AE2610 Introduction to Experimental Methods in Aerospace
TENSILE TESTING OF MATERIALS AND STRAIN GAUGES

Objectives

This experiment is intended to explore the stress-strain behavior of ductile metals subject to tensile loads and to introduce transducers that are used in mechanical testing. The tensile test is the most basic structural test of a material and is used to characterize its response to structural loads. The characterization data obtained from a tensile test is used directly for structural analysis and design. This experiment requires the use of several mechanical transducers that are used to measure the elongation of the specimen and the force applied by the load frame. As part of this lab, you will also be exposed to the physical principles that are used in these devices.

Safety

Wear close-toed shoes in the lab to avoid injuries to your feet if you drop lab equipment, and the eye protection glasses supplied to you. This experiment also involves the use of chemical adhesives and solvents; so make sure to wash your hands after performing the lab.

Background

Stress and Strain

A tensile test is designed to experimentally characterize the relationship between stress and strain. Stress and strain are fundamental concepts in the study of mechanics of materials and we briefly summarize them here.

Stress is a measure of the intensity of a force exerted over an area. In this test, we will measure axial or normal stress. Consider a prismatic bar with a cross-sectional area A_0, loaded at both its ends with opposing forces with magnitude P, the stress in the bar is given by:

$$\sigma = P/A_0 \qquad (1)$$

where σ is the ***normal stress***. Stress has units of force per unit area, which in SI units are pascals [Pa] and in English units are pounds per square inch [psi]. Since the magnitude of stress can be large, it is common to use units of megapascals [MPa] and ksi (i.e., thousands of psi). Note that during the tensile test, the cross-sectional area of the specimen will change; however, we will continue to normalize the force by the initial area. This is usually referred to as ***engineering stress***.

Strain is a measure of the elongation of the structure per unit length. Given a prismatic bar of initial length L_0 and the ***elongation*** of the bar, δ, under load, the ***normal strain*** is given by:

$$\varepsilon = \delta/L_0 \qquad\qquad (2)$$

Since both δ and L_0 have dimensions of length, strain is a dimensionless quantity. The length of the bar will change during the test, especially at high loads, but we will always use the initial bar length.

Tensile Testing Specimens: In this experiment, you will measure the strain in a bar using a strain gauge, and the elongation of the bar under load using an extensometer. These measurement devices are described in a later section.

You will use aluminum that has been machined into a typical material specimen shape, specifically, a dog bone specimen, as shown in Figure 1. The shape of the specimen is designed to produce a uniform tensile stress and tensile strain in the gauge region. If the specimen were to fail outside this region, in either the grip or shoulder areas, then the results from the test could not be used because stress and strain in these regions is not uniform. The dog bone specimen is designed so that we can fasten the test machine to the grips at either end of the specimen to apply an axial load.

Stress-Strain Diagrams and Material Models: In this experiment, you will generate experimental stress-strain diagrams. A sketch of a stress-strain diagram for a generic ductile metal is shown in Figure 2. As engineers, we use mathematical approximations that are designed to model the measured stress-strain response. Thus we can explore how closely these mathematical models match the measured stress-strain diagram.

Material models can be classified as either **elastic** or **inelastic**. An elastic response is one in which the loads on the structure are low enough so that no permanent deformation or damage to the specimen occurs. Once the loads are removed, the specimen returns to its original shape, and the experiment could be repeated to produce the same stress-strain response. An inelastic response is one in which permanent deformation occurs, so that when the specimen is unloaded it returns to a different shape than the original specimen.

The simplest mathematical model of an elastic stress-strain response is ***Hooke's Law***. Hooke postulated a linear relationship between stress and strain, written as follows:

$$\sigma = E\varepsilon \qquad\qquad (3)$$

Here the proportionality constant, E, is called ***Young's modulus*** or the elastic modulus. Note that since the strain is dimensionless, the Young's modulus has the same units as stress. Hooke's Law is often a good model for the stress-strain relationship when the stress is below a threshold

called the ***proportional limit***, σ_p. Some ductile metals have a clearly defined proportional limit, others do not. Beyond the proportional limit, the material may still exhibit an elastic response but the relationship between stress and strain is nonlinear. Another important point on the stress-strain diagram is the ***yield stress***, σ_y. Above the yield stress, materials exhibit inelastic behavior where permanent inelastic deformation occurs, even when the load is removed. Again, this is a model of the response of a ductile metal, and some metals have a clearly defined yield point while others do not.

In ductile metals, as the specimen enters the yielding regime it undergoes a large elongation without a large increase in stress. The slope of the stress-strain diagram, called the stiffness, is much smaller than before yielding. As the yielding progresses, metals often exhibit strain hardening (also called work hardening) where the stress increases as the specimen elongates. At some stress, called the ***ultimate stress***, σ_u, a neck begins to form in the specimen. In this necking region, the local stress and strain increase beyond the engineering stress and strain normalized by the initial length and area of the specimen. In this region, the stiffness is negative, and the load must be reduced as the specimen elongates further. Finally, the specimen will rupture or fail.

True Stress and Strain: Thus far, we have examined engineering stress and engineering strain, which are force and elongation normalized by the initial geometric properties. In addition, there are also true stress and true strain; they represent the force normalized by the instantaneous area, and the elongation normalized by the instantaneous length.

The true stress and true strain can be evaluated from the engineering quantities under a constant material volume assumption. Assuming a constant volume, such that $A_0 L_0 = AL$, we can find the ratio

$$\frac{A_0}{A} = \frac{L}{L_0} = \frac{L_0 + \delta}{L_0} = 1 + \epsilon$$

By combining the area ratio above with the expression for engineering stress, Eq. (1), the true stress is given by:

$$\sigma_T = \frac{P}{A} = \frac{P}{A_0}\frac{A_0}{A} = \sigma(1 + \varepsilon) \tag{4}$$

Similarly the true strain can be related to the engineering strain,

$$\varepsilon_T = \int_{L_0}^{L} \frac{dL}{L} = \ln\left(\frac{L}{L_0}\right) = \ln(1 + \varepsilon) \tag{5}$$

Note that when the engineering stress and strain are small, $\sigma_T \approx \sigma$ and $\varepsilon_T \approx \varepsilon$.

Within the strain hardening regime, ductile materials often satisfy the strain hardening law:

$$\sigma_T = K\varepsilon_T^n \tag{6}$$

where K is called the **strength coefficient**, and n is called the **strain hardening exponent**. On a logarithmic scale, this strain hardening law becomes linear:

$$\ln\sigma_T = \ln K + n\ln\varepsilon_T. \tag{7}$$

Plotting the logarithm of the true stress and true strain for the entire loading history produces a piecewise linear curve, where the first curve is from the linear elastic regime, i.e.,

$$\ln\sigma_T = \ln E + \ln\varepsilon_T. \tag{8}$$

and the second is from the strain hardening regime. An example of a log-log diagram for true stress and true strain is shown in Figure 3. The y-intercept is ln$K$ and the slope in the strain hardening regime is n.

Tensile Testing Equipment

Load Frame: In this lab, we will use a load frame to apply a tensile load to a coupon of an aluminum alloy. The load frame in our lab is an Instron 5982 (see Figure 4) that is capable of delivering 100 kN of axial force to the specimen for testing purposes. It consists of two columns with a crosshead and a base. The crosshead moves up and down the columns driven by lead screws. The crosshead is attached to a load cell, which measures the force applied to the specimen. The test specimen is fastened between two test fixtures attached through pin joints to the base of the frame and the load cell/crosshead. The pin joints ensure that no moments are transmitted to the test specimen.

The load frame controller can operate in either displacement-control mode or a force control mode. In load control mode, the load frame applies a commanded load and measures the extension. Under displacement control, the controller measures the applied force through the load cell and finds the force required to produce the specified displacement. For this experiment, you will use displacement control to measure the full response of the specimen up to the point of rupture or failure.

Strain Gauge: A strain gauge is a device that is used to measure the strain at the surface of a structure. The gauge consists of a thin conductive metal foil grid pattern that is mounted on a flexible backing (see Figure 5). The backing is then bonded with an adhesive to the test specimen. The strain gauge measurement is determined by the change in resistance of a current passing through the gauge. This change in resistance is proportional to the strain through the gauge factor, S_g, which is provided by the manufacturer. The strain is then measured as:

$$S_g = \frac{1}{\varepsilon} \frac{\Delta R}{R} \Rightarrow \varepsilon = \frac{1}{S_g} \frac{\Delta R}{R}. \qquad (9)$$

where ΔR is the change in resistance (and ε is the strain). The gauge factor for many gauges is about 2, however, each gauge may have a slightly different gauge factor and it is therefore important to note this factor in your notes during the experiment. The ratio of the change in resistance to the initial resistance, $\Delta R/R$, is measured using the Wheatstone bridge circuit. The details of the analysis of this circuit are straightforward but beyond the scope of this lab. In our lab, the resistance of the strain gauge is measured by the Vishay 7000. You will input the gauge factor into the Vishay system which will output the strain directly for later data analysis.

Before beginning the structural test, you will first bond the pre-wired linear strain gauge to the specimen. The quality of the bond between the strain gauge and specimen has a direct impact on the quality of the strain measurements. Achieving a good bond between the strain gauge and the specimen requires careful surface preparation while avoiding contamination. Surfaces that have not been thoroughly cleaned must be treated as if they are contaminated. Touching the strain gauge contaminates it and can lead to poor bond quality. Therefore before bonding the strain gauge to the specimen, the surface of the specimen must be prepared.

Extensometer: The extensometer is a linear variable differential transformer (LVDT) that measures the relative displacement between two points on the specimen. As shown in Figure 6, the LVDT is attached to the specimen using arms that are attached to the body of the extensometer. In the lab, you must measure the initial distance between the attachment points on the specimen.

The LVDT is a transducer that measures the displacement using the principle of induction. The LVDT consists of a central primary coil and two secondary coils wired in sequence within an assembly with a movable internal core. An AC current is passed through the primary coil while the induced current is measured in the secondary coils. The secondary coils are wound in opposite directions on either side of the primary coil. The movable core within the assembly is attached to the object whose displacement is being measured. An AC current in the primary coil induces an AC current in the second coil that depends on the relative displacement of the core. The displacement of the core within the LVDT can be estimated by measuring the output AC signal relative to the input signal. An advantage of the LVDT is that it experiences little wear during use and is very robust. In addition, the LVDT can have a high resolution of the displacement.

Load Cell: A load cell is a transducer that is used to measure force. Most load cells are made from an arrangement of strain gauges on a load carrying material with known material

5

properties. The strain gauges are arranged to reduce the sensitivity of the measurement. In subsequent labs, we will see a load cell used to measure forces on an airfoil in a wind tunnel.

These instruments and transducers for measuring the stress-strain data are connected as shown in Figure 7.

PRELIMINARY

1. Before coming to lab, read the lab report and watch the following online Vishay/Micromeasurements videos about surface preparation and strain gauge bonding.

   - for surface preparation: https://youtu.be/a5n4wHYThCc

   - for strain gauge bonding: https://youtu.be/SjXpF61HRys

   NOTE: the following items must also be turned in at the start of your lab session.

2. Go to www.matweb.com and find the Young's modulus (elastic modulus), tensile strength at yield and tensile strength at ultimate of the following materials. Provide values in both SI and English units.

   - *Aluminum 2024-T3*

   - *Aluminum 7075-T6*

   - *Aluminum 7075-T73*

   - *304 Stainless steel.*

3. From the properties that you found, estimate the force at the yield stress for each material based on the following nominal specimen dimensions: 0.5 in by 0.08 in.

PROCEDURE

Bonding linear strain gauge to test specimen

1. **Surface preparation** requires the following steps:

   i. **Degreasing**: This step removes contaminants from the specimen surface that are either chemical residues or organic contaminants. If possible, it is best to degrease the entire specimen so that contaminants are not reintroduced into the bonding area in subsequent steps.

   ii. **Abrading**: This step is performed to remove any coatings, oxides, or other poorly bonded surface adherents that may result in a poor bond. In addition, this step creates surface texture to which the bond can adhere. In this lab, we use a

wet abrading procedure in which the surface is kept wet with M-prep conditioner A.

iii. **Application of gauge layout lines**: Positioning the strain gauge on the specimen in the correct orientation is extremely important so that we measure the component of strain aligned with the axial direction. The best practice is to mark the surface with a pair of perpendicular crossed lines to indicate the positioning of the gauge. In this lab, we'll use a drafting pencil so that it does not score the surface.

iv. **Conditioning**: Apply conditioner A to and scrub the surface with a cotton tipped applicator until the tip is no longer discolored. The lines indicating the gauge location should still be apparent as a burnished (shinny) line.

v. **Neutralizing**: The last step is to apply a neutralizer to the surface to bring the surface of the specimen back to an optimal pH level.

2. Next, **bond the strain gauge to the surface** by following these steps:

i. **Attach the strain gauge to the tape**: Clean the glass working surface. Carefully extract the strain gauge from the packaging and place it on the working surface with the bonding side down. Be careful not to touch the gauge itself.

ii. **Position the gauge on the specimen**: Attach clear plastic tape to the top surface of the gauge, covering the entire gauge. Lift the tape and the gauge from the glass surface, being careful not to damage the gauge or the wires. Position the gauge on the surface of the specimen using the clear plastic tape. Reposition the gauge if necessary.

iii. **Apply catalyst and bond the gauge**: Lift the tape back to expose the gauge. Apply a thin layer of catalyst to the gauge surface. Wait one minute to allow the catalyst to dry. Apply a drop of adhesive epoxy to the specimen. Fold the tape and gauge back onto the specimen and use your thumb to firmly apply pressure on the gauge for one minute. Wait at least two minutes before removing the tape. Inspect the bond to make sure the gauge is well-bonded to the surface.

iv. **Fasten the wires to the RJ45 connector**: This part of the procedure depends on the gauge manufacturer. Ask your TA for guidance.

Instrument configuration

3. **Determine specimen dimensions and gauge length**: Carefully measure and record the specimen dimensions using a digital caliper in order to determine the gauge cross sectional

area. The specimen gauge length (L_0) corresponds to the initial separation of the extensometer (knife edges). Your TA will help you determine the latter quantity.

4. **Record strain gauge data**: Note and record the gauge factor (S_g), resistance (R), catalog number, and active gauge length from the documentation provided by the strain gauge manufacturer.

5. **Specimen mounting within grips of tensile testing machine**: Select the pre-wired linear strain gauge specimen from your group's batch of prepared test specimens. You will conduct a monotonic tensile test on this specimen. Your TA will guide you as to how the specimens are carefully mounted, aligned and clamped by the grips of the tensile testing machine. Carefully center the specimen with respect to the grips and be very careful to avoid any mechanical interference between the extensometer and the delicate strain gauge lead wires. A brief description of the tensile testing machine will be provided along with an explanation of the input/output test parameters such as the programmed displacement rate, specimen dimensions, and recorded (output) data variables such as force, stress, elongation, and strain.

6. **Configuration of the Wheatstone bridge strain gauge data acquisition system**: The lab will also feature the use of a Vishay model 7000 strain gauge data acquisition system, which is controlled through a software interface called StrainSmart. Your TA will guide you through the circuit configuration process. Among the many features that will be highlighted, you will see how the strain gauge type, resistance, the gauge sensitivity factor, and excitation voltage are set within the software. You will also see how the bridge is balanced and then shunted through the software interface in order to compensate for lead-wire resistance. You will then follow the StrainSmart tutorial to configure your linear strain gauge to the Vishay 7000 data acquisition system.

Tensile test procedures

You will be using two specimens: one with both a strain gauge and an extensometer, the other with only the extensometer. The first test measures the full stress-strain response, while the second test examines elastic versus inelastic behavior.

7. **Strain gauge and extensometer test**: Mechanically load the tensile test specimen containing the linear strain gauge as specified in Table 1. Continuous load and strain/displacement data will be acquired using the system load cell, strain gauge, and extensometer. Strain vs. time files acquired by the Vishay 7000 and force-displacement records acquired by the tensile testing machine should be saved at the conclusion of test. The test specimen will be monotonically loaded to failure. Observe the specimen carefully and try to note the peak load achieved during the test. Record this value. Try to see if you

can visually detect at which point the specimen begins to neck. In this test, leave the extensometer mounted to the specimen all the way up to the point of failure.

8. **Measure the necked region**: Remove the fractured tensile test specimen from the grips. Measure the cross-section dimensions of the necked region of the specimen and the region adjacent to the final fracture that undergoes uniform deformation. Your TA should provide you with digital calipers to make accurate measurements of these dimensions.

9. **Extensometer test**: Continuous load and elongation data will be acquired using the system load cell and extensometer. The test software will perform the following test procedure – all while taking data. First it will preload the specimen to 0.18% strain, which is within the *elastic regime*, and then remove the applied load. Note the maximum applied load. The code will then load the sample to 1.5% strain, which moves the sample into the *inelastic regime*, and then remove the applied load. After unloading, the code will then load the sample to 3% strain and then unload the specimen. After unloading at 3%, the code will finally load the sample to failure. Note the peak load and the maximum strain.

DATA TO BE TAKEN

1. Cross-sectional dimensions of both specimens.

2. Initial gauge lengths, L_0, for both specimens corresponding to the initial extensometer separation.

3. Load vs. time, strain gauge strain vs. time and extensometer strain vs. time files for the first test specimen.

4. Load vs. time and extensometer strain vs. time files for the second specimen.

5. Load values from the second specimen test where you began to unload the specimen.

DATA REDUCTION

1. Using the linear elastic region from both tests, isolate and truncate a segment of the data from this region from each data set and estimate the Young's modulus of the aluminum. For the first data set, calculate the relative difference between the Young's modulus estimate using the extensometer and strain gauge results.

2. For the second specimen, isolate and truncate the data for the unloading and reloading curves in the inelastic regime. Determine the tangent stiffness (slope) of the stress-strain diagram in this region.

3. Determine the true stress and strain for the first specimen test, with the true strain from the extensometer readings.

4. Using the data from the first tensile test, estimate the ultimate tensile strength (UTS in [ksi] and [MPa]), ultimate tensile strain, fracture stress, (in [ksi] and [MPa]), and fracture strain directly from your engineering and true stress-strain curves.

5. Calculate the fracture strain using the dimensions you obtained from the fractured test specimen.

6. From the data obtained in the plastic regime, use the procedure explained in the background section to determine the strain hardening index n and strength coefficient K.

RESULTS NEEDED FOR REPORT

1. Cross-sectional dimensions of and initial gauge lengths for both specimens.

2. A single graph of engineering stress vs. strain, with two curves, one based on the strain gauge data and the other using the extensometer data to determine strain. Clearly label the plots in such a way to distinguish between the strain gauge and extensometer data. Plot the stress axis using MPa and the strain axis in microstrain (increments of 10^{-6}).

3. A single graph of engineering stress vs. strain using the extensometer data for the second specimen. Clearly label the points on the stress-strain diagram where you began to unload the specimen.

4. A table that lists your three estimates of the the elastic (Young's) modulus in both ksi and MPa units (i.e., from specimen 1/strain gauge, specimen 1/extensometer, specimen 2/extensometer). The table should also include the relative difference between your extensometer and strain gauge values for E from specimen 1, as well as the moduli of the aluminum alloys you found on www.matweb.com.

5. A table of the tangent stiffness results for the unloading and reloading curves in the inelastic regime from specimen 2.

6. A single graph of the axial strain versus time, with result plotted for both the extensometer data and the strain gauge data. Clearly label the axes, color-code the curves, and identify each curve.

7. A single graph showing both the *engineering* and the *true* stress-strain curves for the first specimen test, based on the extensometer readings.

8. A table of your measured estimates of UTS in ([ksi] and [MPa]), ultimate tensile strain, fracture stress (in [ksi] and [MPa]), and fracture strain (for the latter, provide both the results from obtained from your true stress-strain curve and from the the measurement of the fractured test specimen).

9. A table of your measured strain hardening index and strength coefficient.

Table 1. Parameters for the tensile test.

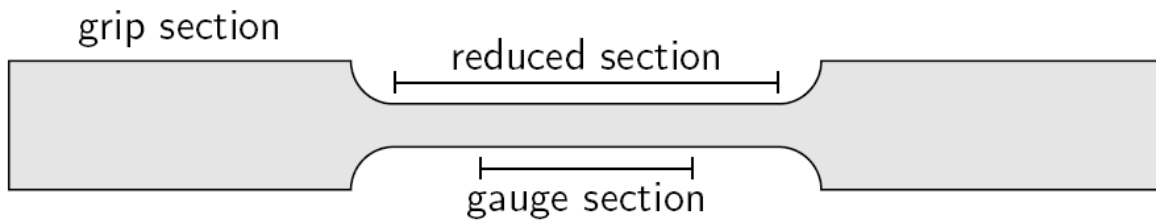| Parameter	Value
Loading Stage (axial gauge)	Monotonic
Loading Range	0-P_{fail}; P_{fail}~3000lb$_f$
Displacement Rate	0.05 in/min
Strain Gauge	YES
Extensometer	YES

Figure 1. Dog bone test specimen.
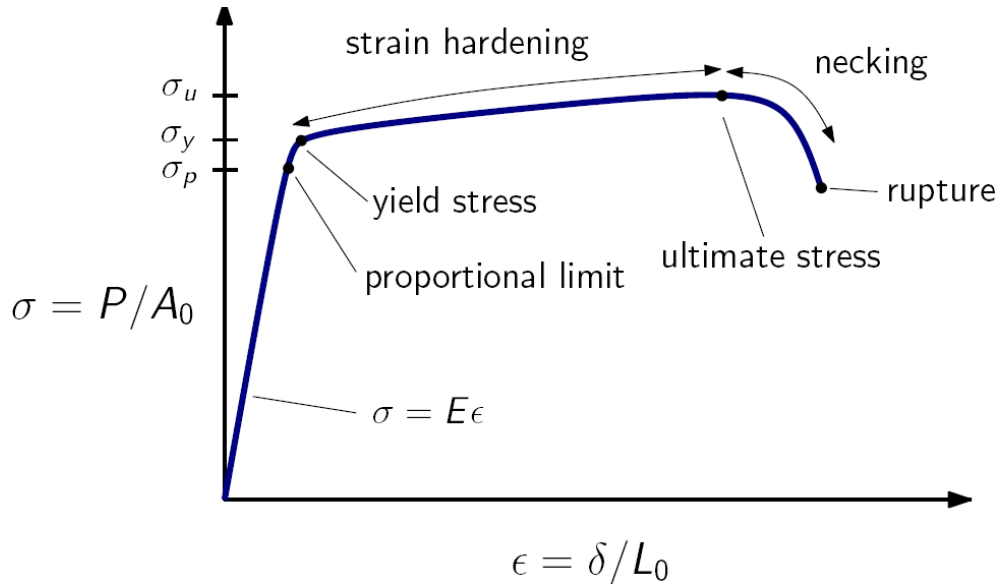
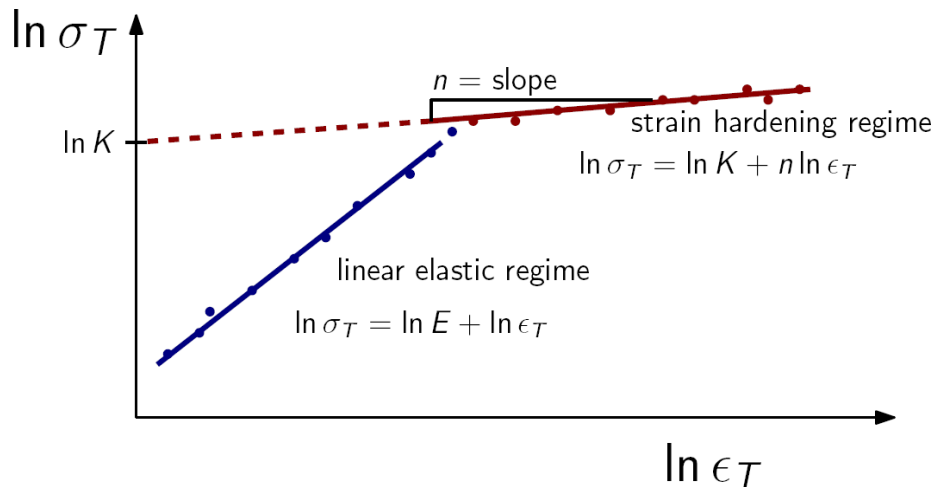**Figure 2**. Stress-strain diagram for a ductile metal.

Figure 3. Log-log plot of true stress vs. true strain.

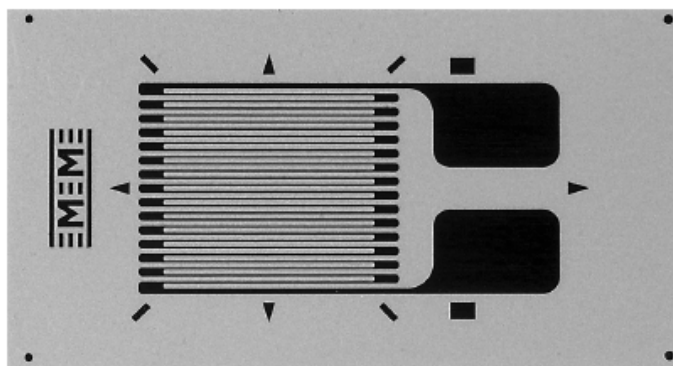**Figure 4**. The Instron 5982 load frame used in the tensile test lab.

Figure 5. A linear strain gauge.

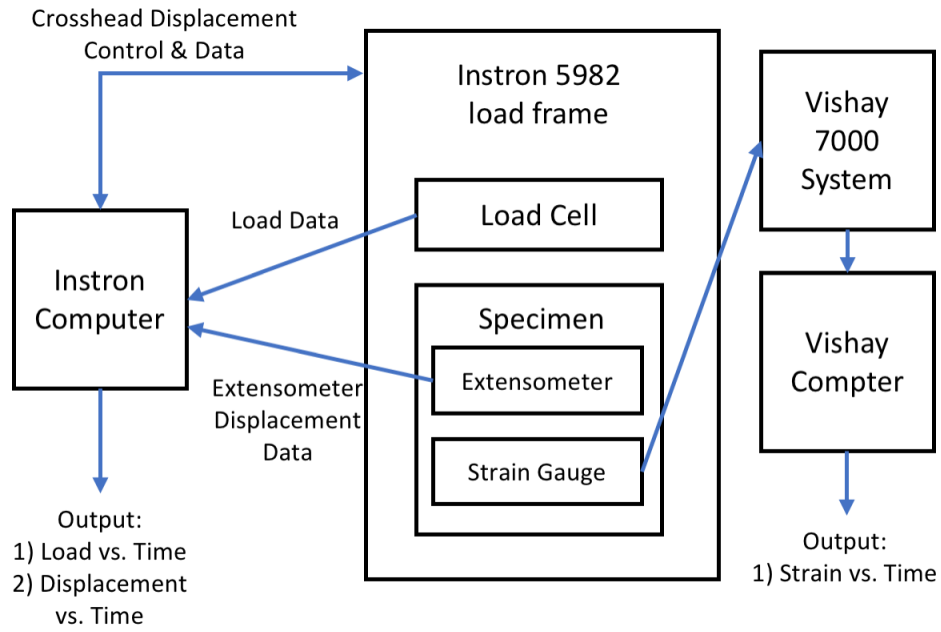**Figure 6**. Extensometer on a test specimen (image courtesy of MTS).

Figure 7. Instrumentation configuration for tensile testing lab.