V. Modeling of High Strain-Rate Deformation of Steel Structures

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Objectives

- The objective of the project is to develop numerical modeling guidelines in order to realistically assess the influence that the properties of strain-rate-dependent materials exert in crashworthiness computations. The dynamic-loading problems are modeled using diverse combinations of modeling approaches (sub-models) that are essential in describing strain-rate sensitivity in computational simulations. Efforts have been focused in a number of technical areas including 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 steels (HSSs) and their effects on peak impact force
- Developed experimental setup for new crashworthiness characterization test based on parallel-plates buckling
- 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 effects on steel tube crashworthiness
- Developed model for tube roll-forming and validated it against manufacturing process
- Developed experimental guidelines based on the two parallel-plates and tube crush tests

Future Direction

- Conduct and analyze octagonal tube crush experiments replicating HSS front rail
- Determine optimal FEM formulations for modeling of crushing of tubes with corners

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 HSS and modeling of complex strain and strain-rate histories. The dynamic-loading problems are modeled using diverse combinations of modeling approaches (sub-models) that are essential in describing strain-rate sensitivity in computational simulations. Sub-models to be examined include finite element formulations, constitutive materials models, contact conditions, etc. The trends, influences, and direct effects of employed modeling techniques will be identified and documented. The relative significance of employed sub-models 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 ORNL and the Auto/Steel Partnership Strain-Rate Characterization Group (see 2.U). Recent results have been published at the International Auto body Conference IABC 2006 [1].

Simulation of Double Plate Experiment

A new experimental setup has been developed for investigation of progressive crush in HSS. The objective of the experiment is to replicate components of loading conditions that occur during progressive crush of tubular structures in a simple structure to minimize the complexity of the problem. The simplicity of the specimen allows for simple correlation with the FEM experiments and for characterization of strain-rate sensitivity effects in basic impact energy-absorption mechanism. The experiment has been used for investigation of inertia and strain-rate effects in Type II structures by Tam and Calladine [2]. Our version of experiment is conducted for three different constant crushing velocities in order to assess the effect of crushing speeds and strain-rate in off-axis compression and bending. The effects of material model types, model parameters, finite element (FE) shell element formulations and spatial discretizations have been included in the study.

A typical test is shown in Figure 1. The specimen is made of two pre-bent parallel plates and is impacted from the bottom and crushed with constant velocity. Figure 1 shows the edge view of the specimen. The forming process has been simulated using the quasi-static material properties. The edge of the simulated plate is superimposed over the image from the experiment and shown as a dark line and marked as "Simulation". The impact loading was imposed using the displacement history of the loading plate from the experiment. Superimposed images of the simulations over the experimental results from the high-speed camera test are shown in Figure 1. The images are ordered in the time sequence.

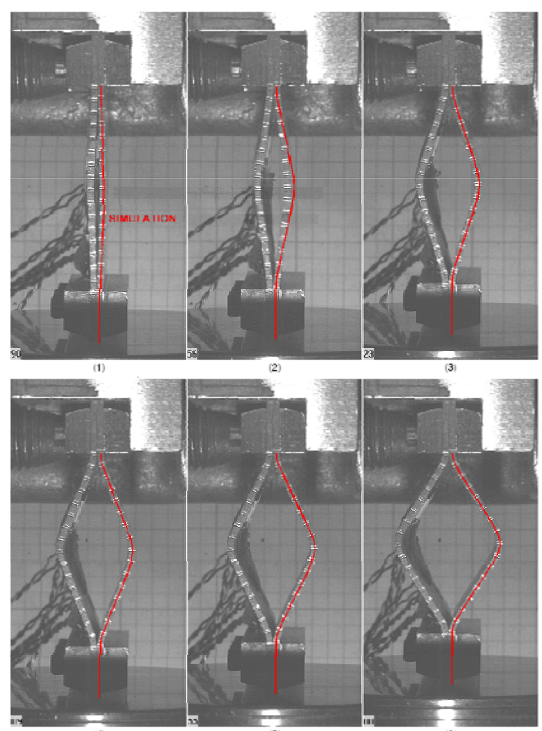

Figure 1. HSLA350 plate crush test. Crush velocity 0.6 m/s.

Simulation results exhibit more flexibility during early stage of impact compared to the experiments in all materials tested. During the early phase of impact, FEM models buckle faster than experiments. Experiment data later catch up with the simulations and the two are essentially overlapped during the rest of the test. Several reasons for the discrepancy are possible and are currently being investigated. The experiment was simulated using different modeling approaches. The comparison of force history between experiments with different impact velocities and simulations is shown in Figure 2. The simulations use a strain-rate-sensitivity model based on plastic strain-rate formulation.

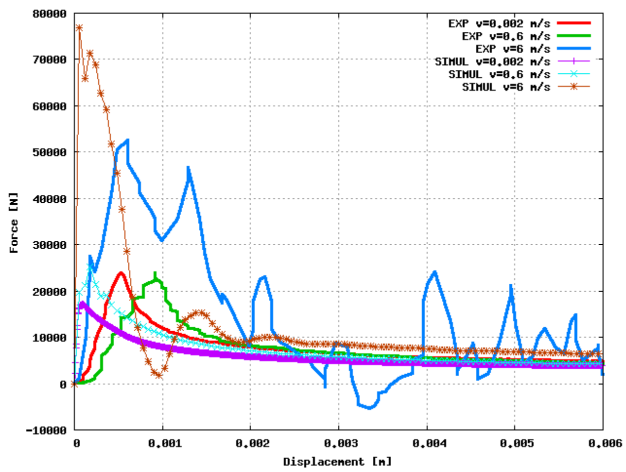

Figure 2. Double plate crush test forces. Experiment vs. simulations.

It was found that the model based on total strain-rate formulation does not lead to realistic strain-stress history in the elements experiencing severe plastic deformation in the plastic hinge areas. Due to the experiment configuration, this discrepancy is reflected on global level such as the force history. A comparison between different formulation results is illustrated in Figure 3.

Analysis of the elements in plastic zones shows that the total strain-rate formulations result in higher stresses and therefore a stiffer structural response compared to plastic strain-rate formulations. The effect is more apparent at intermediate impact speeds where the saturation strain-rate data are lower than the applied rate. In the case where the saturation rate is reached by both formulations, the

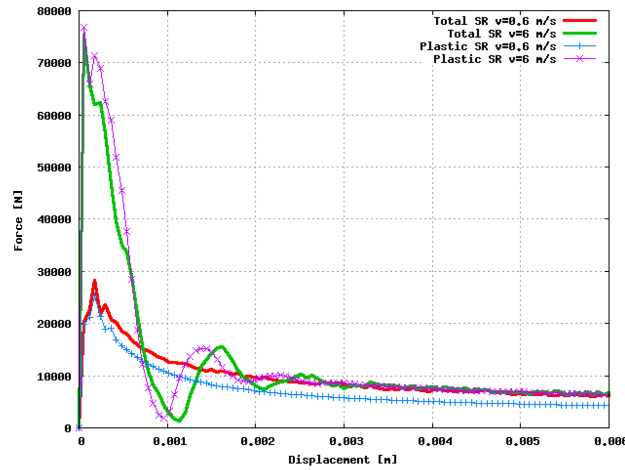

Figure 3. Double plate crush test forces. Total vs. plastic strain-rate formulations.

respective model responses are almost the same. A strain history data comparison for experiments and simulations based on total plastic strain-rate is shown in Figure 4.

The double-plate test has been used to develop modeling guidelines for basic folding mechanism in crash. It was shown that the element discretization required to accurately match the deforming geometry is on the order of material thickness and that the strain-rate-sensitivity effects should be based on plastic strain-rate formulations. Total strain-rate formulation results in stiffer response and the strain-stress history does not match the imposed loading conditions. From the experimental

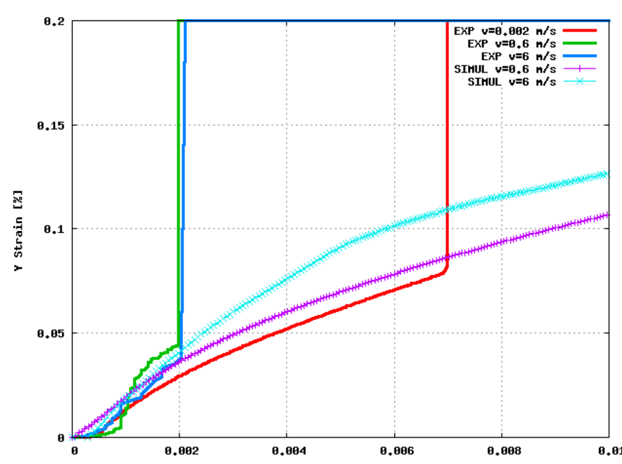

Figure 4. Comparison of test and simulation of strain histories for different impact velocities.

standpoint the main advantages of the double plate impact test are its similarity to principal energy dissipation mechanism in sheet steel under impact, relatively low force requirements, no gage section instability and capability of measuring large strains. The test will be further developed in order to provide a standardized method for measurement of crashworthiness of materials and strain-rate sensitivity in off-axis compression and bending.

Simulation of Axisymmetric Tube Crush Tests

Structural component experiments have been developed using the new, velocity-controlled high-speed hydraulic Test Machine for Automotive Crashworthiness (TMAC) at ORNL.

Due to the axial symmetry of the problem, we can simplify the problem by analyzing a radial segment of the tube length with symmetry boundary conditions imposed in the hoop direction. The comparison between the measured and simulated impact force for high-strength low-alloy (HSLA) 350 tubes crushed at 0.6 m/s and 4 m/s crush are shown in Figures 5 and 6, respectively. Fully integrated elements with side length equal to two plate thicknesses were used.

The overall agreement between the model and the experiment is good. The agreement can be further improved by using finer resolution. However, in large structural simulations such an approach is still not practical. The results illustrate the need for new FEM shell element formulations that would be capable of modeling localized deformation with relatively coarse discretization.

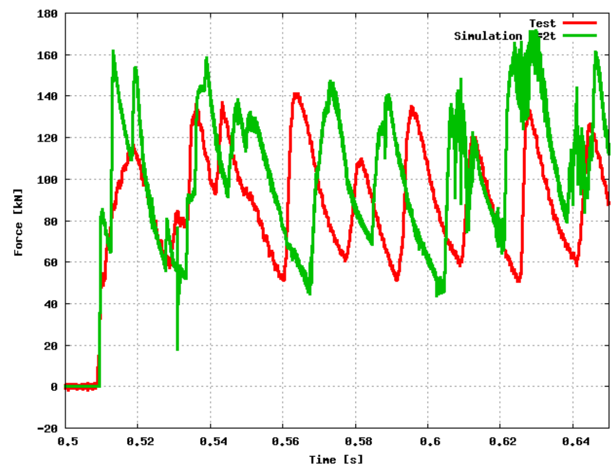

Figure 5. Comparison of test and simulation of 0.6 m/s tube crush, HSLA350.

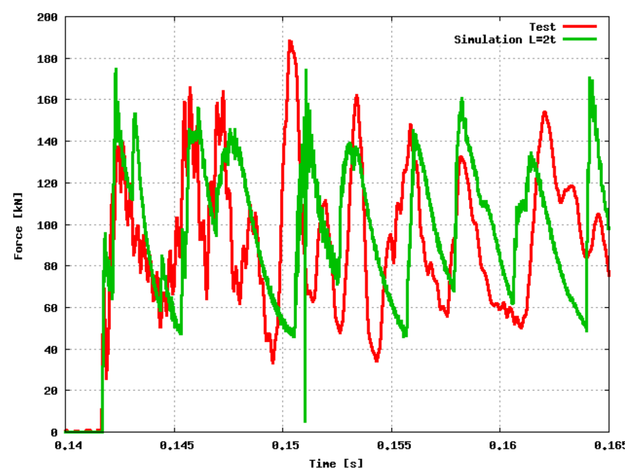

Figure 6. Comparison of test and simulation of 4 m/s tube crush, HSLA350.

Conclusion

New experiment configurations have been developed for characterization of crashworthiness of steel sheet materials. The experiments are based on hydraulic-based testing systems. The systems provide tightly controlled testing environments for material and structural characterization of basic mechanisms of impact-energy dissipation. The main advantages of the double-plate impact test are its similarity to principal energy dissipation mechanism in sheet steel under impact, relatively low force requirements, no gage section instability and capability of measuring large strains. The constant-velocity tube crush test enables characterization on component level and overcomes limitations of the inertia-driven equipment. The experimental data are used for development of modeling guidelines for steel sheet materials and structures under impact loads. Various FEM modeling approaches have been considered, such as material constitutive models, element formulation and discretization, and modeling of contact conditions.

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 octagonal tubes.

4 Development of models and experiments for damage and fracture of HSS in 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.

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