T. 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. Sub-models 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
- 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
- Developed 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
- Developed experimental guidelines based on the two parallel-plates and tube crush tests

Future Direction

- Develop new constitutive models for modeling of damage and tearing of HSS during impact
- Conduct and analyze octagonal tube crush experiments replicating HSS front rail
- Determine optimal FEM formulations for modeling of crushing of tubes with corners

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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 effects resulting from the material constitutive models.

The research project is conducted as a team effort between the ORNL and the Auto/Steel Partnership (A/SP) Strain Rate Characterization Group (see report 2.S).

Simulation of Double-Plate Experiment

A new experimental setup has been developed for investigation of progressive crush in high-strength steel. 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 [1]. The simplicity of the specimen allows for semi-analytical extraction of data and simple correlation with the FEM experiments. The experiment has been used for investigation of inertia and strain-rate effects in Type II structures by Tam and Calladine [2]. Since then, numerous interpretations of the test have been conducted using analytical or computational models. Our version of experiment is conducted for three different crushing velocities in order to assess the effect of crushing speed and to correlate the computational models with experiments.

The effects of material model types, model parameters, FE shell element formulations and spatial discretizations have been included in the study.

A typical test configuration 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. A result of a typical forming simulation for DQSK steel is shown in Figure 2. The edge of the simulated formed plate is superimposed over the image from the experiment and shown in red and marked as “Simulation”. In order to match the formed shape of the specimen, it was necessary to use element discretization that was very close to the plate thickness. This result also illustrates a necessity of a fine discretization for modeling of progressive crush using the current FEM shell element technologies. It also indicates the need for development of new FEM shell formulations that would allow for localized behavior in larger shell elements. The current discretization that is proportional to shell thickness is close to the limit of shell element applicability since the shell element formulation is developed on the basis of assuming that the element thickness is negligible to the shell curvature.

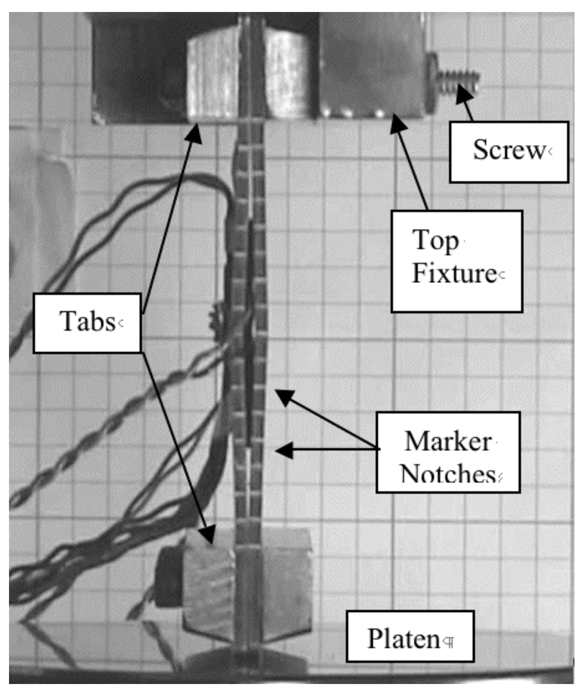

Figure 1. Double-Plate impact configuration

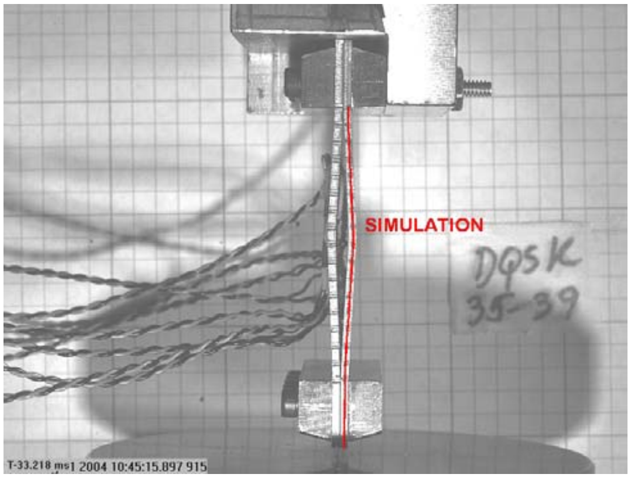

Figure 2. Simulation of the forming process

The formed plates are assembled into a test specimen as shown in Figure 1. The residual strains from forming simulations are used in the impact simulations of the experiment. The simulated forming strains were also compared with the strain calculated from the analysis of the curvature distribution in the experiment and were found to be in a close agreement.

The impact simulation phase was conducted using the same discretization as was used in the forming phase. The material properties now include strain-rate effects. The loading was imposed using the displacement history of the loading plate as obtained from the experiment. A typical history of the displacements for the intermediate velocity test of 0.6 m/s is shown in Figure 3.

Images of the simulations superimposed over the experimental results from the high-speed camera test are shown in Figure 4. The images are ordered in time sequence. The material tested was mild steel (DQSK).

Simulation results exhibit more flexibility compared to the experiments in all materials tested. During early phase of impact after contact between the loading plate and the specimen, models buckle faster than experiments.

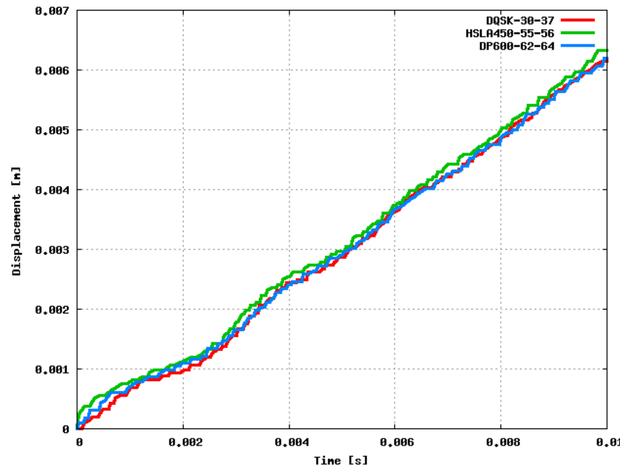

Figure 3. Loading displacement for impact test

Experiments later catch up with the simulations and the two are overlapped during the majority of the test duration. Several reasons for the discrepancy are possible, and are currently being investigated. The transient stress enhancement during the sudden strain rate increase [3, 4] has been considered, as well as effects of element discretization and specimen flexibility. The increase in buckling load can be achieved by changing the material model to account for stress transients and by using a larger element size. The combination of the two effects is used as a guideline for the modeling of progressive crush in larger structures. A relative simplicity of the test also allows for semi-analytical interpretation for certain portions of the test. The semi-analytical approach is combined with the FEM simulations to determine the best combination of modeling parameters. These parameters are correlated with local measures of strain and strain-rate effect and provide verified modeling combination that otherwise could not be provided in an automotive component or tube crush tests.

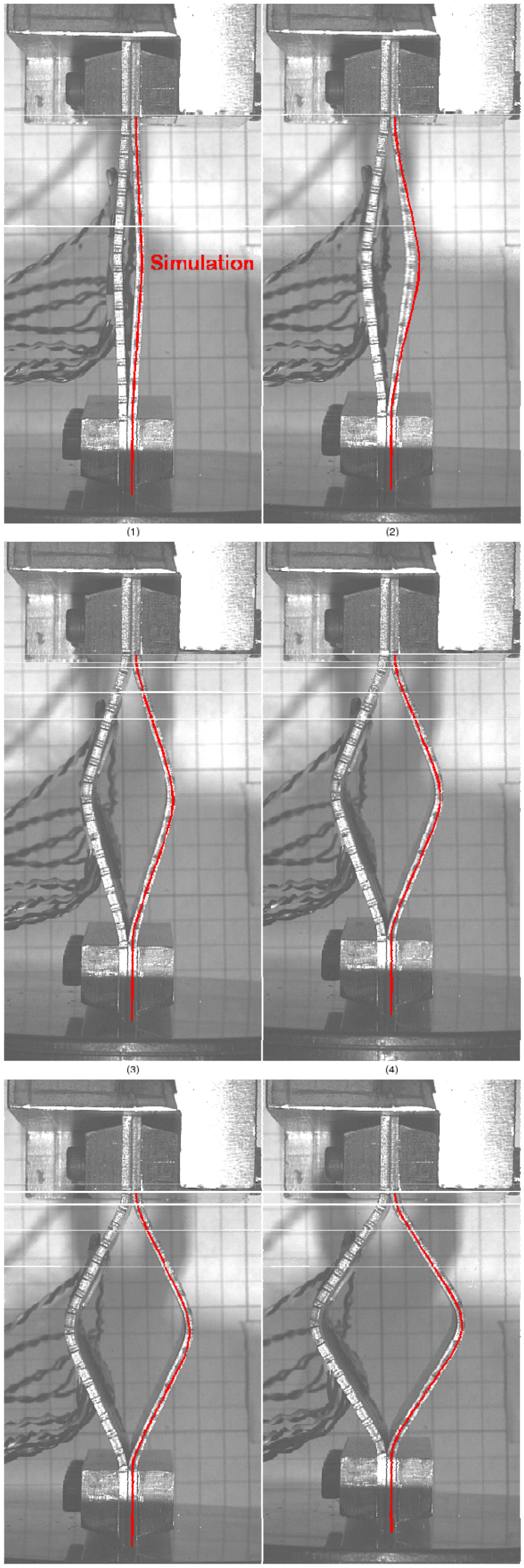

Figure 4. DQSK plate crush test. Crush velocity 0.6 m/s

Simulation of 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. Components are crushed in different modes to investigate crush efficiency, characterize material response and validate models. Different modes of progressive crushing lead to different amounts of energy dissipation in impact. The models are compared to crush tests of different steel grades under various impact velocities. Figure 5 shows typical crushed tubular specimens and the respective crush velocities.

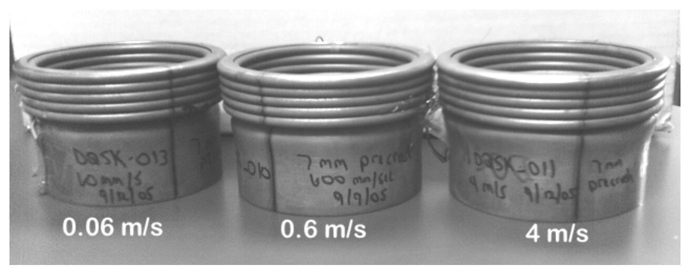

Figure 5. Crushed tube specimens

The comparison between the measured and simulated impact force is shown in Figure 6. The material model used in the simulation uses the latest information from the A/SP experiments and shows the very good agreement with the test. The difference between the measured and simulated force peaks indicates, as in the duble-plate test, that modifications in the material may be needed to account for sudden strain-rate increase.

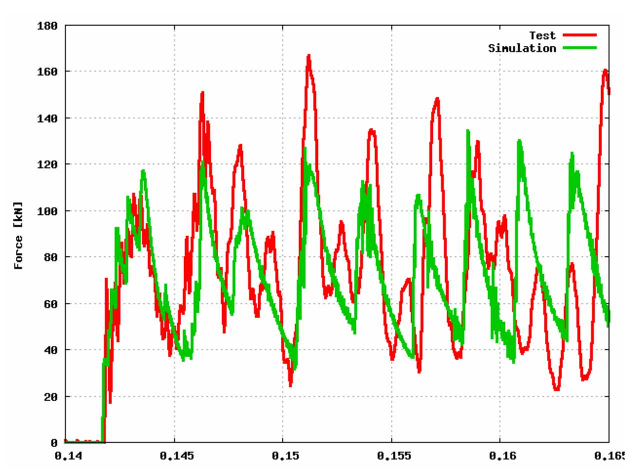

Figure 6. Comparison of test and simulation for tube crush at 4 m/s

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

The remaining most important aspect 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.

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Contact

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