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.

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.

“Weights and measures may be ranked among the necessary 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

Fig. 1 — A stress vs. strain diagram.

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.

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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.
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; its mechanism is not fully understood.

- **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.

**Sensors are at the heart of all mechanical testing measurements.**