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AUTOMOTIVE RESEARCH

CORROSION ALLOYS

ERRORS IN MECHANICAL TESTING

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MEASUREMENT ERRORS IN MECHANICAL TESTING

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Mechanical Testing is that part of engineering design, development, and research that provides data about material properties. Testing is also required during manufacturing to ensure that a material or product meets some predefined specification. In particular, universal testing machines measure the mechanical properties of materials in tension, compression, bending, or torsion.

"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. The knowledge of them . . . is among the first elements of education, and is often learnt by those who learn nothing else, not even to read and write."
John Quincy Adams

Common properties of interest in tension are offset yield strength, Young's modulus, tensile strength, and total elongation. Results of tension tests are the basis for stress-strain diagrams (Fig. 1), from which all mechanical properties are derived. A true picture of the stress-strain diagram can be seen only through accurate measurements. For example, when the test results from one lab do not match those of another, it means that the measurements of one or the other are not accurate: Either the operator is not running the test properly, or the testing machine is not configured properly.

Testing machines are available in two classes, hydraulic and electromechanical. The principal difference is the way that the load is applied. For purposes of this article, only static and quasi-static machines are considered.

Accurate 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 the design functions under test conditions, then the stress vs. strain diagram may be in error.

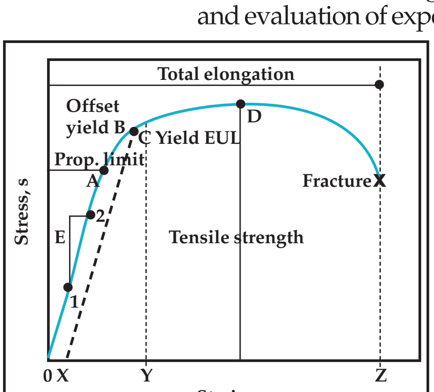

Fig. 1 — A stress vs. strain diagram.

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HYDRAULIC MACHINES

In a hydraulic testing machine (Fig. 2), either a single- or dual-acting piston applies the load. Most static hydraulic testing machines have 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 servo valve for precise control.

ELECTROMECHANICAL MACHINES

In an electromechanical machine (Fig. 3), a variable speed electric motor, gear reduction system, and one, two, or four screws 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.

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

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 sensors. If sensors are mounted in the wrong position, are heated up, or are deformed by mounting bolts, they can introduce measurement errors.

A good test engineer must have an excellent understanding of the sources of error that may be introduced during a test. Before commencing any tests, the engineer should review the choice of sensors and measurement instruments, keeping in mind the suitability and accuracy of each. Knowing how to measure errors is critical to preventing them from creeping into results.

Modulus of plastic in flexure

ASTM D790 governs the determination of the flexural modulus of unreinforced and reinforced plastics. ASTM D790 requires that 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

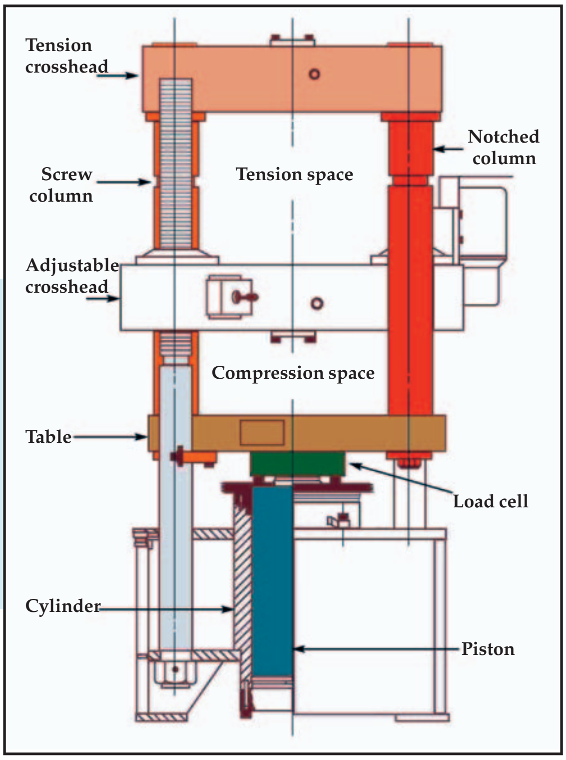

Fig. 2 — Anatomy of a hydraulic universal testing machine.

cell. The test procedure involves deflecting the specimen until the outer surface of the test specimen ruptures, or until a maximum strain is reached.

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

In the test setup shown in Fig. 3, the load cell is directly coupled to the loading nose. If the load cell has been verified to meet ASTM E4 accuracy requirements, it is reasonable to suppose that all force measurements accurately represent the force applied to the specimen. Representative modulus values will therefore result, provided that flexural strain is measured accurately.

Strain measurement errors with rotary encoders

Most modern electromechanical testing machines measure linear crosshead position with a rotary encoder mounted to the motor. (The rotary encoder is shown in red in Fig. 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, the motor shaft should be considered to act 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-linearly, especially at loads that 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 creates a tensile load in the ballscrews that causes them to stretch.

• **Backlash** in the ballnuts. In the unloaded con-

ACCURACY, REPEATABILITY, RESOLUTION

Three basic properties determine how well a testing machine can measure stress and strain: accuracy, repeatability (precision), and resolution. To understand the meaning of each, 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 error is the difference between the positions after several 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 should best be made to determine them is often a hotly debated topic. The biggest concern is the certainty of the measurements themselves.

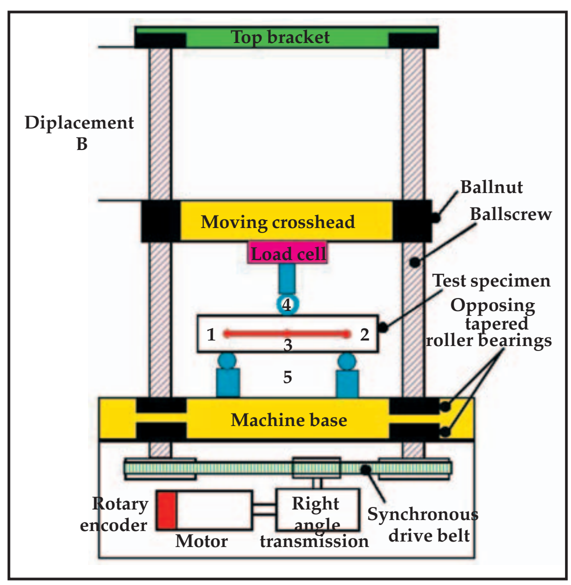

Fig. 3 — Anatomy of an electromechanical testing machine.

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 - 30,000
Hydraulic	0.005 - 3	6 - 12	30,000 - 1,000,000

dition, gravity causes the ball bearings in the ballnuts to contact the *upper* bearing race. When the applied compressive load exceeds the weight of the moving crosshead, load cell, and loading nose, the ball bearings 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; each component should be thought of as a spring.

Considering all of these errors, the important question is: *"How large is the total error compared to the strain I am trying to measure?"*

Unfortunately, there is no clear-cut answer. However, if the overall stiffness of the machine is much greater than the stiffness of the specimen, this is a viable method for measuring flexural strain. A careful analysis of the test setup would be in order prior to measuring the flexural strain with the motor encoder.

Sensors are at the heart of all mechanical testing measurements.

FACTORS THAT AFFECT MEASUREMENT

• **Hysteresis** is the maximum difference in sensor output between measurements made from 0 to 100% full scale output (FSO) and from 100 to 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 it is necessary to 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 drawn through the sensor 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** is important because it must be where the required property can be 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.

Note: If the test specimen were replaced with a specimen that is 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.

Strain measurement errors with a transducer

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 Fig. 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. However, as with the rotary encoder, 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 is in order.

Measuring flexural strain

When these two methods for measuring flexural strain 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. Errors introduced by compliance in the supports and machine base are usually much smaller than the flexural strain in the specimen.

The method with the smallest measurement error involves attaching two bars on opposite sides of the specimen at points 1 and 2 only (See Fig. 3). Points 1 and 2 are directly above the supports and reside on the neutral axis of the specimen. The bars contact the specimen only 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.

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