Measurement Errors in Materials Testing

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"Weights and measures may be ranked among the necessaries of life, to every individual of human society. They enter into the economical arrangements and daily concerns of every family. They are necessary to every occupation and human industry; to every transaction of trade and commerce; to the labors of the husbandman; to the ingenuity of the artificer; to the studies of the philosopher; to the researches of the antiquarian; to the navigation of the mariner; and the marches of the soldier; to all the exchanges of peace, and all of the operations of war. The knowledge of them, as in established use, is among the first elements of education, and is often learnt by those who learn nothing else, not even to read and write. This knowledge is riveted in memory by the habitual application of it to the employments of men throughout life." John Quincy Adams

Materials Testing is that part of engineering design, development and research that relies on laboratory testing of one kind or another to answer questions. Testing is also required during manufacturing to ensure a material or product meets some predefined specification. A universal testing machine is used to measure the mechanical properties of materials in tension, compression, bending or torsion. Common properties of interest in tension are Offset Yield Strength, Young's Modulus, E, Tensile Strength and Total Elongation. In tension, the testing machine is used to create a stress-strain diagram (Figure 1) from which all mechanical properties are derived. A true picture of the stress-strain diagram can only be obtained through accurate measurements. On numerous occasions a company has contacted us because their test results did not match results from another lab or the results they were presently obtaining were different than historical values even though their manufacturing process had not changed. Oftentimes we find that the operator is not performing the test properly or the testing machine is not configured properly in order to take accurate readings.

Mechanical testing, requires not only familiarity with measurement systems, but also some understanding of the planning, execution, and evaluation of experiments. Much experimental equipment is often "homemade" especially in smaller companies where the high cost of specialized instruments cannot always be justified. If the designer of the "homemade" equipment does not carefully consider how his/her design behaves under test, then the stress vs. strain diagram may be in error. Examples of this will be given later.

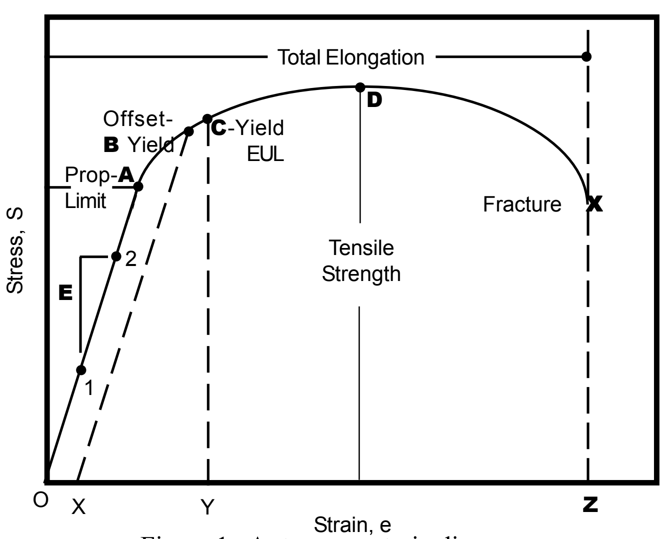

Figure 1 - A stress vs. strain diagram.

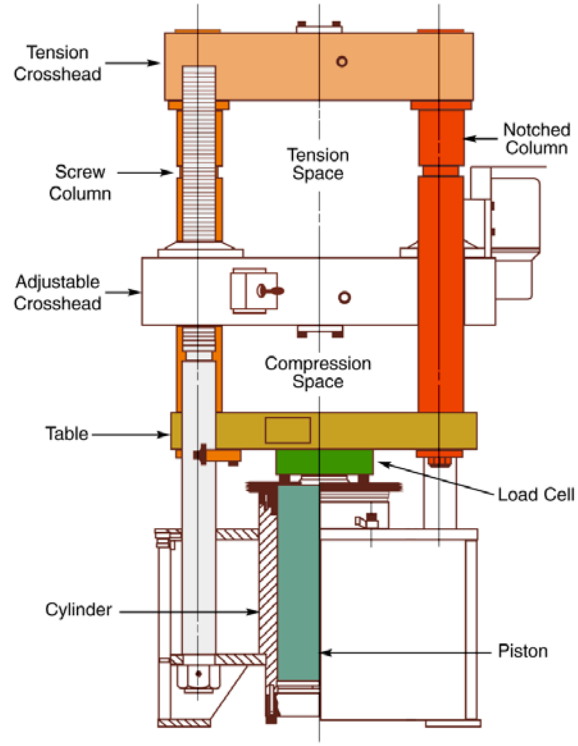

Figure 2 - Anatomy of a hydraulic universal testing machine.

There are two classes of testing machines, electromechanical and hydraulic, the principal difference is how the load is applied (for purposes of this paper only static or quasi-static machines are considered.). The electromechanical machine (Figure 3) employs a variable speed electric motor, gear reduction system and one, two or four screws to move the crosshead up or down. This motion loads the specimen in tension or compression. A range of crosshead speeds can be achieved by changing the speed of the motor. A microprocessor based closed-loop servo system can be implemented to accurately control the speed of the crosshead. A hydraulic testing machine (Figure 2) employs either a single or dual acting piston to move the crosshead up or down. Most static hydraulic testing machines use a single acting piston or ram. In a manually operated machine, the operator adjusts the orifice of a pressure compensated needle valve to control the rate of loading. In a closed loop hydraulic servo system, the needle valve is replaced by an electrically operated servovalve for precise control.

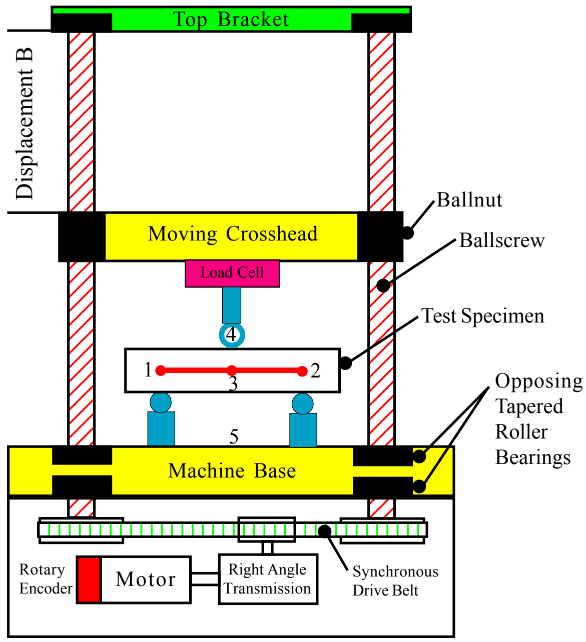

Figure 3 - Anatomy of an electromechanical testing machine.

In general the electromechanical machine is capable of a wider range of test speeds and longer crosshead displacements, whereas the hydraulic machine is more cost effective solution for generating higher forces.

Table 1 - Characteristics of Electromechanical and Hydraulic Testing Machines.

Machine Type	Test Speeds (in/min)	Max Crosshead Displacement (in)	Load Capacity (lb)
Electromechanical	0.0001 - 40	40	100 - 60,000
Hydraulic	0.005 - 3	6-12	60,000 - 1 million

A good test engineer must have an excellent understanding of the sources of errors that may be introduced during a test. Before commencing testing, the test engineer should review the choice of sensors and measurement instruments keeping in mind the suitability and accuracy of each. In order to make accurate measurements, in other words, one should know how to measure the errors in order to keep them from creeping into the results. Sensors are at the heart of all mechanical testing measurements. The test frame, power transmission, grips and fixtures also affect the accuracy and repeatability of it's sensors. Sensors that are mounted in the wrong position, are heated up, or are deformed by mounting bolts all introduce measurement errors.

Accuracy, Repeatability and Resolution

There are three basic definitions to remember with respect to how well a testing machine can measure stress and strain. They are accuracy, repeatability (precision) and resolution. In order to explain the meaning of each, let us consider the positioning of the crosshead on an electromechanical testing machine.

Accuracy is the ability to tell the true position of the crosshead. Accuracy is the maximum error between any two crosshead positions.

Repeatability (precision) is the ability of the crosshead to return to the same position over and over again. Repeatability is the error between a number of successive attempts to move the crosshead to the same position.

Resolution is the larger of the smallest programmable steps in crosshead position or the smallest mechanical step the crosshead can make.

Although these definitions seem straightforward, how measurements are best made to determine them is often a hotly debated topic. The biggest concern is what is the certainty of the measurements themselves used to characterize the machine.

Factors that Affect Accuracy, Repeatability and Resolution

Hysteresis is the maximum difference in sensor output between measurements made from 0-100% full scale output (FSO) and from 100-0% FSO. Although hysteresis is easily measured, its mechanism is not fully understood.

Linearity is the variation in the constant of proportionality between the sensor's output signal and the measured physical quantity. It is often expressed in terms of a percentage of full scale output. No sensor is truly linear so one must fit a straight line to the sensor's output versus input graph. A least squares fit is the most common method of fitting a straight line to the sensor's output graph. The least squares line is the line drawn through the sensors response curve such that the sum of the squares of the deviations from the straight line is minimized. Before microprocessors, the accuracy of the system was largely dependent on the linearity of the sensor. However, it is now possible through multi-point calibrations to effectively map out the non-linearities.

Noise is the magnitude of any part of the sensor's output that is not directly related to the physical quantity being measured. Force and strain resolutions on most testing systems are user programmable. The programmed resolution should always be greater than or equal to the noise.

Sensor Location

The most important consideration in mounting a sensor is where to mount it in order to ensure that the desired quantity is accurately measured. One thing to consider is whether the sensor should be mounted on the input or output ends of a transmission. If the sensor is mounted on the input end of a transmission along with a motor, then the resolution of the system will be enhanced by a factor equal to the transmission ratio. However, backlash and compliance in the transmission, belts, ballscrews, test frame, grips and fixtures will also affect the output of the sensor. On the other hand, if the sensor is mounted on the output end of the transmission, it will more accurately measure the process but the resolution will be reduced.

A Sensor Location Example - Measuring the Modulus of Plastic in Flexure

ASTM D790 governs the determination of the flexural modulus of unreinforced and reinforced plastics. ASTM D790 requires a bar of rectangular cross section resting on two supports be loaded by means of a loading nose midway between the supports. Figure 3 depicts such a test setup. The supports and loading nose are shown in light blue. The loading nose contacts the rectangular specimen at point 4 and is directly connected to the load cell. The test procedure involves deflecting the specimen until rupture occurs in the outer surface of the test specimen or until a maximum strain is reached.

Tangent Modulus, Secant Modulus and Chord Modulus are three properties of interest. All three require accurate force and flexural strain measurements in order to obtain proper modulus readings. Flexural strain is directly related to the deflection of the test specimen at the point midway between the supports.

The test setup shown in Figure 3 has the load cell directly coupled to the loading nose. Assuming the load cell has been verified to meet ASTM E4 accuracy requirements, we will say that all force measurements accurately represent the force applied to the specimen. Representative modulus values will therefore result, if accurate flexural strain measurements are obtained.

Example 1 - Using the Rotary Encoder Mounted on the Motor to Measure Flexural Strain

Most modern day electromechanical testing machines measure linear crosshead position with a rotary encoder mounted to the motor (The rotary encoder is shown in red in Figure 3.). The motor shaft, right angle transmission, synchronous belt, tapered roller bearings, ballscrew, ballnut, moving crosshead, load cell and loading nose are between the rotary encoder and the test specimen. When a force is applied to the specimen, strain measurement errors are introduced by the following:

- Torsional compliance in the motor shaft due to the applied torque. Because no machine component is truly rigid, one can think of the motor shaft as a torsion spring with a certain amount of torsional stiffness.
- Torsional compliance and mechanical backlash between mating gears in the right angle transmission.
- Stretch in the synchronous drive belt.
- Compliance in the tapered roller bearings. Tapered roller bearings deform non-linearily, especially at loads which are a fraction of their rating. Preloading the bearings causes a proportionately smaller amount of deflection but may reduce the effective repeatability and resolution of the moving crosshead.
- Compliance and lead error in the ballscrews. A compressive load applied to the specimen will create a tensile load in the ballscrews which will cause them to stretch.
- Backlash in the ballnuts. When in the unloaded condition, gravity will cause the ball bearings in the ballnuts to be in contact with the upper bearing race. When the applied compressive load exceeds the weight of the moving crosshead, load cell and loading nose, the ball bearings will switch to contacting the lower bearing race.
- Compliance in the moving crosshead, load cell, loading nose, specimen supports and machine base. Again, no machine component is truly rigid, one can think of each component as a spring.

With this in mind, the important questions is: “How large is the total error compared to the strain I am trying to measure?”. There is no clear cut answer but if the overall stiffness of the machine is much greater than the stiffness of the specimen, one may be able to use this method for measuring flexural strain. A careful analysis of your test setup would be in order prior to measuring the flexural strain with the motor encoder.

Note: If one could replace the test specimen with a specimen that was infinitely rigid, the load vs. strain curve as measured by the rotary encoder would be non-linear. The non-linearities make it very difficult to map out the machine errors in software.

Example 2 - Using a Linear Displacment Transducer between the Moving Crosshead and Top Bracket to Measure Flexural Strain

A second approach to measuring flexural strain might be to install a linear displacement transducer between the top bracket (in green) and the moving crosshead. In

Figure 3 it is shown as Displacement B. For this arrangement, when a force is applied to the specimen, strain measurement errors are introduced by the following:

- Compliance in the tapered roller bearings.
- Compliance in the ballscrews.
- Backlash in the ballnuts.
- Compliance in the moving crosshead, load cell, loading nose, specimen supports and machine base.

Because the Displacement B Transducer is closer than the rotary encoder to the specimen, there are fewer sources of error. Like example 1, however, there is no clear cut answer as to whether the errors introduced by measuring the relative movement between the moving crosshead and top bracket are small enough to be inconsequential. Again, a careful analysis of the test setup and results are in order.

Suggested Methods of Measuring Flexural Strain

When the methods used to measure flexural strain as outlined in example 1 and 2 are not sufficient, a device that measures the relative displacement between the underside of the specimen midway between the supports (point 3 in Figure 3) and the machine base (point 5) is commonly used. One such device is a deflectometer which is shown in Figure 4. Errors introduced by compliance in the supports and machine base are usually much smaller than the flexural strain in the specimen.

Figure 4 - A deflectometer mounted on a magnetic base.

The method with the smallest measurement error involves attaching two bars on opposite sides of the specimen at points 1 and 2 (See Figure 3) only. Points 1 and 2 are directly above the supports and reside on the neutral axis of the specimen. The bars only contact the specimen at points 1 and 2 and remain straight and unstressed when a load is applied to the specimen. A linear transducer is then affixed to the bar midway between the supports and measures the deflection of the specimen at point 4.

Conclusion

All experimental measurements include errors. Before commencing testing, a good test engineer will always ask the question: "Are my measurement errors small enough to not matter?" A thorough understanding of the sources and magnitudes of the errors is paramount to making accurate measurements.