Testing Plastics for Material Models in Finite Element Analysis

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Introduction

The physical testing of plastic materials for the purpose of designing material constitutive models in finite element analysis can be very simple or incredibly complex depending on the objective of the analysis. Linear analysis of structural parts is routinely performed using a few simple parameters. More complex analysis may involve elevated temperatures, severe plastic deformation, and strain rate sensitivity requiring customized material model development and rigorous experimentation. The purpose of this discussion is to introduce laboratory experiments that may be used to evaluate the physical properties defined in material constitutive models.

Plastic parts in service may stretch, bend, creep, or break. It is impractical to measure all of the properties of the plastic in use. It is also impractical to build a material model that represents all of the material properties. Good engineering judgment by the analyst is needed to model the properties relevant to the analysis at hand.

The objective in testing for analysis is to perform experiments that put the material in a known state of strain such that there is a closed form analytical solution which describes the stress-strain condition in the test specimen. This allows us to generate experimental data that may be used to calibrate the material constants in material constitutive models (Figure 1).

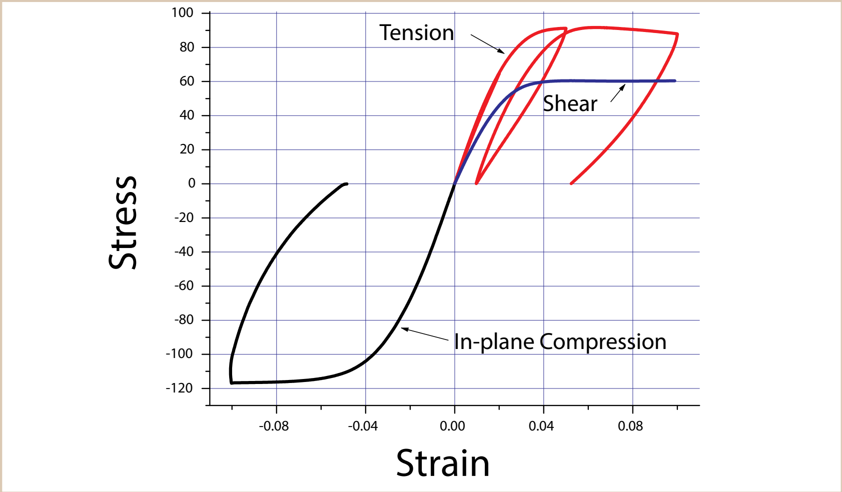

Figure 1, Advanced material models need multiple strain conditions for safe calibration. This data set contains tensile, shear, and in-plane compression data.

Figure 2, Plastic tensile test with an axial extensometer mounted to the specimen.

The Tensile Test

The tensile test (Figure 2) is probably the most commonly used for plastics because the desired state of strain is relatively straightforward to achieve in modern tensile testers and the experiment provides valuable information. Basic parameters derived from a tensile stress-strain curve are the initial material stiffness (Young's Modulus), the material yielding point, and the failure stress and failure strain (Figure 3).

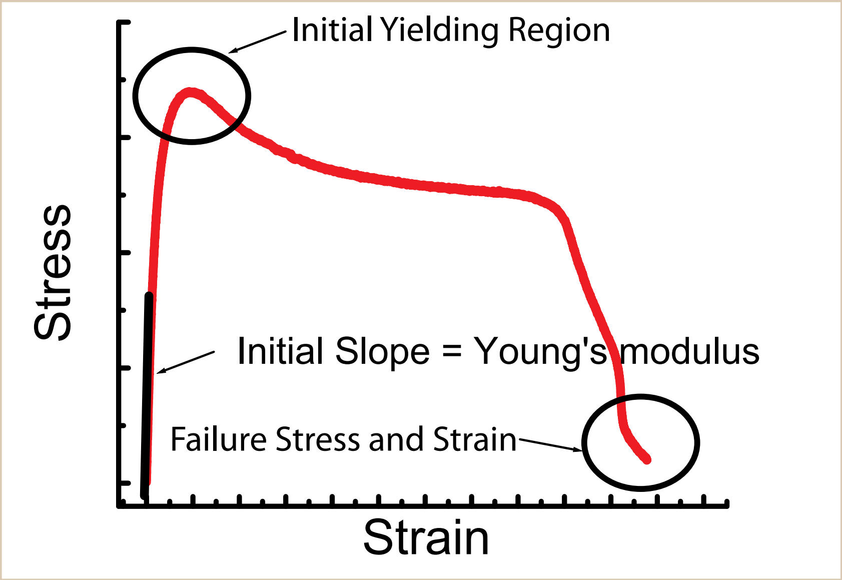

Figure 3, A typical plastic tensile stress strain curve.

Methods for tensile tests of plastics are outlined in various standards including ISO 527, ASTM D638, and ASTM D882. Standards organization provide very valuable testing standards but these methods are not typically written for the purpose of calibrating FEA material models. As such, deviations sometimes need to be made to meet the objectives of testing for analysis.

The tensile test is performed by straining a plastic specimen in one direction such that the sides of the specimen are free to contract.

The tension specimen is made such that the specimen length is very long compared to its width or thickness so that one may assume that lateral straining is unconstrained by either gripping or by specimen geometry. As a practical matter, tensile testing specimens tend to be larger at the gripped ends so that they may be efficiently gripped and so that the local gripping stresses may be distributed (Figure 4). The region of interest is the narrowed section where the desired state of strain is achieved.

Typically, the first critical strain measurement occurs at very low strains where the initial material stiffness (modulus of elasticity) will be determined. Strains in this region of the stress-strain curve are

Figure 4, A variety of standard plastic tensile specimens

Figure 5, Plastic tensile specimen with a digital image correlation strain measuring pattern applied.

Figure 6, A tensile test to very high strain.

typically less than 2%. A common way to make this measurement is to use a clip-on strain gage style extensometer. High resolution optical extensometers using dot tracking or digital image correlation (DIC) techniques are also used at Axel (Figure 5).

Strain measuring devices that provide sufficient resolution for the determination of the modulus of elasticity often have a limited range. For plastics that fail above 10% or 20% strain, a second strain measuring method may be needed. A separate high strain laser or optical extensometer may be added to the experiment or, depending on the application, a crosshead approximation may be sufficient after the high resolution extensometer exceeds its range (Figure 6).

Tensile test with axial strain and transverse strain measurement

Transverse strain is sometimes measured in the modulus region in combination with axial strain such that the ratio of transverse strain to axial strain may be determined. This slope is the Poisson's ratio and is a measure of material compressibility (Figure 7).

Like low strain axial measurements, low strain transverse measurements are typically made with a clip-on strain gage style extensometer but may also be made with other high resolution optical devices (Figures 8 and 9).

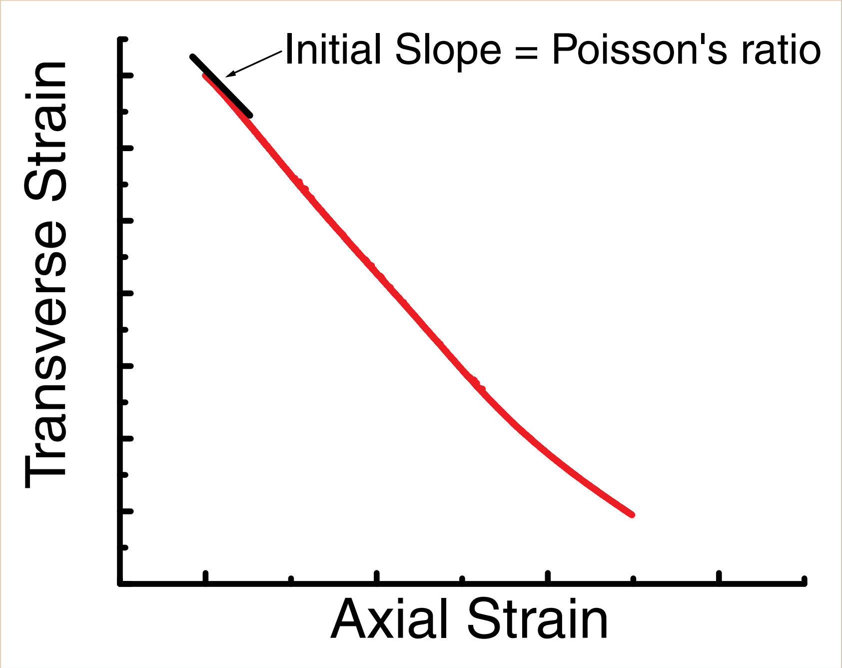

Figure 7, Transverse strain plotted as a function of axial strain. The initial low strain slope is the Poisson's ratio.

Figure 8, A tensile specimen with an axial extensometer and a transverse extensometer mounted.

Figure 9, A tensile specimen being installed in a high strain rate high energy test instrument.

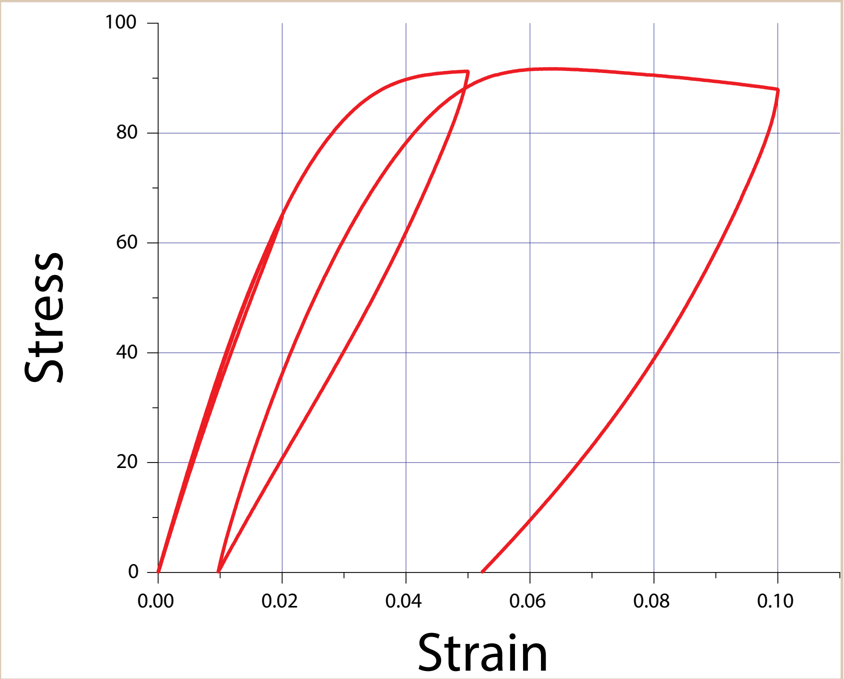

Figure 10, A loading and unloading sequence to separate the elastic and plastic parts of total strain.

Yield Point, plasticity, and loading-unloading experiments

ISO and ASTM methods have definitions for yield stress and yield strain. In one approach, the yield stress is the stress at a strain offset from the initial tangent to the stress-strain curve. In another approach, the yield stress is the first local stress maximum. While these values give us an indication of the stress and strain where the linear region ends, the underlying assumption is that plastics have a distinct transition from elastic-only behavior to elastic-plus-plastic behavior. However, deviation from a linear stress-strain curve could be the result of nonlinear elasticity, viscoelasticity, or plasticity. Unraveling this is impossible without additional information.

In general, yielding is the region where the contribution of plastic strain (or permanent strain) becomes a significant portion of total strain.

Plastic deformation may appear at very small strain values. A more accurate way to determine the yield point is by unloading the specimen. By unloading the specimen from a specific total strain, we can observe plastic strain directly by removing the elastic contribution during unloading to near zero stress. We can then load the specimen to increasingly higher total strain levels and unload at each to observe the increase in the plastic strain contribution (Figures 10-11).

Sometimes, when plastic is stretched beyond a particular strain, incremental straining becomes very localized, resulting in a local narrowing of the test specimen (Figure 12). This phenomenon is sometimes referred to as "necking." This is a complex material behavior and there is no longer a simple tension state throughout the test specimen.

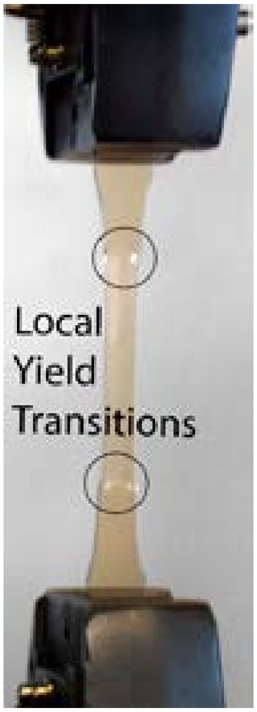

Figure 12, Localized yielding or necking in the tensile specimen - making it difficult to understand the distribution of stress and strain in the test specimen.

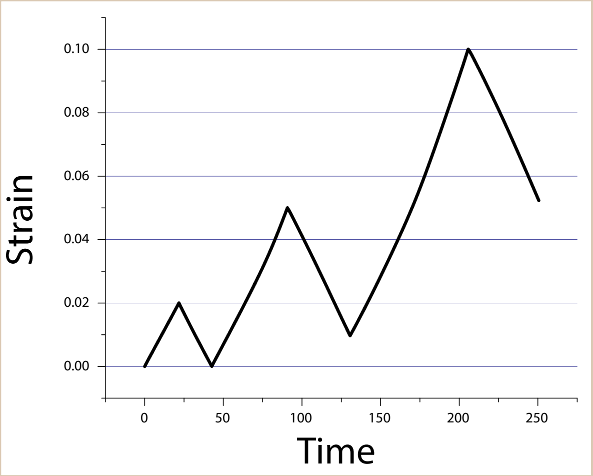

Figure 11, A loading and unloading strain history to separate the elastic and plastic parts of total strain.

Generating a material model to adequately describe this behavior is an advanced modeling idea and is generally not supported in basic material libraries. However, there are modeling techniques, typically involving optimizing software, that start with a specimen geometry and using the force displacement information along with the basic strain information, a material model that describes the macro behavior in the material can be generated with reasonable success.

Compression

The compression state in plastics is naturally of great interest because plastics experience compression in service. Plastics are often injection molded and thin walled structures are common.

To make matters difficult, the structural properties in a sheet of plastic are often different in the plane of the sheet than they are perpendicular to the plane of the sheet. Typically, the tensile, shear, and compression properties in the plane of the sheet are of more interest. Measuring tensile properties in-plane is straightforward. Measuring compression in-plane requires bulky guiding fixtures to compel a thin walled structure to load in compression without buckling (Figure 13).

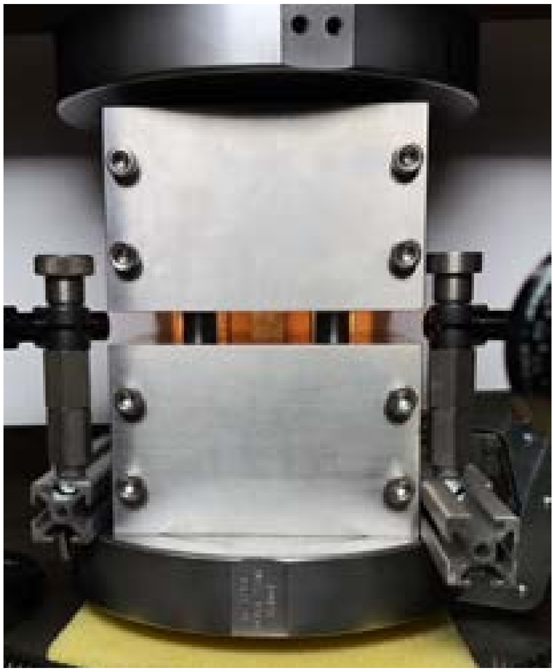

Figure 13, An in-plane compression fixture holding a specimen with an illuminated DIC pattern.

The in-plane compression experiment performed at Axel typically uses the Wyoming Combined Loading Compression Test Fixtures (ASTM D6641) modified for use with optical (DIC) strain measuring.

Out of plane compression tests may also be performed but the results may not match well with tensile data. The experiment is generally performed by placing a right cylinder of the subject material between two flat platens and compressing it. The initial stiffness and sometimes a yielding point may be derived from the resulting stress-strain curve. Direct measure of strain at the platens is usually required (Figure 14).

Figure 14, Compression platens with capacitive strain sensor.

Shear Measurement

The shear state of strain can be an important addition to the fitting of a material model. Shear tests for plastics include various 'notch' based experiments including the Arcan and the V-NOTCHED Rail (ASTM D7078) specimen style. The shear experiment can provide meaningful data across a wide range of material stiffness and a broad strain range.

In this experiment the region of interest is a narrow area between the notches. This is where the stress is intentionally localized to create a pure shearing condition. The strain must be measured in the region of the test specimen where the desired strain state is achieved. For very rigid materials, users have bonded strain gages. In this case, an optical surface strain measurement technique is used. To do this, a speckle pattern is painted onto the specimen surface and a small region is identified where the shear strain is measured using DIC (Figure 15). The system used at Axel Products is the Vic 3D Gage system produced by Correlated Solutions, LLC. (1) This system also allows the calculated shear strain to be returned to the tensile testing instrument as a continuous analog signal during the experiment. This triggers the unloading of the test specimen providing valuable load-unload test data (Figure 16).

A three dimensional system with 2 cameras can accurately capture shear strain measurements even if they occur out of the original plane of the specimen. This is important because

Figure 15, Rail shear specimen installed with DIC pattern.

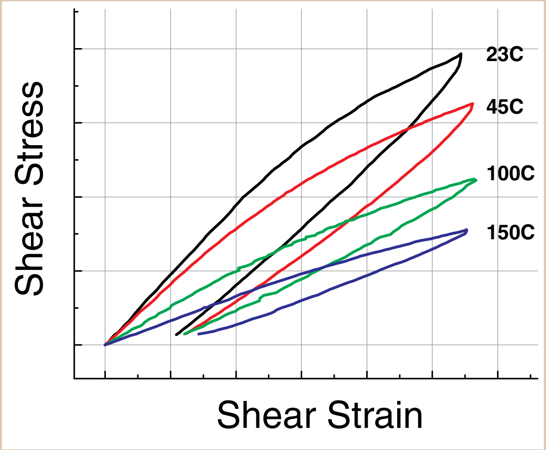

Figure 16, Shear stress strain loading unloading curves at several temperatures.

of the potential for the specimen-holding fixture to rotate slightly and also because some specimen shearing may naturally be somewhat out of plane.

Bend tests

The bend test is a classic plastics experiment. A wealth of data is generated using this test. However, the value of the bend test data for the calibration of material constitutive models is low because it is hard to determine the state of strain in the material. The specimen bends about a neutral axis but the location of that axis is unknown and the shape of the experiment under test is also unknown. The bend test, however, can be a useful experiment to verify the performance of a material model that is calibrated based upon other states of strain (Figure 17).

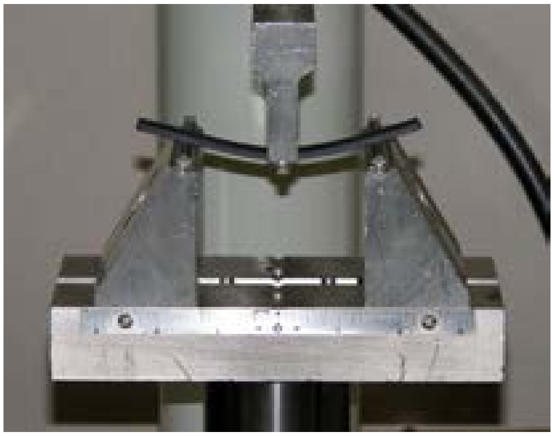

Figure 17, Plastic specimen in a bending fixture.

Figure 18, The in-plane compression fixture is used to support compressive straining in the plane of the material sheet. This can be used for creep tests of low strain compression.

Creep

As a stress is applied to plastic, the material will strain. If the stress is held constant, the plastic will continue to strain. This behavior is called creep or viscous behavior. Combined with elasticity, we have viscoelastic behavior.

At small resulting strains over relatively short times, the release of the stress on the material will result in the material returning to its original shape. At larger strains or longer times, release of the stress will likely reveal a permanently deformed plastic.

Short term creep and long term creep are both important material properties. Short term creep measurements are typically made at stresses resulting in small strains in the material such that plastic deformations do not significantly enter into the measurement. These

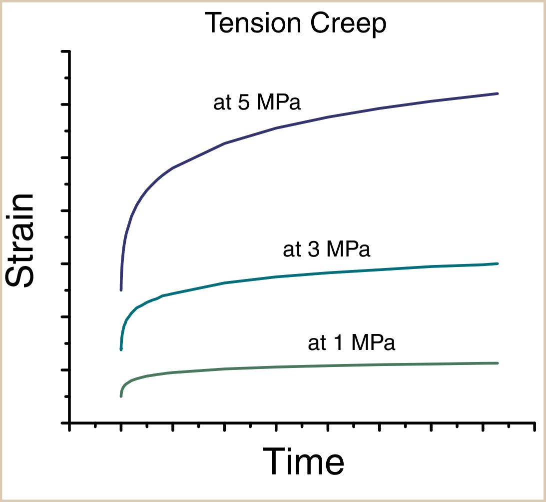

Figure 19 Short term creep at 3 stress levels.

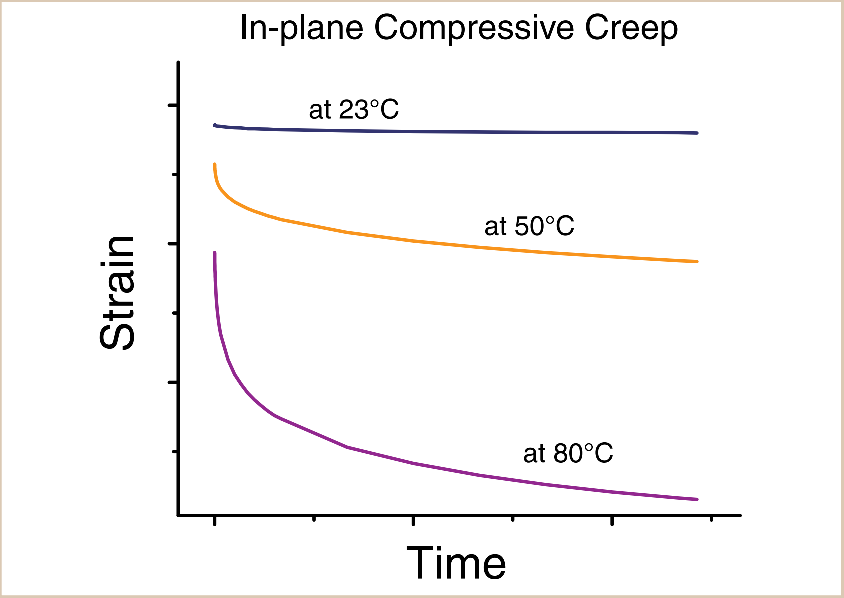

Figure 20, Short term creep at 3 temperatures.

experiments typically last less than two hours, over which several decades of time may be captured.

Temperature is a significant factor in plastic creep. A typical set of short term creep experiments might include 3 stress levels and 3 temperatures (Figures 18-20).

Long term creep experiments are often performed at elevated temperatures and the data is sometimes used to predict material behavior beyond the time frame of the actual experiment (Figure 21). Plastics are generally considered to creep more than metals at similar temperatures, making it critical to understand this vulnerability in metal replacement applications.

While these experiments are easily described by the duration of the experiment, there are significant practical considerations in the design of short term creep vs. long term creep experiments. It may be reasonable and cost effective to use a universal tensile tester such as an Instron to perform short term experiments, but it is prohibitively expensive to engage these same instruments to perform long term experiments. At Axel Products, long term creep experiments use simple dedicated creep frames (Figure 22). Weights are loaded onto a pan and the weight is transmitted through a lever arm into a loading fixture set up for tension or compression.

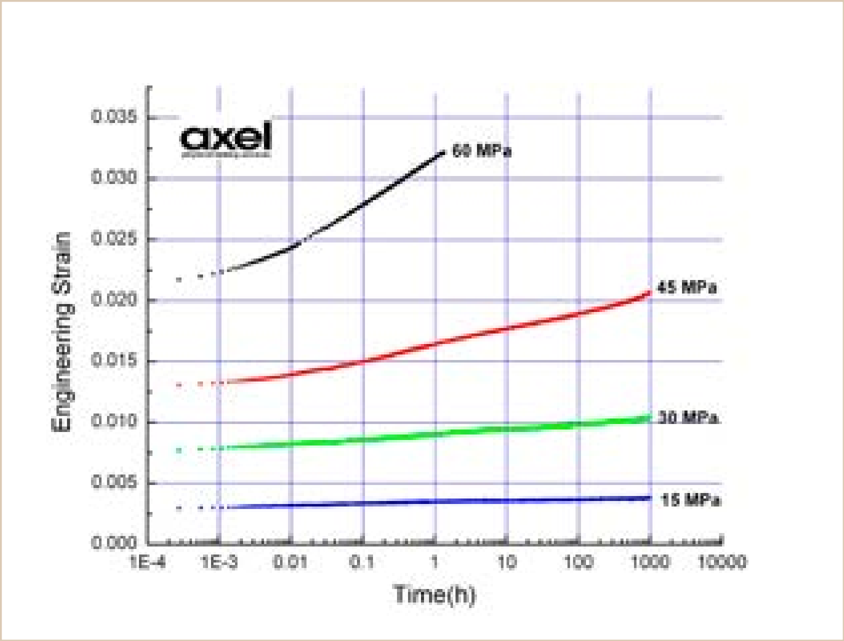

Figure 21, Example of creep data collected at 120°C at 4 separate stress levels.

Figure 22, Multiple creep frames in the "creep farm".

Measuring strain during creep experiments is challenging for several reasons. The strain must be measured in the gage section of the specimen where the state of strain is known and the stress is understood. This typically requires a clip-on style extensometer that will need to endure the specimen temperatures (Figure 23).

The extensometer used for long term creep experiments must also meet another demand: that it measure precisely over a broad range of strain. The measurement of interest is the creep of the test specimen after a stress is applied. However, the extensometer is attached to the specimen prior to loading which means that the extensometer will need to have sufficient range to capture both a large initial loading strain

Figure 23, Plastic tensile specimen with extensometer (green) mounted inside the temperature chamber of a creep frame.

followed by a potentially small creeping strain. The creeping strain continues to be of interest over several decades of time, meaning that smaller and smaller strain changes are of interest.

Rate of Straining

The rate or speed at which a stress is applied to a plastic will alter the response of the material. At slow speeds, most plastics will stretch farther before failure and will yield at lower stress values than if the stress is applied quickly. This effect becomes measurable with order of magnitude rate changes (Figure 24).

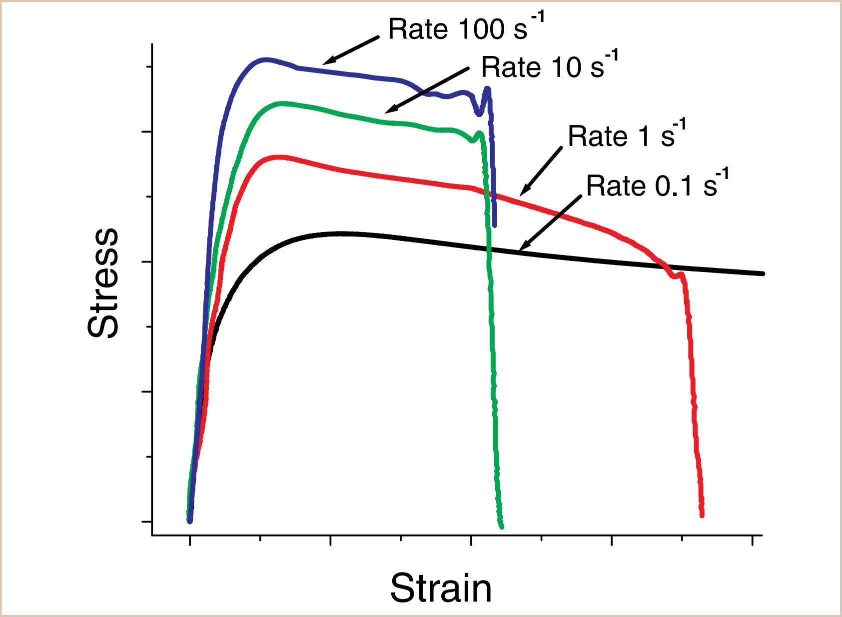

Figure 24, Plastic tensile stress strain data at decade increments of strain rate.

The difference between the rates of loading of plastic parts in normal service and the rates of loading in rare impact or crash events can be many orders of magnitude resulting in dramatically different material properties. One can imagine that the plastic in a cell phone in one's hand experiences a different rate of straining than a cell phone spiked into the pavement!

Testing at slow speed requires very stable strain and force measurement in addition to careful control of temperature. Testing at automotive crash strain rates requires specialized loading systems, customized strain and force measuring, as well as high speed data collection systems (Figures 25-26).

Figure 25, A high energy high strain rate test system.

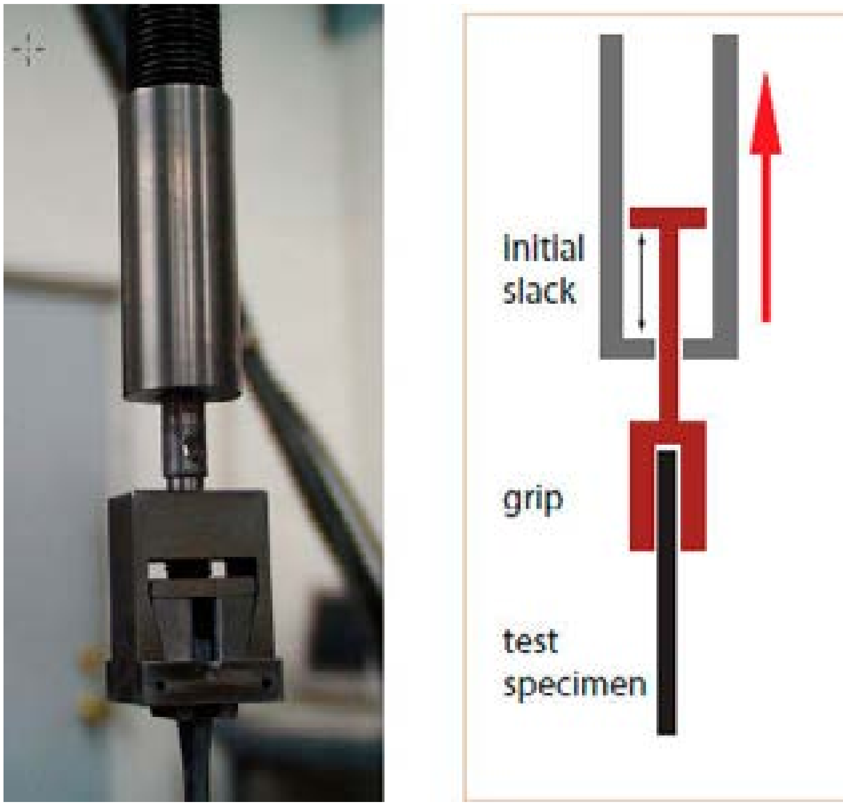

Figure 26, High strain gripping system allows the system to achieve a high speed before engaging the specimen.

Figure 27, A tensile specimen with axial and transverse extensometers mounted on a test specimen in an environmental test chamber.

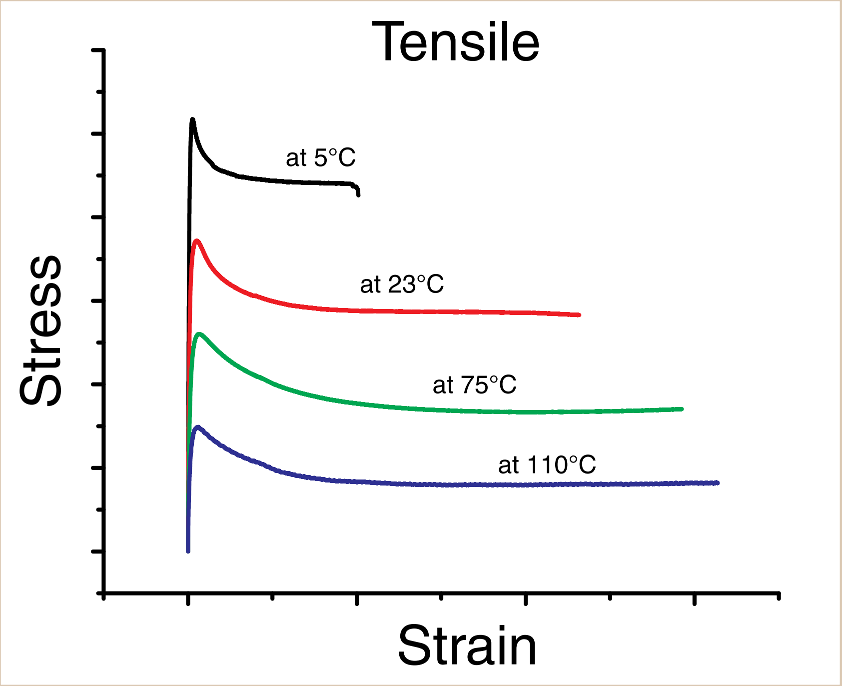

Figure 28, One plastic material tested at several temperatures.

Non-ambient properties

The physical properties of plastics can change significantly with temperature. Therefore these material properties need to be measured at application temperatures (Figures 27 - 28).

Thermal Expansion

Changes in temperature can cause plastics to expand or contract. In fact, plastic may expand far more than the surrounding steel parts. Thermal expansion is readily measured using either a dilatometer or a thermal mechanical analysis (TMA) instrument (Figure 29).

Thermal expansion is often reported as a simple coefficient of thermal expansion (CTE) and for small temperature changes, this coefficient is a reasonable predictor of the change in part shape. For large temperature changes, however, the complete thermal expansion curve over the actual range of temperatures should be considered because the expansion may not remain linear over the larger range (Figure 30).

Significant changes in the rate of thermal expansion over small temperature changes are indicative of material transitions such as the glass transition temperature (Tg) or the melting temperature (Tm). Other intermediate transitions may also occur. The thermal expansion experiment is a relatively low cost experiment that provides qualitative and quantitative information across a broad range of temperatures.

Figure 29, A black plastic disk specimen rests between glass platens in a thermomechanical analysis test instrument in advance of a thermal expansion experiment.

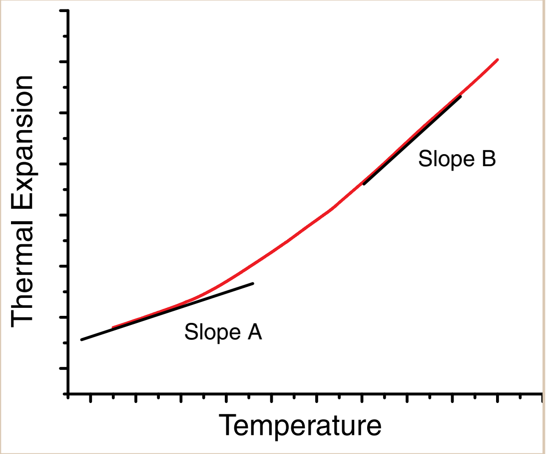

Figure 30, Thermal expansion as a function of temperature. The slope (CTE) over a large temperature ranges may change significantly.

Summary

Application and analysis objectives drive the material model and the testing program. It is impractical to test and model all of the properties of plastic. Testing with appropriate strain measurement at the correct temperatures and rates can provide much of the information needed to develop material models.

Specialized loadings may be necessary to sort out the yielding condition.

References:

1. Correlated Solutions, Inc., Columbus, SC, http://www.correlatedsolutions.com

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For more information, visit www.axelproducts.com.

Axel Products provides physical testing services for engineers and analysts. The focus is on the characterization of nonlinear materials such as elastomers and plastics.

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