ [MPa]

Elastic Modulus: $6.4311 \leq \sigma \leq 10.8492$ [GPa]

We are 95% confident that the intervals above capture the true population standard deviation for max load, flexural strength, and elastic modulus respectively of undamaged glass. Thus, by using the 95% confidence interval approach and a conservative estimate of the interval, or the upper end we could find a range for the population mean using the sample mean. According to the normal distribution probability law, 95.5% of all data falls within two standard deviations of the mean. This range of two standard deviations can be seen in Table 4 along with the properties for undamaged glass.

Table 4 Sample mean of the data and the range of true population mean of all undamaged glass

Type	Mean	Standard Deviation Conservative	Range of Means			Units
Max Load	56.70	18.5589	19.5809	≤ μ ≤	93.8165	[N]
Flexural Strength	947.37	310.1099	327.1507	≤ μ ≤	1567.5903	[MPa]
Elastic Modulus	93.25	10.8492	71.5532	≤ μ ≤	114.9500	[GPa]

Thus, we can say that we are 95% confident that 95.5% of all samples of undamaged glass will have a max load, flexural strength, and elastic modulus within the range listed in Table 4.

Damaged Glass Vertical Scratches

The confidence intervals for the standard deviation of vertically damaged glass are as follows, noting that σ represents standard deviations in this case.

Max Load: $1.7715 \leq \sigma \leq 3.2274$ [N]

Flexural Strength: $29.6363 \leq \sigma \leq 53.9939$ [MPa]

Elastic Modulus: $4.2044 \leq \sigma \leq 7.6600$ [GPa]

We are 95% confident that the intervals above capture the true population standard deviations of max load, flexural strength, and elastic modulus for vertically damaged glass respectively. Just as before, these ranges can be used to determine the interval for the population expected value of the properties of interest. From this range of data, we can take our data and find a mean value for max load, flexural strength, and elastic modulus. For the vertically damaged glass, the properties can be seen in Table 5.

Table 5 Sample mean of the data and the range of true population mean of all vertically damaged glass.

Type	Mean	Standard Deviation Conservative	Range of Means			Units
Max Load	38.16	3.2274	31.7061	≤ μ ≤	44.6157	[N]
Flexural Strength	637.63	53.9939	529.6373	≤ μ ≤	745.6129	[MPa]
Elastic Modulus	82.23	7.6600	66.9107	≤ μ ≤	97.5507	[GPa]

Thus, we can say that we are 95% confident that the interval in Table Y for the means captures the true population means for 95.5% of all vertically damaged glass for each specific property.

Damaged Glass Horizontal Scratches

The confidence intervals for the standard deviation of horizontally damaged glass are as follows, again noting that σ represents standard deviations.

Max Load: $1.6866 \leq \sigma \leq 3.5820$ [N]

Flexural Strength: $28.1929 \leq \sigma \leq 59.8765$ [MPa]

Elastic Modulus: $0.2644 \leq \sigma \leq 0.5616$ [GPa]

We are 95% confident that the intervals above capture the true population standard deviations of max load, flexural strength, and elastic modulus for horizontally damaged glass respectively. As before a range for the means can be calculated and the results are shown in the Table 6 below.

Table 6 Sample mean of the data and the range of true population mean of all horizontally damaged glass.

Type	Mean	Standard Deviation Conservative	Range of Means			Units
Max Load	23.45	3.5820	16.2813	≤ μ ≤	30.6093	[N]
Flexural Strength	391.74	59.8765	271.9912	≤ μ ≤	511.4972	[MPa]
Elastic Modulus	78.50	0.5616	77.3752	≤ μ ≤	79.6216	[GPa]

Thus, we can say that we are 95% confident that the interval in Table 6 for the means captures the true population means for 95.5% of all horizontally damaged glass for each specific property.

From an examination of the data from Tables 4 - 6, one can see that the undamaged glass has significantly higher max load capacity, flexural strength, and elastic modulus. This is to be expected because the scratching of the surface introduces sharp edges that act as stress concentrators decreasing the load that the damaged glass can take. The question then becomes, which scratch direction decreases the max load, flexural strength, and elastic modulus more? From looking at Tables 5 and 6, it can be seen that the glass with the horizontal scratches is weaker than the vertically scratched glasses. In the flexure test, loads cause cracks, and therefore failure, in the horizontal direction. Horizontal scratches cause stress concentrations in the direction of crack propagation, causing the horizontally scratched specimens to fail under the lightest loads. Thus, more of the force goes directly to the line of concentrated stress than in the case where the load is perpendicular to the line of stress concentration (vertical scratches). In addition, while we see in Table 5 that there is some overlap in the ranges, for example, the low end of the elastic modulus of the vertically scratched glass falls below the low end of the horizontally scratched glass. This is simply because there was more variation in the data for the vertically scratched data. If more data was acquired for both, the ranges would begin to converge to the mean. Thus, the conclusion that the horizontally damaged glass has a lower load capacity, flexural strength, and elastic modulus than the vertically damaged glass is still true based on the data in Table 4 - 6.

Tensile Testing

The tensile testing of each material, besides glass (Table 2), was done to obtain stress-strain curves that are used to estimate mechanical properties for each material. These mechanical properties are obtained from the stress-strain plots for each material (Fig. 4). The elastic modulus is the slope of the linear portion, the ultimate stress and strain are from the maximum stress value, and the yield stress and strain are calculated using the 0.2% offset method. Table 7 below summarizes all of the utilized published mechanical property values.

Table 7 Published mechanical properties of all materials for tensile testing

	Elastic Modulus (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)	Percent Elongation (%)	References
1018 Steel	200	350	450	15	[8]
6061 Aluminum	70	330	365	13.6	[9]
110 Copper	120	280	320	20	[10]
Teflon	0.575	9	30.5	450	[11,12]
Nylon	0.9	27	30	230	[13]
PLA	2.3465	49.5	50	5.2	[14,15]
PETG	1.1	28.3	24	5	[16]

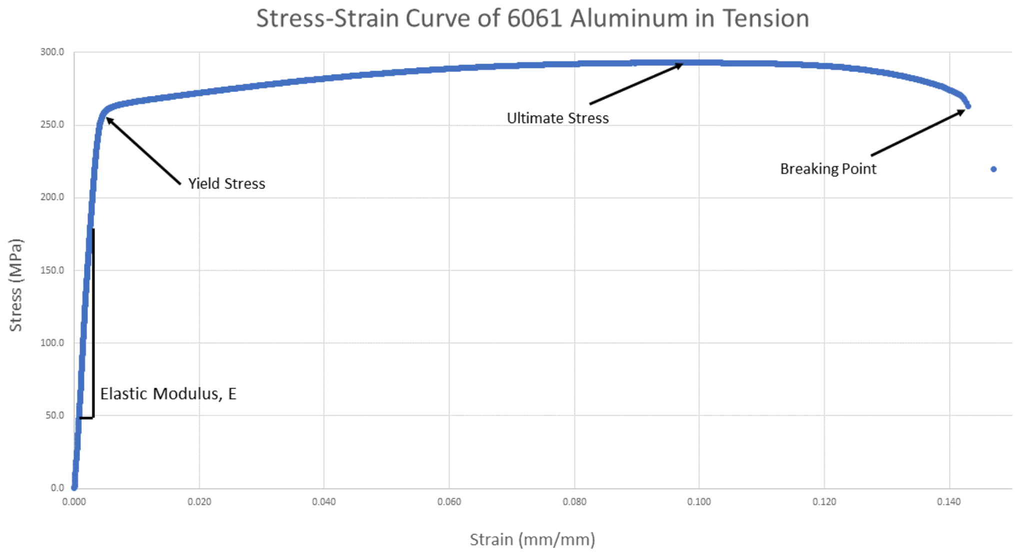

Fig. 4 Sample stress-strain curve that was produced, of 6061 Aluminum in this scenario, for all tensile testing results. Various mechanical properties are labeled.

Table 8 below summarizes each of the Excel calculated mechanical properties from the stress-strain curve (Fig. 4), for each material. Average values of these properties were taken for Nylon, PLA, and PETG since there was more than one test specimen for these materials.

Table 8 Estimated mechanical properties of each material based on the stress-strain plot.

	Elastic Modulus (GPa)	Yield Stress (MPa)	Yield Strain (mm/mm)	Ultimate Stress (MPa)	Ultimate Strain (mm/mm)	Percent Elongation (%)
1018 Steel	266	384.3	0.00434	639.3	0.0153	16.7
6061 Aluminum	63.2	262.1	0.00592	292.8	0.0963	14.3
110 Copper	85.4	275.9	0.00291	292.6	0.0352	18.8
Teflon	0.801	9.935	0.0577	26.35	4.93	493
Nylon (Average)	0.553 ± 0.00161	22.91 ± 0.2841	0.156 ± 0.0197	25.00 ± 0.9724	0.556 ± 0.00545	362 ± 25.3
PLA (Average)	3.07 ± 0.199	49.45 ± 2.405	0.0174 ± 0.000740	55.12 ± 4.192	0.0212 ± 0.00119	3.11 ± 1.77
PETG (Average)	1.30 ± 0.0463	27.44 ± 0.3726	0.0251 ± 0.000800	32.08 ± 0.5640	0.0394 ± 0.000928	4.25 ± 0.343

For the PETG samples, the third sample's percent elongation was omitted from the dataset since it was deemed to be an outlier (Fig. A.12). During the experiment, it was observed that the testing machine did not realize that the specimen was broken since there was still a portion of the specimen that remained, Fig. 5. This difference in data can also be seen through the stress-strain curves for each of the three specimens, Fig. A.10 - A.12.

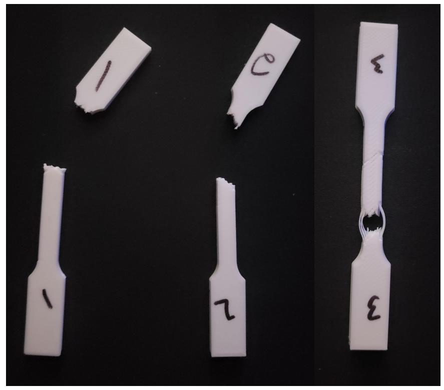

Fig. 5 **All three PETG samples are shown after undergoing the tensile test. The third specimen, labeled with the number 3, is shown to have behaved in a different manner, allowing for a much larger percent elongation than expected.**

Table 9 below represents each of the percent errors for the calculated mechanical properties, Table 8, compared to the published values for each material, Table 7. Strain values were not published and therefore left out of the percent error analysis. Nylon, PLA, and PETG percent error values are derived from the averages in Table 7.

Table 9 **Percent error in mechanical properties of each material, compared to published values.**

Material	Elastic Modulus (%)	Yield Stress (%)	Ultimate Stress (%)	Percent Elongation (%)
1018 Steel	32.8	9.793	42.07	11.4
6061 Aluminum	9.72	20.56	19.77	5.12
110 Copper	28.9	1.476	8.575	5.80
Teflon	39.4	10.39	13.62	9.54
Nylon	38.6	15.13	16.65	57.5
PLA	30.8	0.09410	10.24	40.1
PETG	17.7	3.023	33.68	15.0

We found 1018 steel to have an Elastic modulus of 266 GPa which is 32% greater than the published value of 200 GPa. The ultimate stress of the steel was measured to be 639.3 MPa which is 42.07% greater than the published value 450 MPa (Table 7 - 9). These results are significantly more than the 20% margin for error anticipated in our experimentation. There are many ways to process steel, strain hardening and quenching to name two. Each process significantly alters the microstructure of steel, allowing for large differences in material properties. We do not know how the steel used in our experiment was processed, but it is reasonable to assume that our sample processing has altered our metal and caused the large deviation from published values.

We found 6061 Aluminum to have a yield stress of 262.1 MPa, which is 20.56% smaller than the published value of 330MPa (Table 7 - 9). This is only slightly outside of the 20% margin. As with 1018 steel, material processing may affect the material properties, thus it is reasonable to assume some of the variation of our measured ultimate strength for 6061 aluminum, from the published value, may stem from materials processing.

We found the elastic modulus of 110 copper to be 85.4 GPa, which is 8.9% outside of the 20% acceptable error when comparing to the published value of 120 GPa (Table 7 - 9). Once again, we propose that differences in material processing between our sample and the samples used to determine the published value may be the cause of the deviation of our measured value from the published value.

The biggest issue for the 3D printed plastics was that we do not know any of the printing properties for the supplied specimens, which strongly affect the overall material properties. For example, the present infill, the infill pattern, the printing temperature, and the nozzle size all play significant roles in the mechanical properties of a 3D printed plastic. As such, the range of published values for each of the plastics was very large. In general, the large range of published values instituted a lot of the variation seen in the plastics.

However, there were also issues in the testing. For example, with the PLA we see that percent elongation was off by 40% from published values. One issue with the PLA was the location of the failure. The break happened near the top of the section of the decreased width seen in Fig. 1. In cases 2 and 3, the break actually happened where the sample was thicker which leads to the idea of the presence of internal flaws. This main issue with the location of this break is this is where the extensometer was placed, so when the break occurred, instead of holding steady with the crosshead the extensometer actually shifted so we actually measured decreases in strain at the breaking point which is not correct.

With both the Nylon and the PETG, we see this characteristic behavior of very elasticstat materials that actually break in strands instead of as a whole. Again, this could be influenced by the way that the samples were printed. But the issue is that there is a lot of internal breaking and the failure happens over a long period of time so it is difficult to isolate a failure point.

Conclusion

Determining the plastics and metals mechanical properties through tensile testing provided results that were mostly consistent with researched published values by comparing these values to within ± 20%. The values that are outside of this ± 20% threshold likely stem from errors with the chosen published values not corresponding to the proper material processing method for the provided specimens. Each plastic data also had an extremely large range of published values that yielded some of these large variations in choosing values that do not correspond to the exact processing method of the provided specimens. The metals data appears to follow the expected results (Fig. A.1 - A.3) with some variation in a few of the mechanical properties.

Through the use of the chi-squared confidence interval, we were able to determine a range of standard deviation for all properties at each test state. With the range of standard deviations, a conservative range of means could be calculated using ± 2 standard deviations. According to the normal distribution theory, we know that 95.5% of all the data, in our case property values, fall within two standard deviations of the mean. Thus, for each relevant state of the sample, we can say with 95% confidence that the listed intervals (Tables 4-6) capture the true expected value of each respective property for 95.5% of all cases. With this knowledge, we can conclude that damaging the glass changes its properties significantly by decreasing max loading capacity, flexural strength, and elastic modulus. In addition, the directionality of the damage matters. We observed that the horizontally damaged glass was weaker than the vertically damaged glass.

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Appendix A

The following figures, Fig. A.1 - Fig. A.12, are stress-strain curves for all of the specimens. The title of each plot signifies the specimen material and in some cases the sequence at which one was tested. Fig. A.13- A.14 shows the force vs displacement curve of the 4-point bending flexural test.

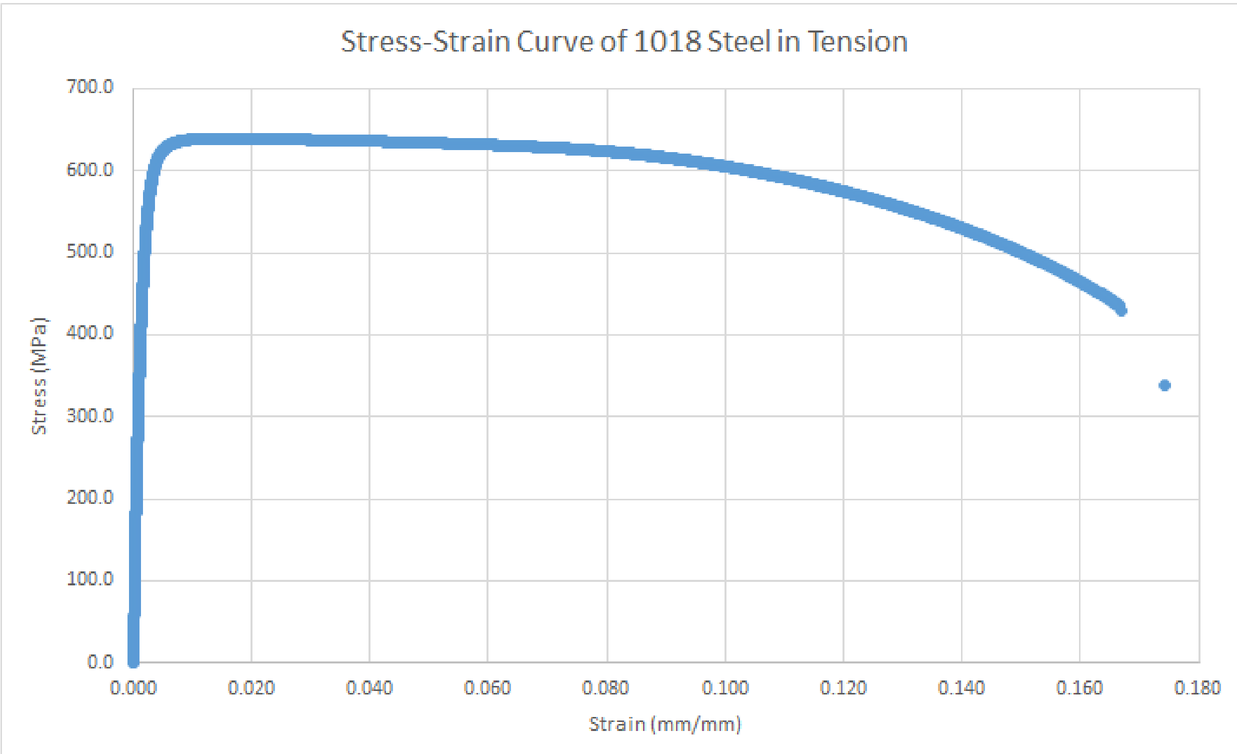


Fig A.1 Tensile testing stress-strain curves for 1018 Steel in Tension

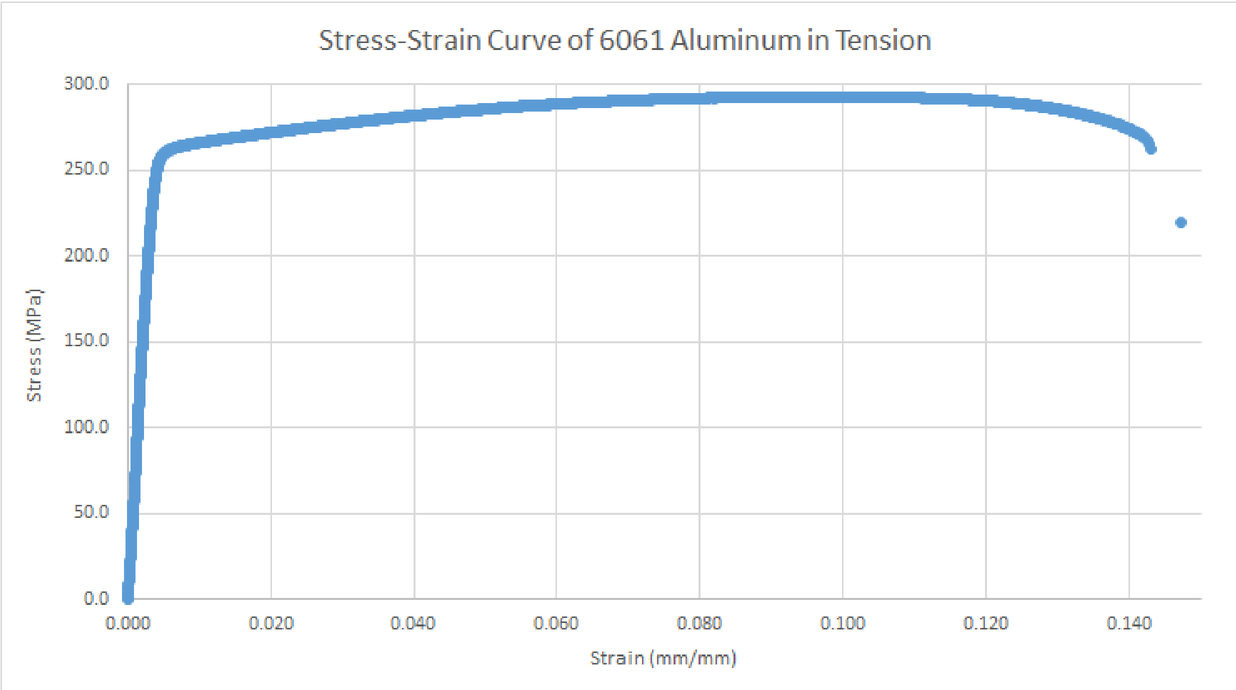


Fig A.2 Tensile testing stress-strain curves for 6061 Aluminum in Tension

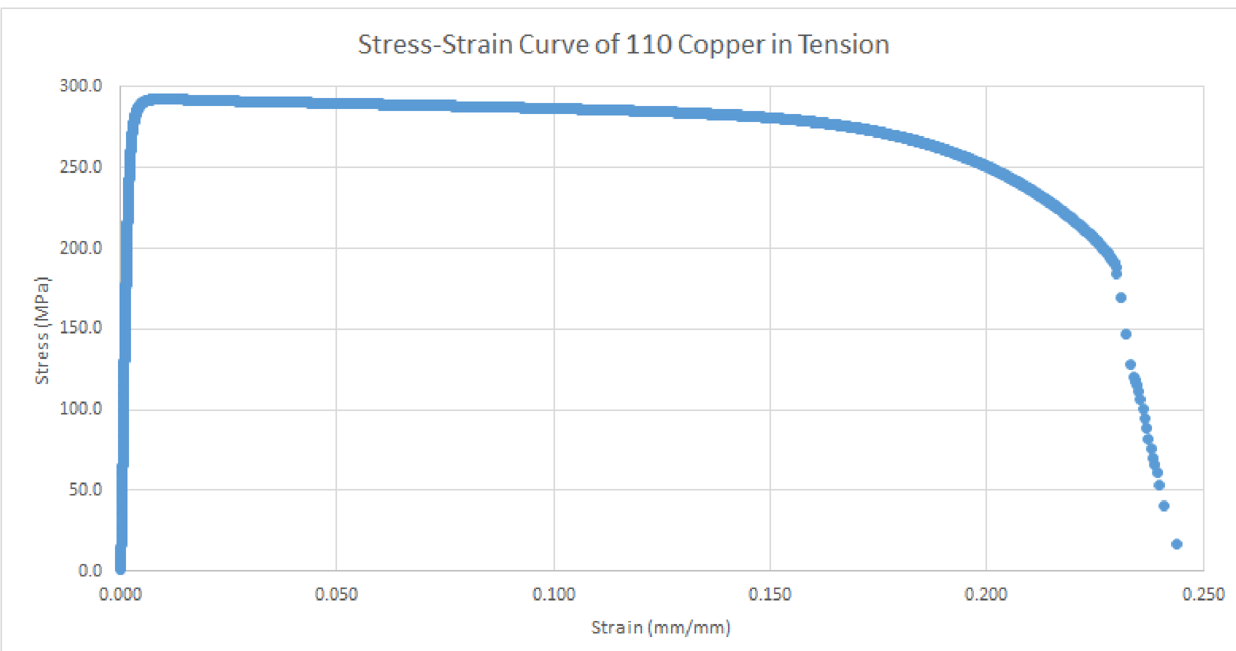


Fig A.3 Tensile testing stress-strain curves for 110 Copper in Tension

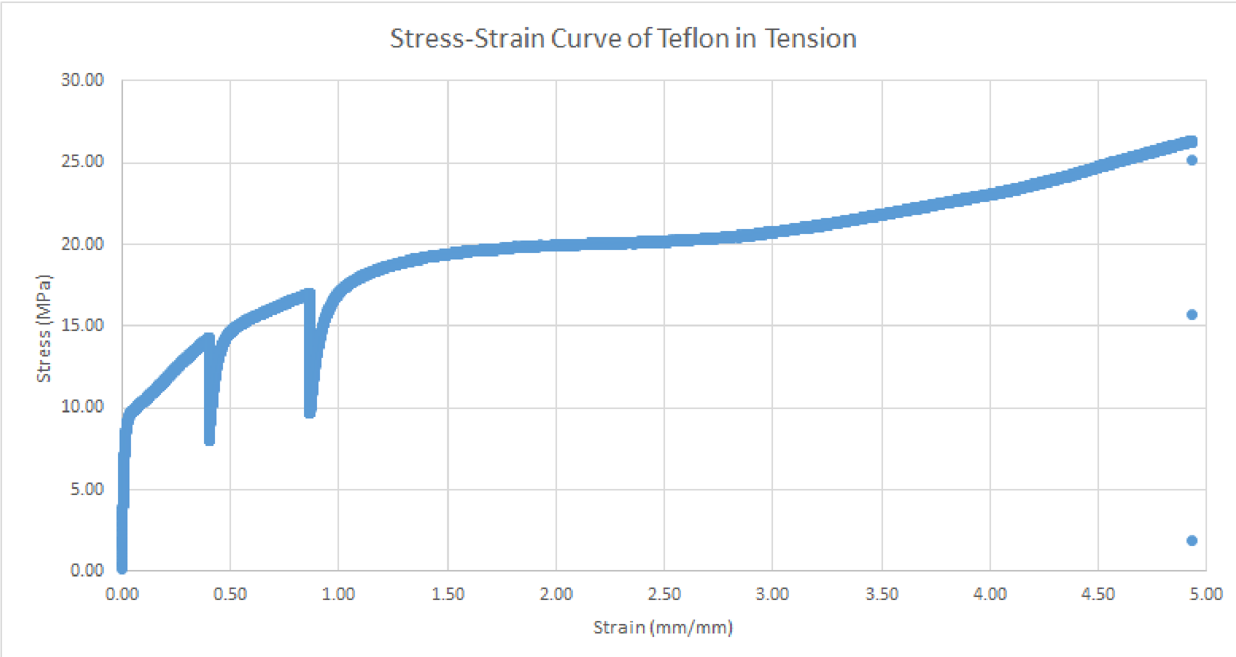


Fig A.4 Tensile testing stress-strain curves for Teflon in Tension

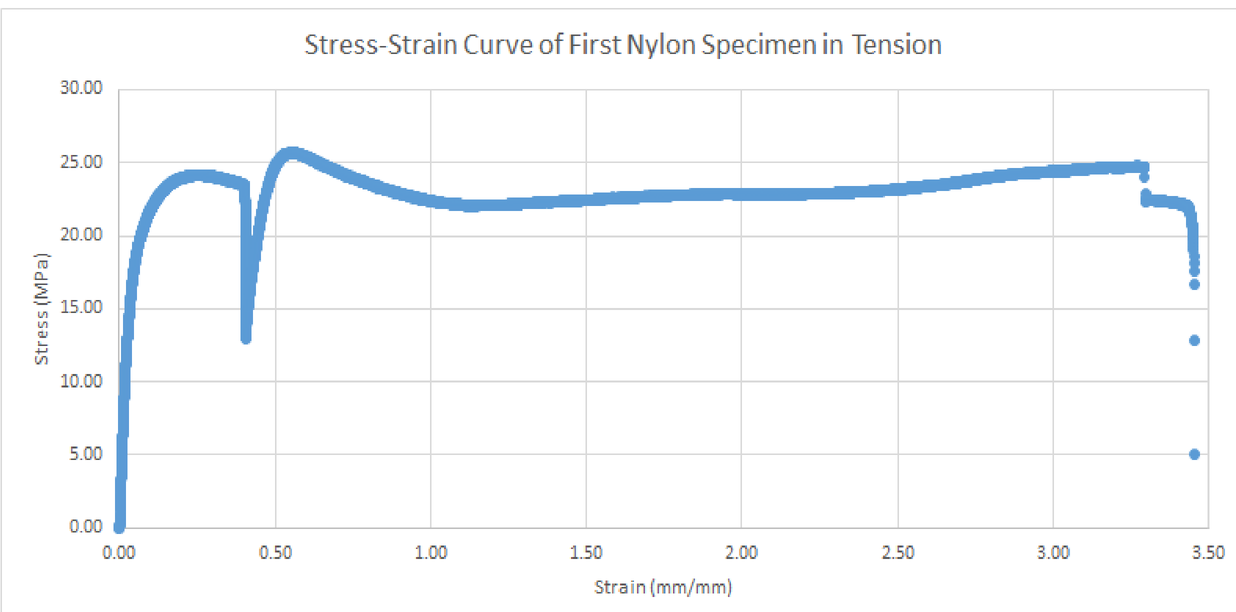


Fig A.5 Tensile testing stress-strain curves for Nylon (1) in Tension

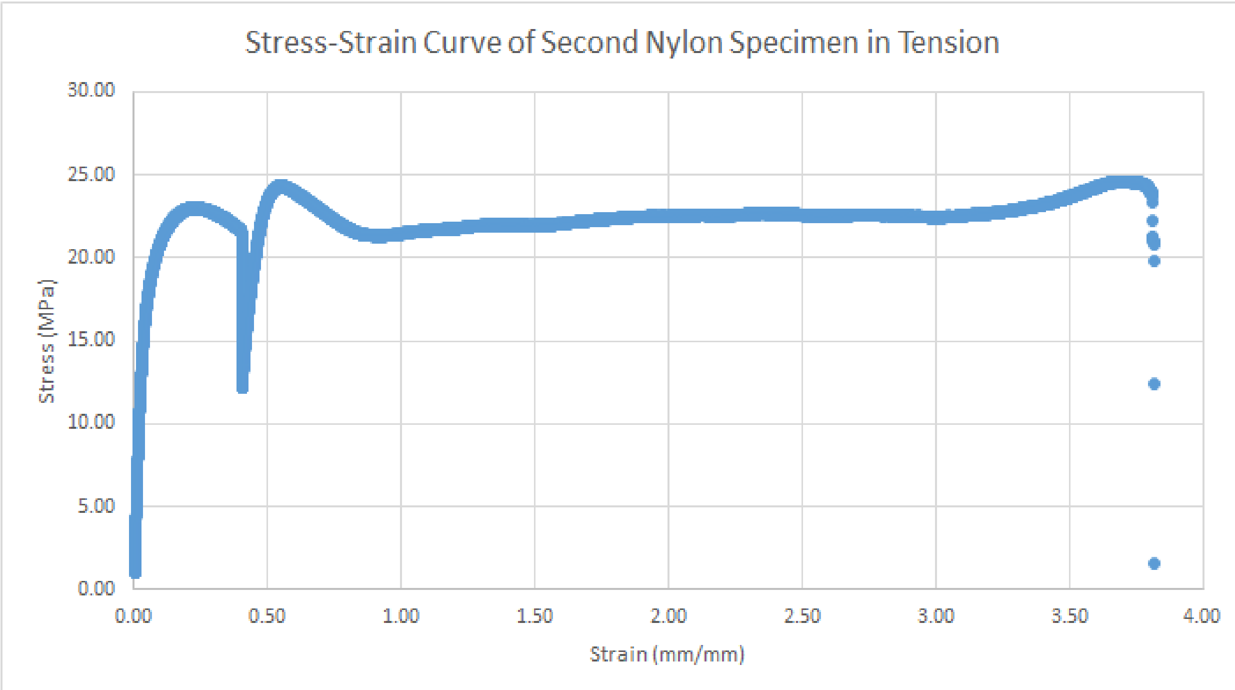


Fig A.6 Tensile testing stress-strain curves for Nylon (2) in Tension

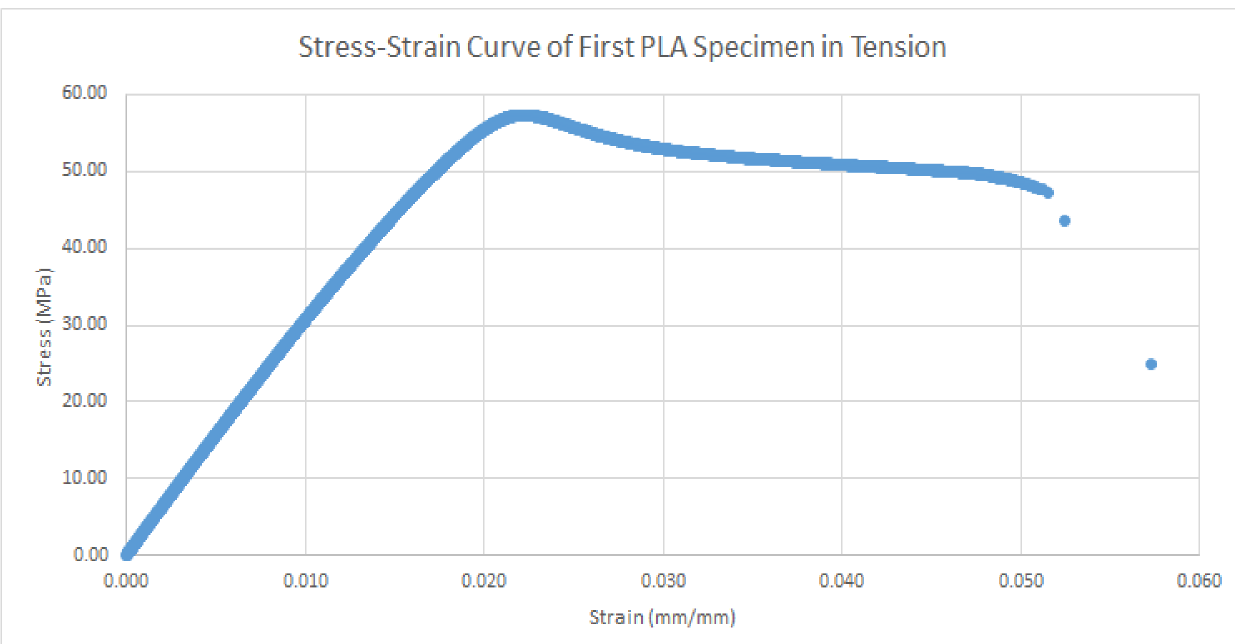


Fig A.7 Tensile testing stress-strain curves for PLA (1) in Tension

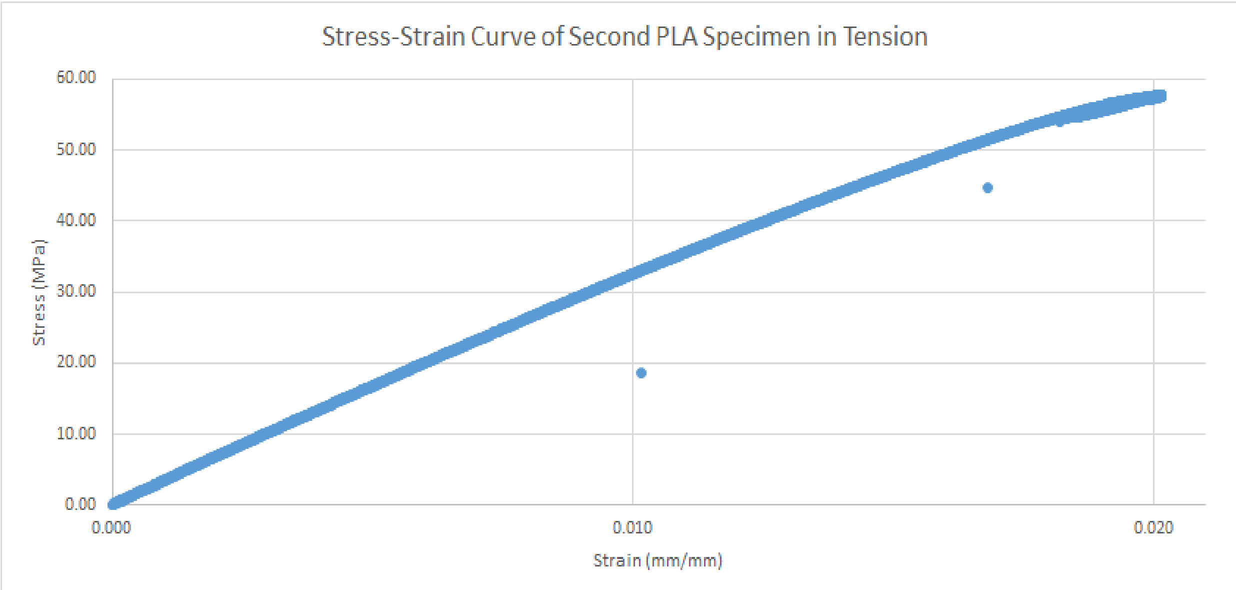


Fig A.8 Tensile testing stress-strain curves for PLA (2) in Tension

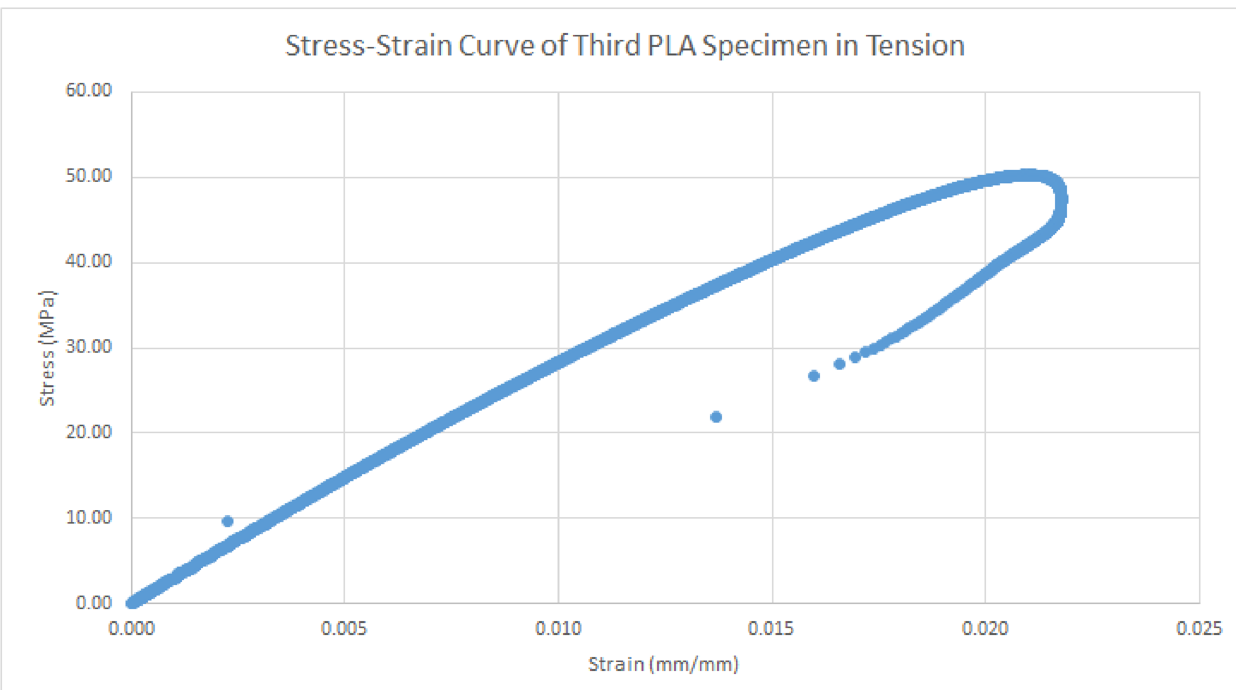


Fig A.9 Tensile testing stress-strain curves for PLA (3) in Tension

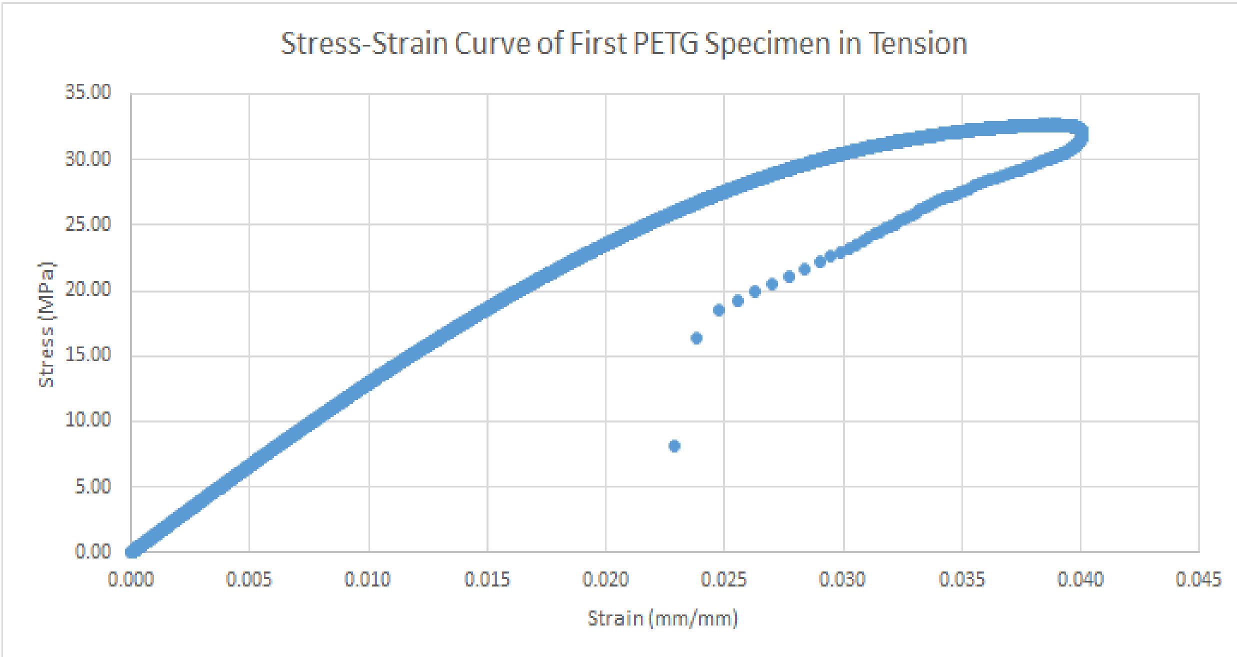


Fig A.10 Tensile testing stress-strain curves for PETG (1) in Tension

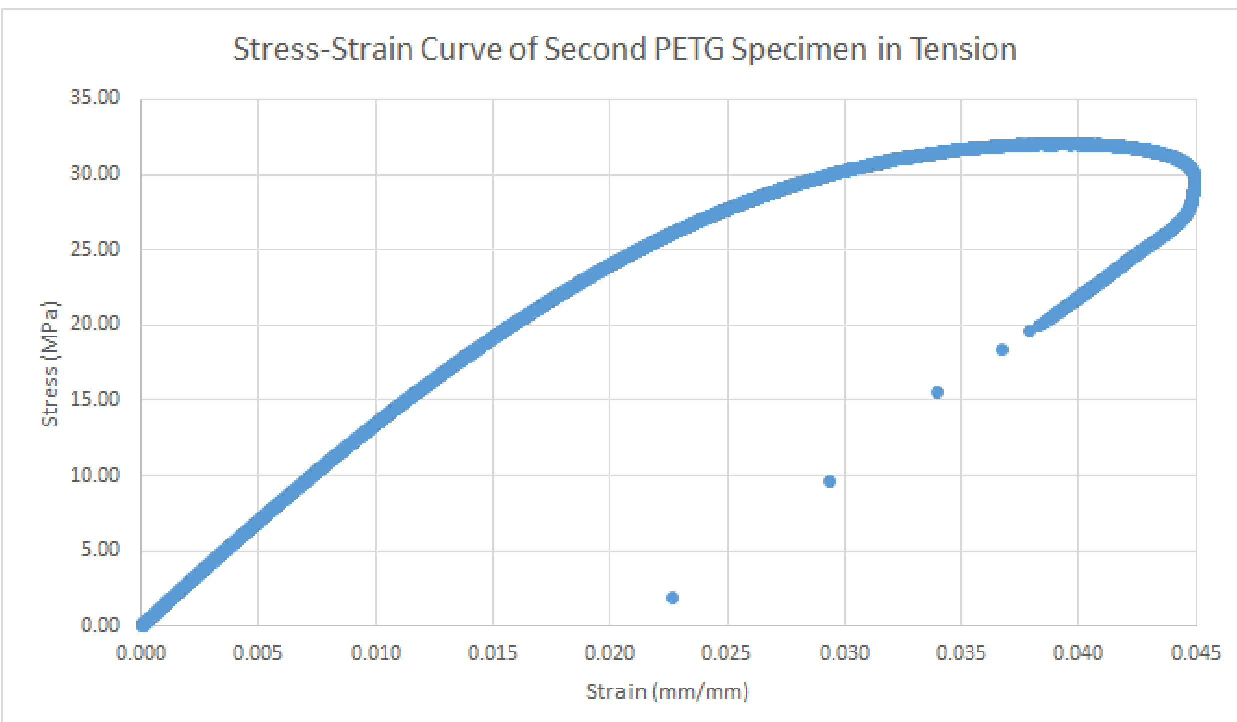


Fig A.11 Tensile testing stress-strain curves for PETG (2) in Tension

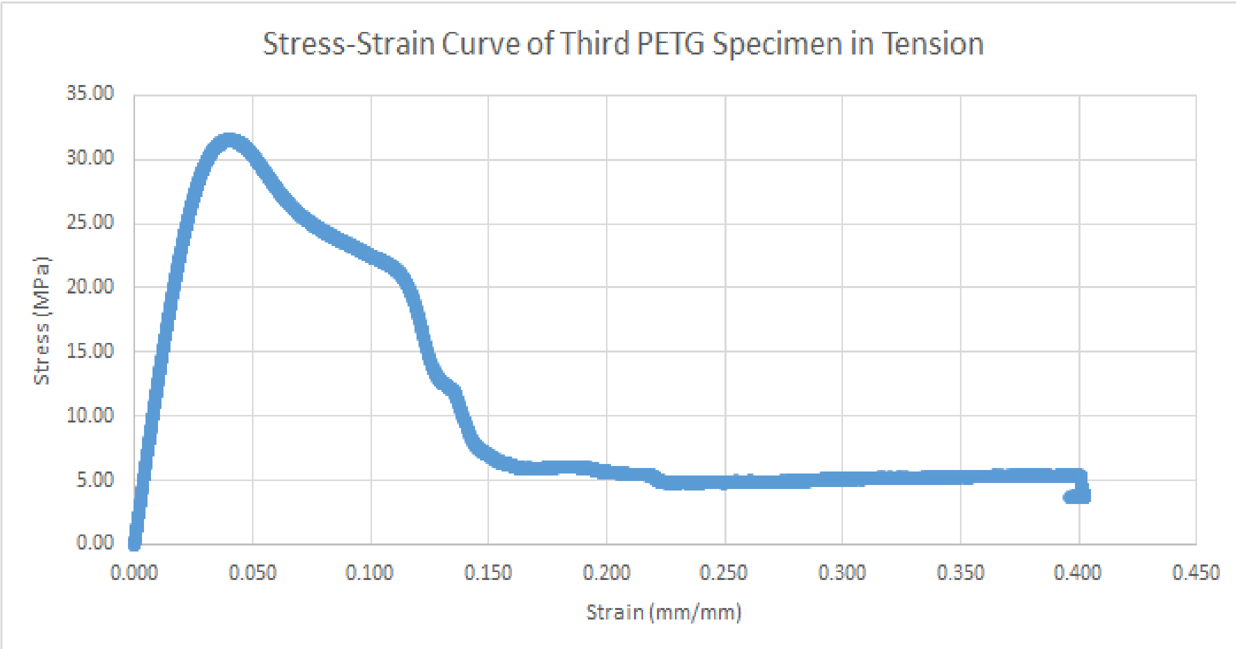


Fig A.12 Tensile testing stress-strain curves for PETG (3) in Tension

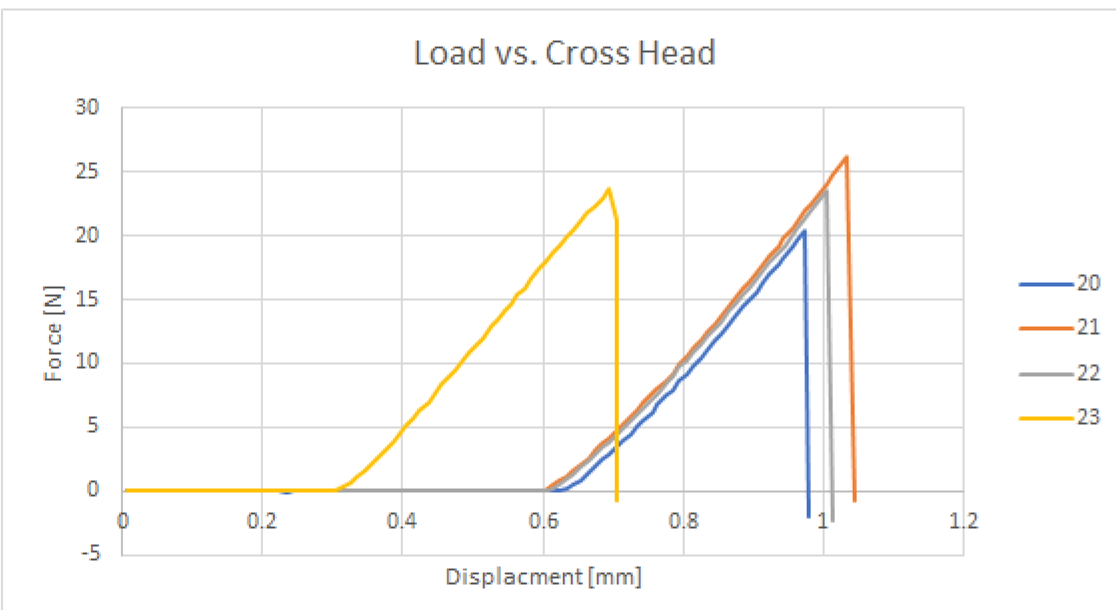


Fig A.13 4 Point bending for the horizontally damaged glass.

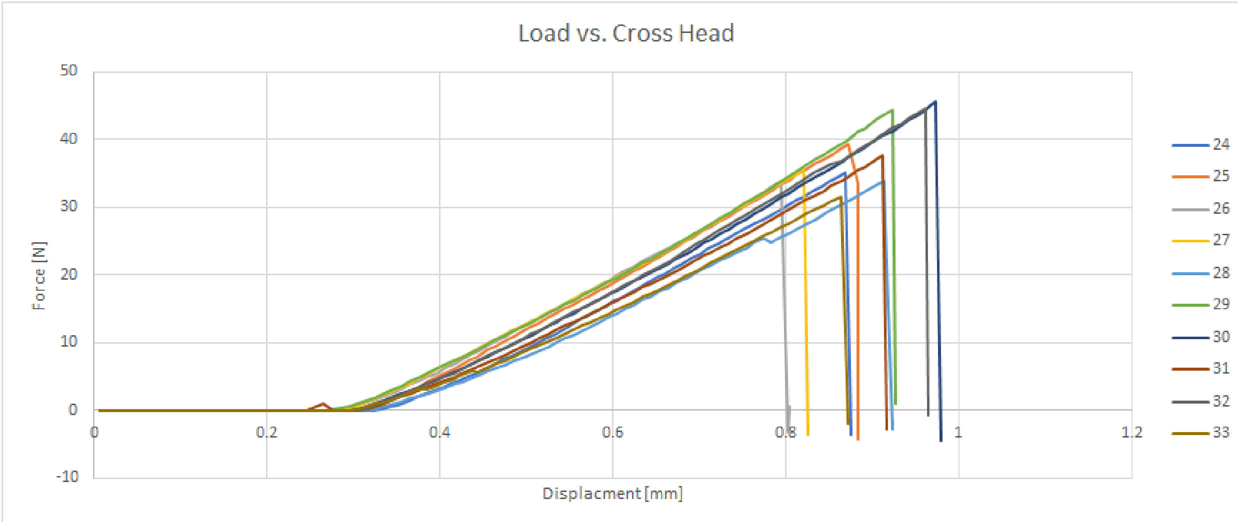


Fig A.14 4 Point bending for the vertically damaged glass.

Appendix B

Fig. B.1 below depicts a free body diagram of the flexure test on the glass slide with labeled distances between the applied forces.

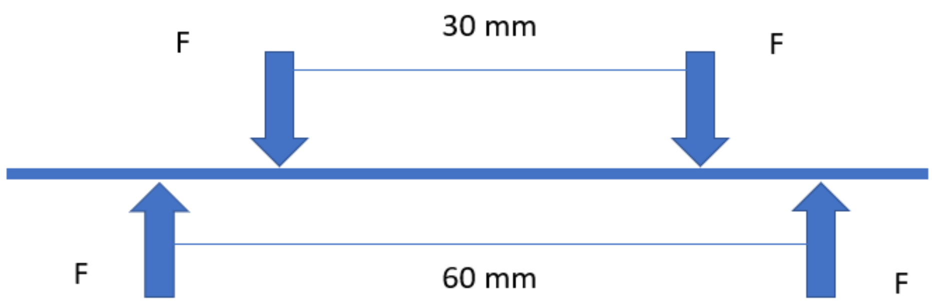


Fig. B.1 Free body diagram of the flexure test

The following figures, Fig. B.2 - B.4, represent relevant sample calculations for each of the calculated mechanical properties.

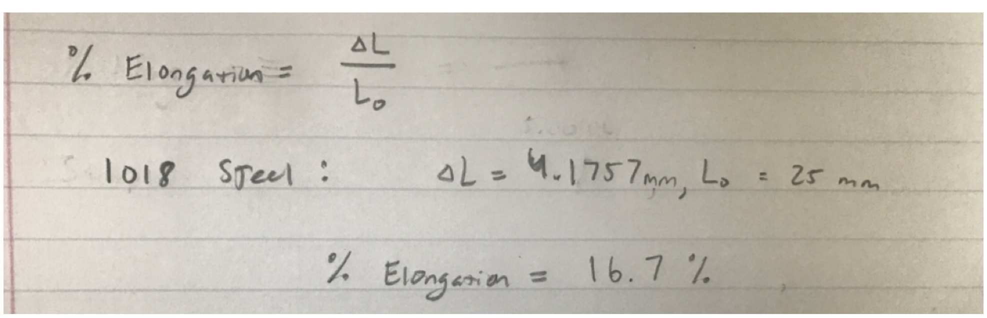
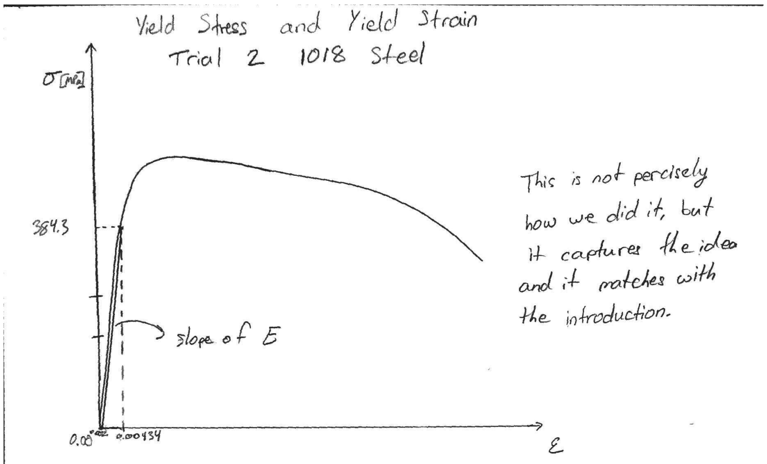


Fig. B.2. Sample calculations for the percent elongation in the tensile test.



$E = 266$ GPa

from 2% rule as demonstrated

$\sigma_y = 384.3$ MPa

$\varepsilon_y = 0.00434$

Fig. B.3 Sample calculations/procedure for yield stress and strain in the tensile test.

Ultimate Flexural strength:

Trial 34 unannealed glass

$$\sigma_{fs} = \frac{3 P_u L}{4bd^2} = \frac{3(42.48)(0.6)}{4(0.0249)(0.00104)^2}$$

$$\sigma_{fs} = \boxed{709.8 \text{ MPa}}$$

Max in excel

$P_u = P_{max} = 42.48$ N

$L = 0.6$ m

$b = 0.02490$ m

$d = 0.00104$ m

$D =$ final displacement − initial noise

$D = 0.64$ m

$$\epsilon_{fs} = 4.36 \frac{Dd}{L^2} = 4.36 \frac{0.64(0.00104)}{0.6^2} = \boxed{0.008}$$

$$E = \frac{709.8(10)^6 \text{ Pa}}{0.008} = \boxed{88.34 \text{ GPa}}$$

Fig. B.4 Sample calculations for flexure strength, strain, and elastic modulus for four-point bending.