D. Development of Advanced Tools for Energy Management

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Objectives

- Develop numerical modeling guidelines to realistically assess the influence that the properties of strain-rate-dependent materials exert in crashworthiness computations.

Approach

- Model the dynamic loading problems using diverse combinations of modeling approaches (submodels) that are essential in describing strain-rate sensitivity in computational simulations. Submodels examined include finite-element method (FEM) formulations, constitutive materials models, material properties under different strain rates and loading conditions, contact conditions, etc, as well as material property changes caused by component processing.

Accomplishments

- Investigated effects of stress transients for high-strength steel (HSS) and their effects on peak impact force.
- Developed experimental setup for new crashworthiness characterization test based on parallel-plates buckling (test under way at the University of Dayton Research Institute).
- Developed program for analysis of history of strain-rate calculations.
- Analyzed history of strain rates in unsymmetric crushing.
- Determined modeling effects on strain-rate history in unsymmetric crushing.
- Develop new constitutive models for HSS to account for strain-rate history and transients.
- Investigated forming and welding effect on steel tube crashworthiness.
- Developed model for tube roll-forming and validated it against manufacturing process.

Future Direction

- Develop new constitutive models for modeling of damage and tearing of HSS during impact.
- Conduct and analyze crush experiments (parallel-plates and tube crush).
- Develop experimental guidelines based on the two tests above.
- Determine optimal FEM formulations for modeling of crushing of rectangular tubes.
- Develop experimental program for crushing of rectangular tubes.
- Develop modeling guidelines for rectangular tubes.

Introduction

The objective of the project is to develop numerical modeling guidelines for strain-rate-dependent materials in crashworthiness computations. The scope of the project is to study specific structural problems in automotive impact, develop new experimental and analytical techniques for characterization of strain-rate sensitivity of high-strength steel (HSS) and modeling of complex strain and strain-rate histories. The dynamic loading problems are modeled using diverse combinations of modeling approaches (submodels) that are essential in describing strain-rate sensitivity in computational simulations. Submodels to be examined include finite-element formulations, constitutive materials models, and contact conditions. The trends, influences, and direct effects of employed modeling techniques will be identified and documented. The relative significance of employed submodels is established, particularly in relation to the strain-rate effect resulting from the material constitutive models.

The research project is conducted as a team effort between the Oak Ridge National Laboratory (ORNL) and the Auto/Steel Partnership Strain Rate Characterization Group (see 8.C).

The Effect of Stress Transients on Impact Peak Force

Impact experiments with steel tubes and coupons have shown a pronounced force peak for some types of steels that cannot be accounted for with existing strain-rate-dependent constitutive models. These same steels in coupon-level strain rate experiments show pronounced stress transients with increasing strain rate. These transients are usually discarded in development of constitutive models because presence of softening regions in stress-strain relation brings about significant problems with FEM formulation and uniqueness of the results. However, when strain-rate sensitivity is present in the model, and when it is evaluated in certain fashion, these problems are to a large extent eliminated, and stress transients during initial impact and strain rate variations can be taken into account. Figure 1 shows modified stress-strain data where stress transients based on experimental data were added from rate 0.1/s.

When this model is used for simulation of tube crush, an excellent agreement with the initial force peak is found. The comparison of the simulation and the model is shown in Figure 2.

The softening regions of the stress-strain curves do not severely affect the uniqueness of the solution if the material model is based on plastic strain rate. Together with strain-rate sensitivity, this introduces a characteristic length scale, stabilizes the model evaluation, and alleviates spurious mesh sensitivity.

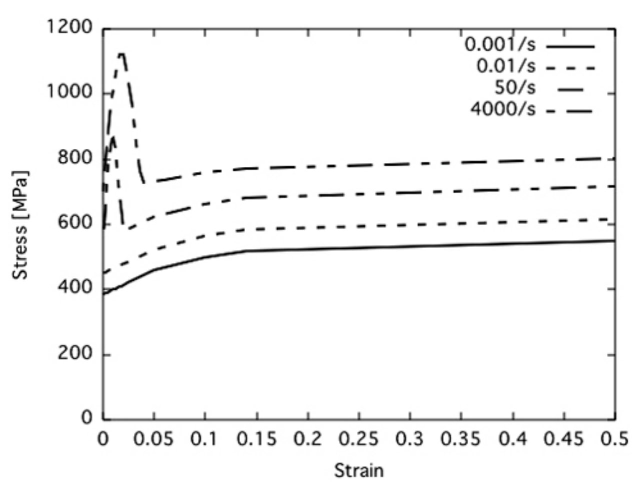

Figure 1. Modified high-strength low-alloy (HSLA) constitutive model with stress transients.

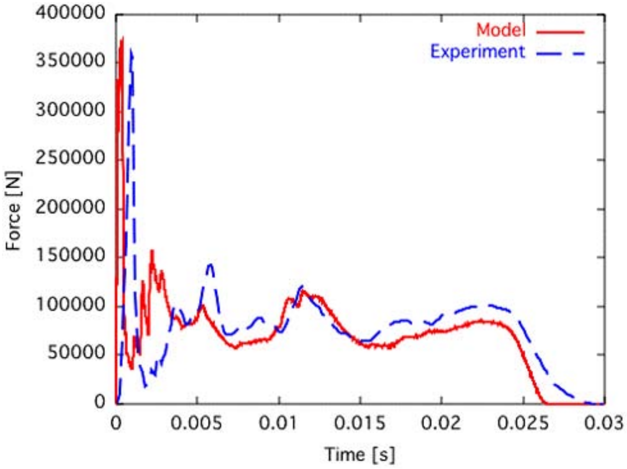

Figure 2. Modified HSLA constitutive model with stress transients.

The stress transients are dependent on strain-rate history, and the above treatment is just a first-order approximation of the phenomena. A more fundamental approach is described in the following section and is a subject of a journal publication under preparation.

Development of New Material Model for Stress Transients in Impact

Preliminary tube crush experiments were conducted at the ORNL Test Machine for Automotive Crashworthiness (TMAC) equipment described in 7C of the overall report. Tubes made of DP590 and TRIP590 steels were crushed at various speeds. Imperfection was introduced by making the top edge of the tube at a prescribed angle with the actuator, as shown in Figure 3.

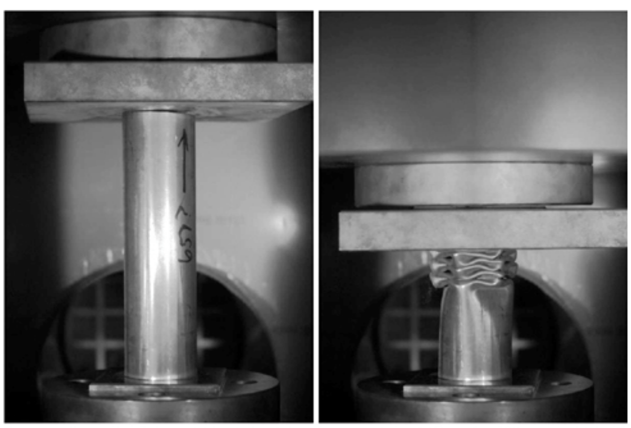

Figure 3. TMAC tube test.

The experiments were simulated using an isotropic plasticity and strain-rate dependency described by piecewise linear-plasticity model. The simulation was conducted for dual-phase (DP) steel tube under constant crush velocity of the actuator of 0.6 m/s. Figure 4 shows the comparison between the experiment and the model. Data have not been filtered.

The model correctly predicts the initial stiffness of the tube, but fails to achieve experimental peak. The origins of the peak impact force have so far been difficult to isolate because of the coupling between the test specimen and testing equipment and inertia of the measurement devices. The current results indicate that the peak value is not an artifact of testing but that such force is really experienced by the specimen. The actuator rigidity and inertia together with the measurements from the load washer at different constant loading velocities, imply that the origin of the peak force is in the material behavior. The material model would, therefore, have to be modified to include strain-rate history effects. Strain-rate history effects had been investigated in the past, but have not yet found a wide acceptance in the engineering practice.

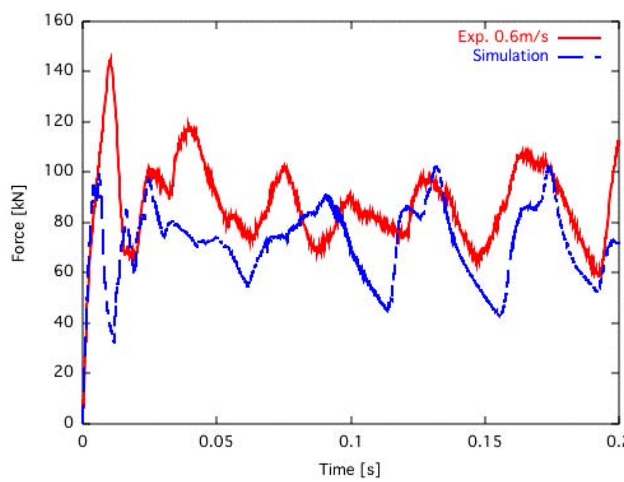

Figure 4. DP tube crush force; crush velocity 0.6 m/s.

Model Background

The complexity of material characterization under dynamic loading[1] is compounded with the difficulties of and filtering of equipment artifacts from the genuine material behavior. This filtering is especially difficult for materials that exhibit pronounced transient effects during the onset of yielding or rapid change in loading rate.

The transient effects during the loading rate change have been subject of research over the last several decades. In general, two theories were put forward for addressing the transient material response under sudden changes in loading rate. The first theory attributes the transient behavior to the stiffness of the testing equipment and the sample, whereas the second theory characterizes the observed material response as the fundamental property of the material. Experimental results obtained on very stiff testing equipment with feedback control favor the later explanation. Earlier results with shocked material[2] and dynamic torsion bars[1] also support the notion of significant material microstructure evolution during the loading rate jumps. The delay-yield phenomenon and its rate dependence also fall in the same general category. These phenomena have been satisfactorily explained by dislocation theory,[3] which was used in engineering simulations to improve modeling of the peak impact forces.

In the earlier studies,[4] strain-rate history effects in face-centered cubic (FCC) and body-centered cubic (BCC) metals have been studied based on the concept of fading memory. Based on this concept, the material loses its memory of the previous strain rate gradually within the duration of the current loading rate. Other models that are based on dislocation mechanics account for the strain-rate history through evolution of its internal variables. Because many use the strain-rate jump tests for investigation of superposition of strengthening mechanisms and strain-rate sensitivity evolution with the strain, they incorporate strain-rate history effect although not as their primary scope. Recent investigation[5] of the ability of modern micromechanics-based material models to simulate the strain rate jump tests found that the models could not accurately fit all the transients.

Transient Stresses in BCC Metals

Several major differences between the deformation characteristics of FCC and BCC alloys exist.[6] Contrary to the FCC metals, the primary short-range obstacle to dislocation motion is the Peierls-Nabarro frictional stress, and the stored dislocations behave as long-range obstacles; thus the hardening rate is not strongly affected by the strain rate. Experiments on BCC metals[7,8] indicate that the slip becomes finer and that mobile dislocation density increases with increasing strain rate. In the BCC metals, the mobile dislocation density increases rapidly with the applied strain and reaches an equilibrium state that gives the lowest stress at a given strain rate. This implies the existence of an attractor state for each applied strain rate toward which the current material state will eventually evolve if the loading is continued. In other words, the consequence of the existence of an attractor state is that there exists a unique characteristic strain rate for which the material microstructural state would be in equilibrium.

The material model proposed in this paper introduces a new scalar internal state variable (ISV), r_{ISV}, associated with the characteristic strain rate of the material microstructural state. The stress due to the strain-rate transition is superimposed onto the base stress that would otherwise be obtained if the strain-rate changes were not accounted for. Stress enhancement due to the difference between the applied and characteristic strain rate ISV is modeled by a viscous rheological element, and is based on the transients observed in experiments. The evolution law of the strain-rate ISV is such that it will eventually saturate to the applied strain rate according to the fading memory rule.

Model Formulation

Figure 5 presents the model's rheological scheme.

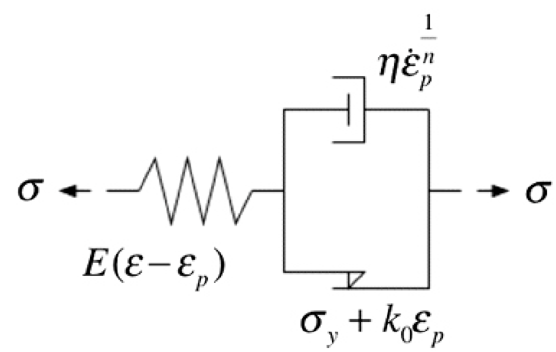

Figure 5. Elasto-visco-plastic material.

The stress balance is written in the form of a linear differential [Eq. (1)] that can be solved in closed form.

$$\eta \dot{\varepsilon}^{1/n} \left(\frac{d\varepsilon_p}{d\varepsilon} \right)^{1/n} + \sigma_y + k_0 \varepsilon_p - E\left(\varepsilon - \varepsilon_p \right) = 0$$

$$\varepsilon_p \left(\frac{\sigma_y}{E} \right) = 0 \quad . \quad (1)$$

The associated stress-strain curves corresponding to Eq. (1) for different constant strain rate tests are shown in Figure 6.

The material response in Figure 2 indicates that Eq. (1) is not suitable for modeling the effect of stress transients during the early loading.

Figure 7 presents the scheme of the proposed model, where a new element has been introduced to account for the evolution of internal microstructural state that accommodates the strain-rate jump.

As mentioned earlier, in BCC metals, the material's structure responsible for accommodating the imposed strain rate will gradually transition between its current equilibrium state described by r_{ISV} to the state that corresponds to the imposed external strain rate. For simplicity, we have used the imposed total strain rate as the target rate. Variable r_{ISV} represents the characteristic strain-rate variable for the current material state. The element resembles a viscous element as it is proportional to a difference of two rate terms. The new equilibrium equation is

$$\eta \dot{\varepsilon}_{p(ISV)}^{1/n} + \sigma_y + k_0 \varepsilon_p + k_2 \left(\dot{\varepsilon} - r_{ISV} \right) - E\left(\varepsilon - \varepsilon \right) = 0 \ ,$$

$$\varepsilon_p \left(\frac{\sigma_y}{E} \right) = 0 \quad . \quad (2)$$

The initial value for r_{ISV} can be estimated from the experimental data as the highest constant strain rate that does not produce noticeable stress transients (overshoots) and is denoted as r_{ISV}^0. The evolution law for r_{ISV} (fading of memory of the previous strain rate) is assumed to be in the exponential form with a time relaxation constant τ:

$$\dot{r}_{ISV} = -\frac{1}{\tau} \left(r_{ISV} - \dot{\varepsilon} \right) \quad . \quad (3)$$

We restrict the analysis only to the initial loading so that we can integrate Eq. (3) analytically:

$$r_{ISV} = \dot{\varepsilon} + \left(r_{ISV}^0 - \dot{\varepsilon} \right) e^{-t/\tau} \quad . \quad (4)$$

Parameter τ in Eq. (3) can be estimated based on the duration of the transients in experiments. Another obvious choice for the evolution law would be to base it on plastic strain increment. However, in the present study, Eq. (2) is selected because it can be analytically solved. Figure 8 presents the

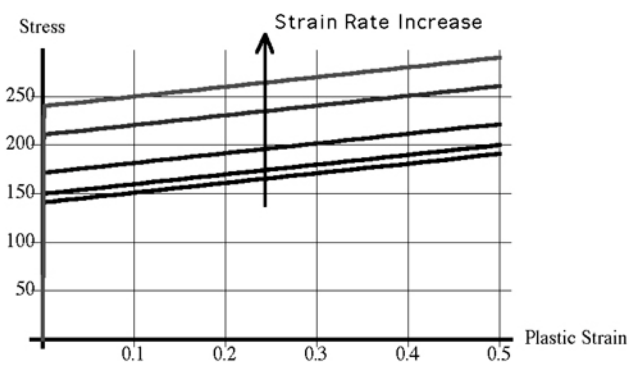

Figure 6. Stress-strain curves (strain rates 0.1, 1, 10, 50, 100/s, stress in MPa).

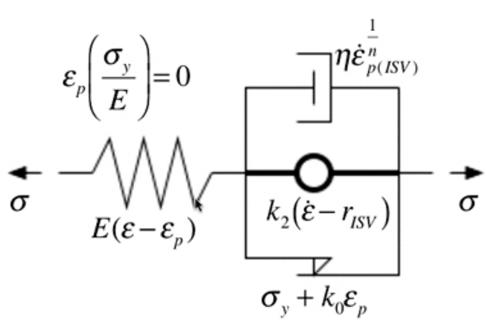

Figure 7. Elasto-visco-plastic material with strain rate history effect.

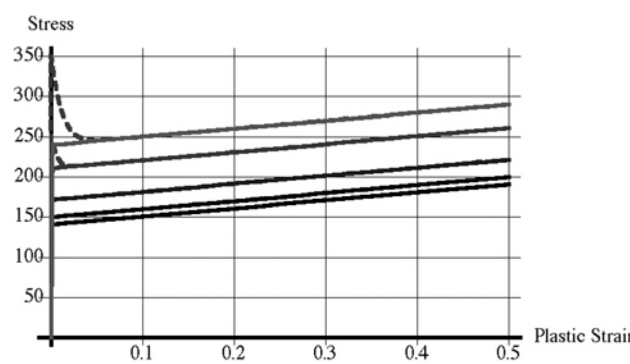

Figure 8. Stress-strain curves for model with strain rate history effect (strain rates 0.1, 1, 10, 50, 100/s).

solutions for imposed constant strain rate tests assuming that $r_{ISV}^0 = 0$.

The grey curves correspond to classical solution, whereas the dashed curves include the stress enhancements due to the transition of the internal state component responsible for strain rate accommodation. The overall trends in Figure 8 correspond favorably to the trends observed in experiments. The duration, shape, and magnitude of the transients can be modified using a different evolution law for r_{ISV} and more complicated rheological element.

Model Summary

We propose a new internal state variable corresponding to the characteristic strain rate associated with the material's current microstructural state for describing the strain-rate history effects. The new ISV is added to the classical elasto-visco-plastic model to illustrate its ability to model the jumps in the applied strain rate. The new model has been documented in an article submitted to a peer-reviewed conference.

Modeling of Forming Effects on HSS Tube Crash Performance

An FEM model has been developed to simulate roll forming of HSS tubes used in TMAC testing at ORNL. The model uses piecewise linear-plasticity material model. The tube forming includes spring-back simulation after forming that brings tube to its desired radius. The model was verified against manufacturing conditions. The formed tube information is transferred to the crush model using the initial plastic strains through the tube thickness. Figure 9 shows the comparison between the crush force of a DP tube using models with and without incorporated forming effects for an HSLA tube.

It can be seen that the incorporation of roll-forming effects does not impart significant difference onto the crush force and energy dissipation. The differences may mainly occur through the change of crush folding mode.

We have also incorporated laser weld effects through the modification of material parameters in the weld region based on measured hardness levels. The effect of welding was also found to be marginal except for triggering of the folding pattern.

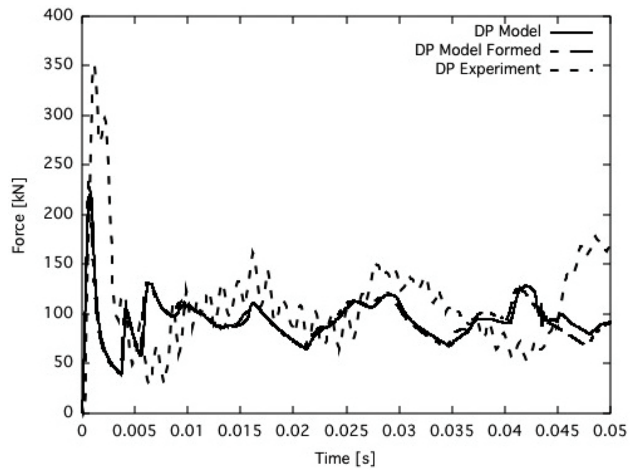

Figure 9. Tube crush force for models with and without forming effects. Green dotted line denotes experimental result.

Conclusions

The current project concentrates on investigation of different FEM modeling approaches for modeling of impact in HSS structures. The research is performed in collaboration with an experimental program on characterization of HSS under impact (8.C). The modeling is also used for development of new high-strain-rate material and structural characterization tests. The results of the project are used for development of more accurate modeling approaches for automotive design. The research results are also applicable in high-strain-rate forming operations.

Future Work

The future work on the project will focus on four topics:

1. Support of the strain-rate experiments on coupon and component level.
2. Development and validation of material models and modeling techniques.
3. Modeling of HSS rectangular tubes.
4. Development of models and experiments for damage and fracture of HSS in a crash.

The remaining most important aspects to address from the modeling of HSS crashworthiness are the methods to model the crush of tubes with rectangular (polygonal) cross section, modeling of damage that the HSS experiences during the deformation, and incorporation of processing into the models.

Acknowledgments

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