Simulating plastics in drop and crash tests

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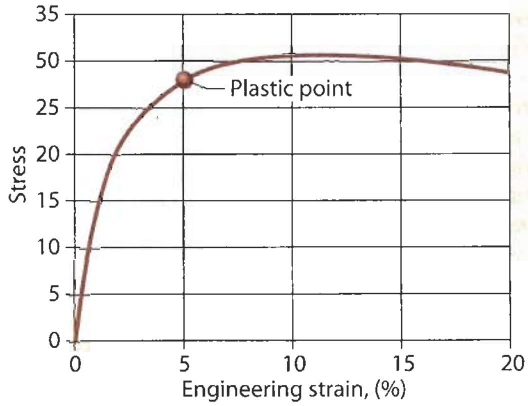
If you want a crash simulation involving plastics to yield useful results, it is important to model the material behavior appropriately. The high strain rates have a significant effect on the properties and failure can be ductile or brittle in nature, depending on a number of factors And although the LS-Dyna solver is mentioned and used frequently, the ideas here are applicable to other FEA software as well.

Nonlinear behavior of plastics



A common stress-strain curve for a plastic shows a constant change and little similarity to that of common engineering metals, such as steel. Positioning the plastic point becomes an engineering decision.

A few fundamentals

Polymers are complex materials with mechanical properties that vary with stress level, time (rate), temperature, and other parameters. This means plastics perform in a nonlinear way that is not easily captured by conventional material models with roots in metals theory. Consider just two effects.

Dependency of the stress-strain relation on stress level. It is unique for plastics. Hyperelastic materials (elastomers) have highly nonlinear elastic behavior but show no plasticity. Metals, on the other hand, show a highly linear elastic behavior, with plasticity becoming relevant only after yielding.

But the stress-strain behavior of plastics is neither hyperelastic nor linear. Contrary to metals, plastic strain begins prior to yield. In addition, the elastic behavior is nonlinear. Trying to model this behavior using metals theory poorly approximates the actual behavior and leads to several compromises. For instance, trying to accurately predict the onset of true plastic behavior underpredicts material stiffness at low stresses. Attempting to be true to the material's elastic modulus predicts too much plastic strain as one is forced to assume the onset of plastic strain much before it actually occurs. And in the second effect:

The rate-dependent behavior of a polymer brings additional complications. Up to the vicinity of yield, some plastics exhibit significant rate-dependency of modulus while others do not. This contrasts with metal behavior in which the expected behavioral trend is toward no dependency of modulus with strain rate, as exemplified by the frequently used MAT24 material model in LS-Dyna. (Other FEA programs feature a similar material model) As a consequence, polymers with a modulus rate dependency cannot be described by a MAT24 model. Applying this model to polymers ends up in a significant error in stiffness predictions. Nonetheless, it is possible to conduct meaningful simulations by selecting models that closely match the behavior shown by material data.

Many plastics show a remarkable consistency with respect to rate dependency. An idea gaining wider acceptance is described in the Eyring equation, which describes a linearly increasing relationship between yield stress versus log strain rate.

In contrast, the Cowper-Symonds equation, used extensively for metals and implemented in MAT24, does not capture the behavior of plastics, which leads to inaccuracy in modeling-rate dependencies.

Another problem arises with fiber-reinforced plastics. In addition to increasing stiffness, fibers also change how the plastic fails. With such materials, failure often changes from ductile to brittle. Finally, with some plastics, an increase in strain rate causes a gradual change from ductile to brittle failure. This variation in postyield behavior with strain rate is not easily captured in available material models.

The problem

LS-Dyna's MAT24 is the one of the most widespread material models. It is used to simulate tests such as, crash, drop, and other rate-dependent phenomena. It's simplest and most commonly used capability couples a Cowper-Symonds equation (it describes the change of yield stress with strain rate) with an elastic-plastic curve this way: The elastic rate-independent region occurs up to an arbitrarily or otherwise determined yield point, beyond which the stress-strain curve at the lowest strain rate of interest is described

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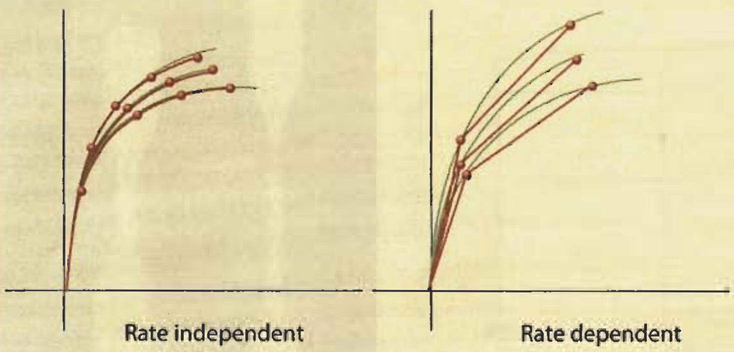
How strain rate affects modulus



Stress-strain curves for different materials (left) show that the classic yield formation often seen in metals is not easily identified in plastics. The curves on the right come from the same plastic tested at different strain rates.

by an elastic-plastic model. This produces a curve of stress versus plastic strain — the plasticity curve. The left of the accompanying image, *How strain rate affects modulus*, shows the classic yield formation often seen in metals but not easily identified in plastics. The accuracy of the classic (metal) model depends on three conditions: The stress-strain relationship is linear up to the chosen yield point, the initial linearity is not rate dependent, and the shape of the plasticity curve is uniform and independent of strain rate. But for most plastics, these are simply not true.

Plastics should be modeled with a nonlinear elastic region followed by an elastic-plastic period, so the location for the transition is usually identified somewhere along the increasing part of the stress-strain curve to indicate the onset of plastic strain. However, this not possible with current crash material models. Compromises are needed.

Selecting a modulus based on the initial region for MAT24 shows fidelity to the linear-elastic region and results in predicting too much plastic strain because the material is still elastic at stresses far exceeding the "linear-elastic" region. On the other hand, using a secant modulus (the slope of a line drawn from the graph origin to the plastic point) to describe behavior up to the plastic point results in a material model that predicts too little stiffness in the elastic region. There is no recourse with MAT24 other than to choose a value for the elastic modulus that locates in a plastic point somewhere between these extremes, often leaning toward the initial linear region so as to be as close as possible to the stress-strain data.

After assigning a modulus, it is a simple matter to discretize the static stress strain and convert the data into plastic strains following elastic-plastic-model rules. For instance, pick a series of points on the stress-strain curve and use the modulus value in an equation to convert total strain into plastic strain, generating a plasticity curve.

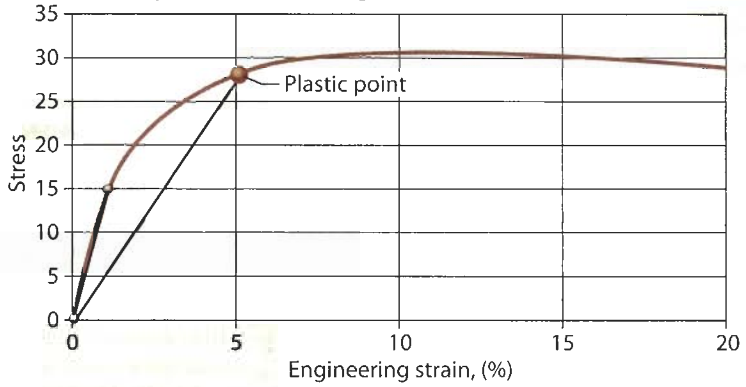
Applying the Cowper-Symonds equation allows scaling this plasticity curve to other strain rates. The equation allows smooth extrapolation without limits. However, because the equation cannot describe the rate dependency of the yield phenomenon, it does not accurately scale a plastic's rate dependency. One solution (called the LCSR option) allows applying a table containing a scale factor for each strain rate. This option allows fidelity to test data because it does not depend on an equation, but uses actual test data.

However, use LCSR with caution. High strain-rate data is experimentally difficult to obtain and there is often scatter in the data. This scatter must be smoothed so the resultant model contains no spurious behavior. The Eyring Equation (yield stress versus log-strain rate is a straight line) appears to accurately describe the rate dependency of most plastics and can be used to perform this smoothing. The LCSR table can be derived from a best fit of the yield stress versus log-strain-rate data. This approach has two advantages: it eliminates noise and can extrapolate the model to higher-than-tested strain rates because an LCSR-based MAT24 terminates rate-dependency computation when it exceeds the highest strain rate in the table. Using MAT24 with LCSR can overcome limitations of the Cowper-Symonds model when simulating plastics rate dependencies.

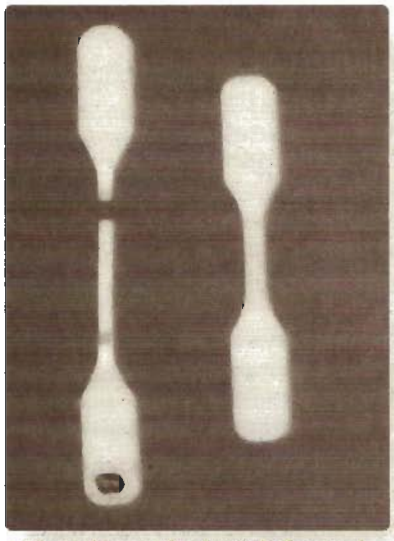
However, a serious drawback of MAT24 arises from the fact that with plastics, failure strains often drop with increasing strain rate. The model does not accommodate this variation. Instead, the model assumes that failure strain is constant and independent of strain rate. Failure in MAT24 is defined as the accumulated plastic strain in an element reaching a specified failure value. At each time step, if the computed trial stress lies outside the yield surface (Von Mises), LS-Dyna scales the stress back to the yield surface and derives accumulated plastic strain by using the material model to calculate a corresponding effective plastic strain (EPS) at the strain rate of the element. If this accumulated plastic strain exceeds a specified failure value, the element is removed from the model. The failure value is usually chosen by the analyst as largest failure strain in the material data. This is a conservative approach. If the data shows a variation in failure strains with strain rates, analysts must review the strain-rate experienced by the part, to assign a value at that corresponding strain rate.

Another option in MAT24, LCSS, is useful when the shape of the plasticity curve changes with strain rate, a phenomenon seen in some plastics. In this case,

Selecting an initial region for the MAT24 model



Selecting the plastic point at the 5% strain mark means the model will overpredict plastic strain.



Test specimens of a plastic before and after a test. "Necking," or the narrowing and stretching of the high stress area, is visible on the left.

submitting a plasticity curve for each strain rate lets users describe stress-strain behavior as a function of strain rate. It may still be a useful exercise to smooth the rate-dependency using the approach outlined earlier. However, LCSS offers no relief in modeling ductile-brittle transitions because of the limitation of the failure criteria, which allows specifying only one failure strain, rather than varying failure strain with strain rate.

LCSS requires extrapolating all plasticity curves to the largest failure strain for the model. Consequently, simulation loses information regarding the change in failure strain with strain rate.

Polymers such as polycarbonate, polyethylene, and polypropylene exhibit long tails of postyield strain and can absorb significant energy in this phase of deformation. Stress-strain curves for nonbrittle plastics go through an inflection or local maximum commonly referred to as the yield point. Do not confuse this with the Von Mises yield which corresponds to the onset of plastic deformation.

Complications arise when handling postyield behavior. For example, most postyield behavior is accompanied by necking, a localized nonuniform deformation in which the cross section of the deformation zone is unknown. Consequently, stress is also unknown and only crudely estimated by making assumptions about the cross section. The most common assumes that the true stress calculation applies in this region as well, which means the slope of the stress-strain curve gradually increases with increasing strain.

In the case of olefin-based materials, such as polypropylene and polyethylene, necking is more closely equated with unraveling of the dendrite structure, so it is more likely that stress remains constant during necking. In any case, to model these regions using MAT24, it is essential to eliminate negative slopes in the model.

A number of fiber-filled plastics have rate dependent modulus followed by small strains to failure. A small plastic strain accumulates in the material prior to failure. This behavior is difficult to model using MAT24 for several reasons. First, the stress-strain curves diverge almost immediately as seen on the right of *How strain rate affects modulus*. Consequently, MAT24 either underpredicts the stiffness at low strain rates or overpredicts stiffness at high strain rates, depending on the choice of the elastic modulus. Although this may significantly affect simulating most plastics, it is more dramatic for filled plastics because failure strains are small, typically 2%. Even though MAT 19, another material

For further reading:

1. **Lobo, H., Lorenzo, J., "High Speed Stress-Strain Material Properties As Inputs For The Simulation Of Impact Situations," IBEC, Stuttgart, Germany (1997).**
2. **Grison, A., Sinopoli, M., Lobo, H., Fedewa, B., "Evaluation of High Strain Rate Test Methods of Thermoplastic Polyolefins Used for Automotive Interior Structural Analyses," SPE TPO Conference, Detroit, (2003).**
3. **Croop, B., "Developing Material Model Parameters for Impact Simulation of Plastics and Foams," ABAQUS User's Conference, Boston (2004).**
4. **Perkins, L. and Lobo, H., "A Novel Technique to Measure Tensile Properties of Plastics at High Strain Rates," SPE ANTEC Proceedings, Boston (2005).**
5. **Lobo, H., Hurtado, J., "Characterization and Modeling of Nonlinear Behavior of Plastics," ABAQUS User Conference, Boston (2006).**
6. **Lobo, H., "Advances in the Measurement and Modeling of Plastics for Impact Simulations," 9th International LS-Dyna User's Conference, Detroit (2006).**

model, suffers from being bilinear, it is better suited than previous models and comes closer to replicating experimental data. And it can precisely indicate the failure envelope of a material by using failure strain versus strain-rate dependency. In addition, the model allows for failure based on tensile plastic strain only.

MAT89 is an elastic-plastic material model that does not need data broken into elastic and elastic-plastic regions. The developer of LS-Dyna recommends it to handle the complex behavior of ductile-brittle transitions where failure strains can vary anywhere between 100 and 10% for some plastics. With MAT89, the initial stress-strain curve is entered as true stress-strain data. LS-Dyna internally checks the slope of the curve. When the slope falls below the modulus *E* specified in the material card, the material is assumed to have yielded. The treatment of plasticity then follows MAT24, as described earlier. The LCSR scaling of the stress-strain curve allows scaling this model to high strain rates in a manner similar to MAT24.

The table of yield stress versus strain rate in the LCSR option is a better choice for modeling rate-dependency than the Cowper-Symonds equation for the same reasons described earlier. The key benefit of MAT89 is a table (called LCFAIL in the software) which lets users enter failure strains versus strain rate. The feature overcomes the limitation of MAT24, which restricts its ability to model plastics in which failure strains change significantly with strain rate. **MD**

Help with this article came from Brian Croop of ***DatapointLabs*** *and Suri Bala of* ***Livermore Software Technology Corp.***