Stress-Strain Relationship of Different Materials

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***Abstract*— The objective of this lab is to introduce students to tensile and compression tests using the Instron machine. While conducting these tests students will better understand the different stress-strain relationships for different materials such as metals, plastics, ceramics, and composites. Another goal of this lab was to find the identity of an unknown metal sample by finding properties of the sample through tensile tests. The unknown metal was found to have modulus of elasticity of 62 GPa, yield strength of 246 MPa, ultimate strength of 342 MPa, breaking strength of 281 MPa, and density of 2.6 g/cm^3. Cross-referencing those values with known mechanical properties of different metals, the unknown metal was found to be 6061 Aluminum.**

***Index Terms*—** *Instron, Strain, Stress, Tensile Test*

I. Introduction

THE purpose of this lab is to explore the *stress strain* relationship of materials by conducting tensile or compression tests on different material samples. Three dog-bone samples will be used for the tensile tests: carbon fiber, nylon, and an unknown metal. For the compression test, a Plaster of Paris sample will be used.

In this lab, an Intron testing system was used to conduct all tests. The Instron system allows the user to accurately conduct tensile and compression tests by clamping a material sample onto the machine and inputting either a compression or an extension rate. The machine then extends or compresses the sample at the desired rate, all the while measuring the stress and strain experienced by the sample. From the data gathered through these tests, certain readings will be emphasized. The data will characterize the material's *yield strength*, *ultimate strength*, *breaking strength*, *modulus of elasticity*, and *toughness*. Note that yield stress refers to the stress value at which the material enters plastic deformation regime, ultimate stress refers to the highest stress value experienced by the material after which the material is compromised, breaking strength relates to the stress level at which the material breaks, modulus of elasticity is the slope of the stress-strain graph during linear regime, and toughness is the area under the stress-strain curve.

The goal of the lab is to compare the stress-strain relationship for different types of material to better understand how and why they fail. It is important to be able to get good readings regarding the critical stress values mentioned in the previous paragraph. Therefore, the lab will also include finding out the identity of the unknown metal sample by cross-referencing its properties.

II. Procedure

Required Materials for Lab

This lab will require: dog bone samples of uniaxial carbon fiber composite, nylon 6-6 and unknown metal, cylindrical sample of Plaster of Paris, Instron testing system, computer with the required VI or Instron Software, an extensometer, calipers, a micrometer, and a commercial scale. All of the above supplies will be provided in lab.

Required Sample Measurements

In order to start the lab, all samples need to be measured. The dog bone sample of unknown metal is measured first. Since the identity of the metal needs to be assessed based on the its properties found through the tensile test, accurate data is trivial for the success of the procedure. Therefore, the width and thickness of the sample was measured 10 times each to ensure a more accurate reading. Width measurements were made with calipers and thickness measurements used a micrometer. The sample was then weighed using a commercial scale. Horizontal lines were then drawn on the sample at 2'' apart from each other (this length will be compared to the distance between marks after the test is run).

The other two dog bone samples were then measured. The width and thickness of both samples were taken using a caliper and micrometer respectively. Then, the length between the grips in each sample were measured using a ruler. Horizontal marks were then drawn 2'' apart on the nylon 6-6 sample, similar to the unknown metal markings. Lastly, the height and the diameter of the Plaster of Paris sample were taken, both using calipers.

Loading Samples onto Machine

Samples were then loaded onto the Instron machine by the TAs.

The first test run was the compression test on the Plaster of Paris. Sample was loaded onto machine that was programmed to run a compression test at a rate of 2 mm/min. The test was run until the sample had significant fractures.

The next test was a tensile test on the unknown metal sample. The sample was loaded onto the machine programmed to run a tensile test at a rate of 7 mm/min. The test ran until the sample failed.

Then, a tensile test was conducted on the carbon fiber composite. The machine was programmed to run at an extension rate of 7 mm/min and the test ran until the composite failed. Finally, a tensile test was conducted on the nylon 6-6 sample. The machine was programmed to run at an extension rate of 7 mm/min for the first minute, after that extension rate was increased to 70 mm/min. The test was conducted until the sample failed.

III. Results

The first test conducted was the compression test with the Plaster of Paris sample. The test was conducted at a compressive rate of 2 mm/min. The test lasted a little over 160 seconds before the sample displayed significant fractures. The sample did not deform significantly before fracturing (Fig. 1). Once it did fracture all the fault lines were mostly vertical, as expected from a ceramic (Fig. 2).

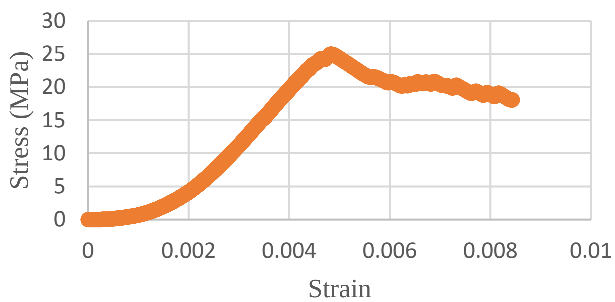

Fig. 1: Stress-strain plot for the compression test on Plaster of Paris sample. The strain readings during the test were very small, with a max of 0.008.

Fig. 2: Plaster of Paris sample after failure. Vertical cracks can be observed running through the sample. Sample also presents brittle characteristics.

The next test was a tensile test on the unknown metal (dog bone #4) sample. The test was conducted at an extension rate of 7 mm/min and it lasted a little under 2 minutes before the sample failed. The metal sample experienced significant deformation before reaching its break point. The 2'' marks previously made were 2.4'' apart after the test was complete. The sample started necking at a stress value of 342 MPa, eventually breaking at a 45° angled plane (Figs. 3 & 4).

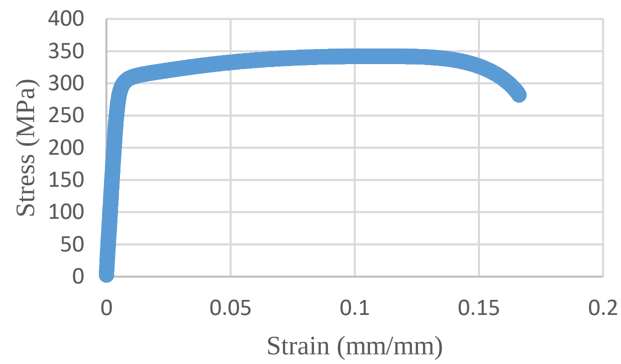

Fig. 3: Stress-strain plot for unknown metal sample.

Fig. 4: Unknown metal sample after failure. The sample failed in a plane angled at 45°

A tensile test was then conducted on the carbon fiber composite sample. The test was conducted at an extension rate of 7 mm/min over a 38 second period when the composite completely failed. The sample did not undergo any significant deformation before failing. However, the sample suffered a local failure a few seconds before it completely failed (Fig. 5). This sample failed along the vertical into individual fibers (Fig. 6).

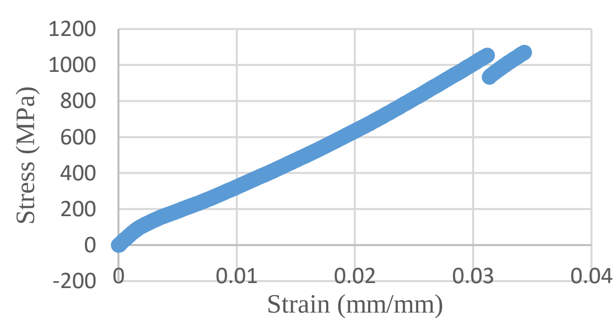

Fig. 5: Stress-strain plot for carbon fiber composite. The stress levels are significantly higher than the ones for the other samples.

Fig. 6: Carbon fiber sample after failure. Sample failed in vertical lines along the borders of separate fibers. Single fibers can be seen after failure.

The last sample tested was the nylon 6-6 dog bone test was conducted at an extension rate of 7 mm/min for the first minute and then the rate was increased to 70 mm/min in order to break the sample in a timely manner. The sample experienced very significant deformations before ultimately breaking (Fig. 7). The sample started necking at a stress value of about 10 MPa and continued to deform until failure (Fig. 8).

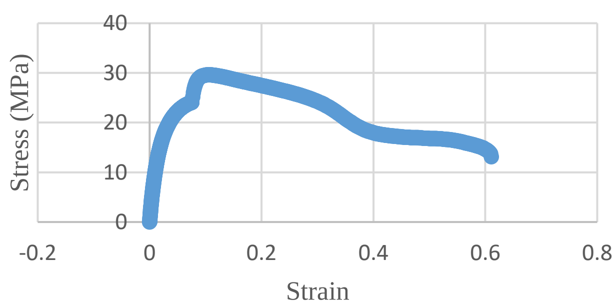

Fig. 7: Stress-strain plot for nylon 6-6 sample. The plot shows strain values that are significantly larger than the ones for the other samples with a max value of 0.6.

Fig. 8: Nylon sample after failure. The sample was stretched significantly more than all the other materials, necking can be observed.

Measurements of strengths (yield, ultimate, and breaking), toughness, percent elongation, and modulus of elasticity for each sample are presented below for reference during the discussion section (Table I).

TABLE I
UNITS FOR MAGNETIC PROPERTIES

	Unknown Metal	**Carbon Fiber**	**Nylon 6-6**	**Units**
Modulus of Elasticity	62.44	60.32	1.40	GPa
Yield Strength	246.14	1054.43	9.98	MPa
Ultimate Strength	342.11	1069.38	29.63	MPa
Breaking Strength	281.85	1069.38	13.48	MPa
Percent Elongation	16.61	3.43	61.06	%
Toughness	23.59	18.35	4.15	MJ/m^3

IV. Discussion

This lab illustrated the various relationships between stress and strain for different materials. In particular, it showed some of the primary differences between ceramics, plastics, metals, and composites. These different types of materials have very different properties when it comes to strength, stiffness, and ductility (Fig. 9).

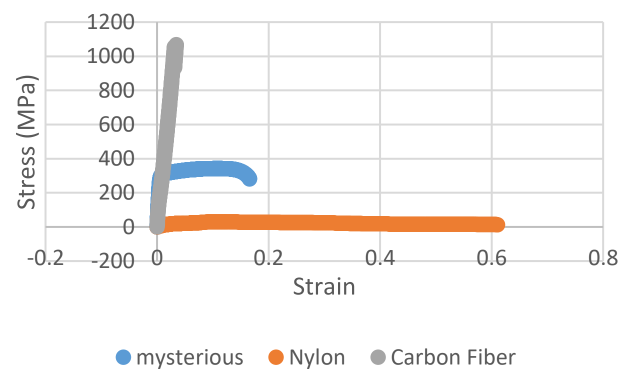

Fig. 9: Stress-strain plot of all three dog bone samples together. Notice the apparent differences in stress-strain relationship between the different samples.

The lab started dealing with a ceramic sample, the Plaster of Paris. With this sample, a compression test was conducted instead of a tensile test. That was done specifically because of the properties of ceramics. These materials are strong under compression but are significantly weaker under tension, thus a tensile test wouldn't be applicable in this case. During the compression test, the sample barely experienced any strain because it is very stiff. It was also found that the material was brittle since the vertical cracks created by the test quickly caused the sample to start crumbling.

One of the goals of this lab was to also find the identity of an unknown metal sample. Through the tensile test conducted on the sample, a few properties of the material stood out. The modulus of elasticity found through the test data was around 62 GPa with an uncertainty of 862 MPa. That put the modulus of elasticity at range of around 61MPa to around 63 MPa. Another property worth taking a look at is the yield strength. The unknown sample had a yield strength of 246 MPa. That leaves it with a yield strength range between 226 MPa and 266 MPa. Next, the ultimate strength was found to be 342 MPa with an uncertainty of 20 MPa giving it a range between 322 MPa and 362 MPa. Lastly, one more property was verified to confirm the identity of the metal at hand. Given the geometry of the sample, a 3D model of the sample was created to calculate its volume (Fig. 10). With the newly found volume and the measured mass of the sample, the density of the material was calculated. The material density found was 2.6 g/cm^3. Cross referencing all these values with known properties of different metals, the unknown sample was found to be 6061 Aluminum.

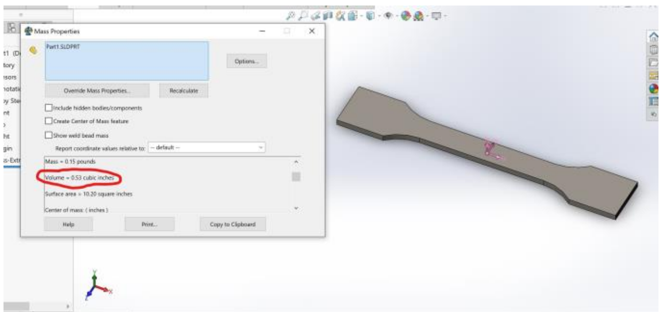

Fig. 10: Screenshot of CAD model of dog bone sample with volume calculated.

The last couple tests conducted were more tensile tests, now on a carbon fiber sample and a nylon sample. The carbon fiber was found to handle significantly more stress than any of the previous materials tested. The sample had a thickness of 0.0144'' and was still able to withstand a load of 8 kN, which is about 2/3 the max load the unknown metal sample was able to withstand while only having about 1/5 the cross-sectional area of that sample. The composite sample also did not experience much strain before it failed due to its stiff nature. This sample failed in a very different manner than all the other samples (Fig. 6). The carbon fiber failed that way because it is a composite, its structural integrity was compromised by the test which ripped the separate fibers apart from each other. The last test was conducted on the nylon sample representing plastics. This was the longest test, taking about 2 minutes to break the sample. It's worth noting that the test was conducted at the standard 7 mm/min rate at which the other two tensile tests were conducted only for the first minute. After that, the rate was increased to 10 times that. This illustrates how much more ductile this plastic material is compared to the metal and composite samples. The nylon had the largest percent elongation by far at 61% (compared to the second largest value of 16% for the metal sample).

V. Conclusion

This lab illustrated the different stress-strain relationships for different types materials (metals, ceramics, plastics, and composites). It showed that ceramics are very stiff and brittle, while metals were more ductile. Carbon fiber was found to be the strongest material of the ones tested and nylon was found to be the most ductile. The unknown metal was 6061 Aluminum.

Appendix

TABLE II
Uncertainty Measurements

Symbol	Description	Uncertainty
U_b	Uncertainty in calipers	0.005 in
U_E	Uncertainty in Modulus of Elasticity	896.86 MPa
U_h	Uncertainty in micrometer	0.0005 in
U_L	Uncertainty in ruler	0.5 mm
U_σ	Uncertainty in Stress	
U_ε	Uncertainty in Strain	0.5 %
U_A	Uncertainty in Area	6.8E-4
U_F	Uncertainty in Load	0.5 %

A. *Uncertainty in Stress*

The definition of stress is:

$$\sigma = \frac{F}{A} \tag{1}$$

The uncertainty in stress can then be calculated using the equation

$$U_\sigma = \sqrt{\left(\frac{\partial\sigma}{\partial F}\right)^2 U_F^2 + \left(\frac{\partial\sigma}{\partial A}\right)^2 U_A^2} \tag{2}$$

By evaluating the partial derivatives, we get

$$U_\sigma = \sqrt{\left(\frac{1}{A}\right)^2 U_F^2 + \left(\frac{-F}{A^2}\right)^2 U_A^2} \tag{3}$$

Where U_F is provided by the manufacturer. U_A can be calculated by using the equation

$$A = wt \tag{4}$$

Where w is the width and t is the thickness. Then, the uncertainty in A can be calculated using the equation

$$U_A = \sqrt{\left(\frac{\partial A}{\partial w}\right)^2 U_w^2 + \left(\frac{\partial A}{\partial t}\right)^2 U_t^2} \tag{5}$$

Where U_w is the uncertainty of the calipers and U_t is the uncertainty in the micrometer used, both provided in Table II.

B. *Uncertainty in Strain*

This value is usually obtained from the extensometer manual. Usually, the error in strain should not exceed ± 0.5% ($U_\varepsilon = \pm 0.5\%$).

C. Uncertainty in Elastic Modulus (Monte Carlo Simulations)

A Monte Carlo simulation was done to calculate the uncertainty in the Elastic Modulus values acquired during lab. Five strain values and their corresponding stress values were inputted into the spreadsheet along with their respective uncertainties. The result can be seen in below (Fig. 11). The uncertainty of modulus of elasticity was $U_E = 896.86\ MPa$. I'm not sure about this value, it seems a little high given the nature of the stress values. I believe I might have not completely understood which stress and strain values to use as inputs.

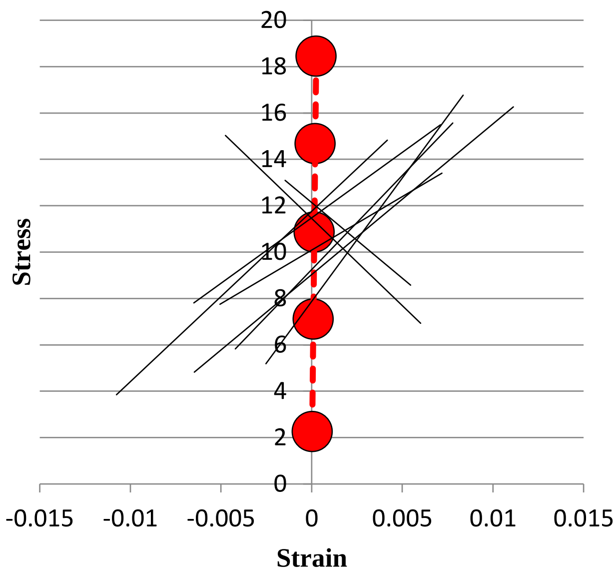

Fig. 11: Monte Carlo Simulation plot calculating the uncertainty in elastic modulus.

References

[1] N. Arakere,"Lab 3 Lecture Notes", WEIM 1064, 2019.

[2] G. Subhash and S. Ridgeway, Mechanics of Materials Laboratory Course. Morgan & Claypool Publishers, 2018, pp. 87-101.