U. Strain-Rate Characterization (ASP 190[i])

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Contractor: United States Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objectives

- Develop new experimental setups for characterization of crashworthiness and strain-rate sensitivity of both high-strength steels (HSS) and structural designs.
- Replicate impact conditions that occur in automotive impact by simpler and more manageable experiments in order to generate meaningful data for computer modeling.

Accomplishments

- Developed experimental setup procedures for new crashworthiness characterization test based on parallel-plates buckling, a procedure developed at the University of Dayton Research Institute (UDRI).
- Developed and conducted constant-velocity crash experiments on circular tubes made of mild steel, dual-phase and transformation-induced plasticity steels.
- Developed graphics-oriented tools for data analysis from parallel-plate and tube-crush experiments

Future Direction

- Develop experiments for characterizing strain and strain-rate history in tubular components in octagonal, spot welded double-hat tube crush tests.
- Provide high-quality data for material and finite-element modeling (FEM) development.

Introduction

Crashworthiness characterization of HSS requires testing of materials and structures under increased strain-rates, large plastic strains, and large displacements that are characteristic of actual impact events. Aside from providing a physically quantitative measure of crashworthiness, the experiments also provide benchmarks for verification of FEM models that are used for automotive design and analysis. Typical crashworthiness experiments involve crushing of tubular objects, such as circular or rectangular tubes. Due to a combination of relatively high velocities and force levels required for progressive crushing, the experiments are usually conducted in inertia-based equipment, such as drop towers or impact sleds. For example, in a drop tower the drop height and the drop mass can be adjusted to generate desired crush force and length. However, there are practical limits on the mass and the velocity that can be used in a drop tower. The kinetic energy of the impact must be such that it can be expended in the deformation of the specimen and the safety restraints in order not to damage the testing equipment. Vibrations of the falling mass are practically impossible to eliminate, and the lateral forces are not easily measured nor controlled. The velocity of impact cannot be kept constant and gradually reduces from the onset of impact.

The objective of this project is to develop and conduct coupon- and component-level experiments for the characterization of crashworthiness of HSS. The project will also provide high-quality data for development of material and structural FEM models, and, therefore, enable more accurate modeling and design of lightweight crashworthy vehicles.

Design of Experiments

Tube Crush Experiments

To improve experimental investigations of the material and structural behavior for automotive impact, the Oak Ridge National Laboratory (ORNL) and the Automotive Composites Consortium (ACC) of USCAR have developed a new integrated virtual and physical test system for hydraulic, high-force, high-velocity crashworthiness experiments of automotive materials and structures. The unique system, a test machine for automotive crashworthiness (TMAC), permits controlled, progressive crush experiments at programmable velocity profiles and high force levels. More details about the TMAC system can be found on http://www.ntrc.org.

The tube crush experiments were conducted at the National Transportation Research Center user facility in Oak Ridge, Tennessee. The TMAC system is shown in Figure 1.

Figure 1. Test machine for automotive crashworthiness.

The ability to control displacement (velocity) and the large lateral stiffness of the machine allows for strain history measurements that are not practical in drop tower equipment. TMAC's high load capacity allows for controlled velocity history during the test. This can be seen from the displacement history in Figure 2. The figure shows the progression of the displacement of the loading plate during the 4 m/s crush test. The slope of the displacement denotes velocity, which was constant for the duration of the first 18 milliseconds corresponding to the investigated tube crush length.

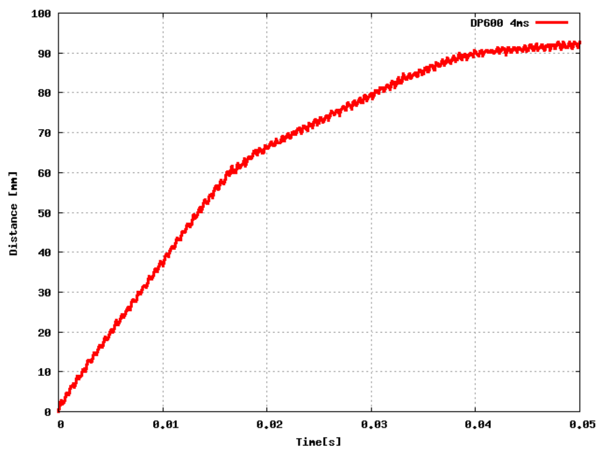

Figure 2. Displacement history for the 4 m/s tube crush.

At this, relatively high, velocity, the data-acquisition-system effects become more pronounced compared to the lower crush speeds. The effects are visible in the small oscillations in distance in Figure 2. These oscillations are of relatively constant amplitude and frequency. The oscillations are of less importance at the low speeds but at high impact speeds may render some calculations invalid. The accurate displacements measurements are needed for deriving instantaneous velocities and crush energy and its rates. One of the possible remedies is to filter the derived quantities. However, such an approach does not clearly link the physical phenomena to the filter interval and its respective parameters. A better approach is to filter the data at the origin so that the data acquisition artifacts do not propagate in the data processing.

When raw displacement is plotted against the measured force for the purpose of calculating the crush energy, the oscillations in the measured displacements become more apparent with the crush-speed increase. This phenomenon is illustrated in Figure 3 where it can be seen that the displacement-force curves become more distorted with increasing crush speeds.

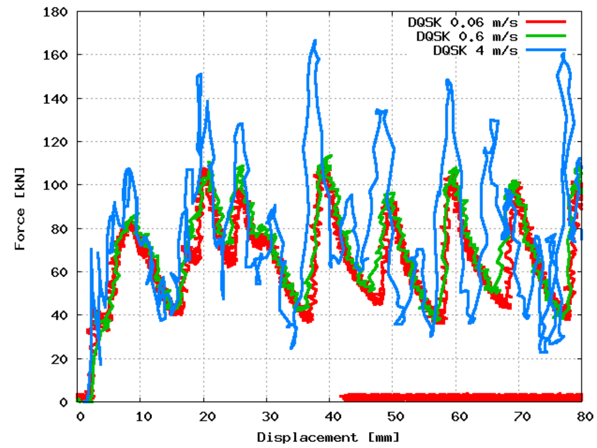

Figure 3. Displacement-force for the DQSK tube crush at various crush velocities.

It is natural to expect that the velocity-based quantities that are needed for rate-type measures will show even higher oscillations as the data-acquisition rate increases with the increasing crush velocity. When looking at the time-displacement trace for 4m/s impact in a short time interval, it was found that displacement raw data have a high-frequency oscillatory component. The displacement raw data were filtered using a second order Butterworth filter according to the SAE J211 with the cut-off frequency of 300Hz to yield a smooth velocity curve in accordance with observed optical traces from the high-speed camera and other system controls. The resulting displacement-force curves for the filtered displacement data are shown in Figure 4.

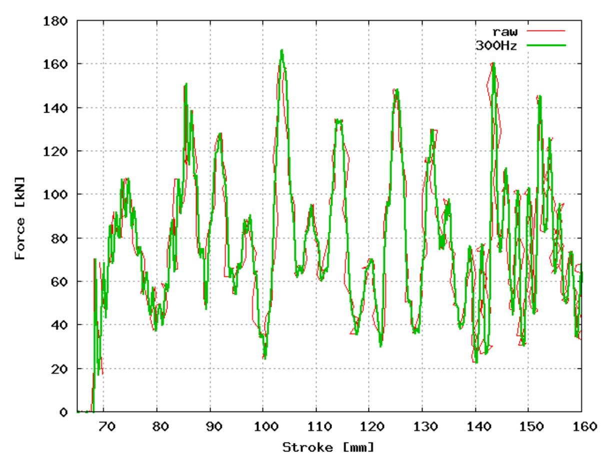

Figure 4. Displacement-force for the 4 m/s DQSK tube crush, entire test interval.

The data with processed displacements allow us to have better quality rate and energy measurements that are needed for characterization of crashworthiness efficiency and correlation with the FEM models.

The first set of materials tested in FY 2005 included mild steel (DQSK), high strength low alloy (HSLA) 350 MPa and dual phase (DP) 600 MPa steels. The test velocities were 0.06 m/s, 0.6 m/s and 4 m/s. These tests were completed in fiscal year (FY) 2006. Different test configurations were made to trigger symmetric and asymmetric crush modes. The symmetric mode is triggered in DQSK and HSLA350 tubes by a specially designed fixture. The DP600 tubes could not be symmetrically crushed primarily due to manufacturing imperfections that could not be overcome by the symmetric pre-crush. The asymmetric crush is triggered by the high imperfection at the impact end of the tube. Axially symmetric crush of HSLA350 tube is shown in Figure 5.

Asymmetric crush of DP600 tube is shown in Figure 6.

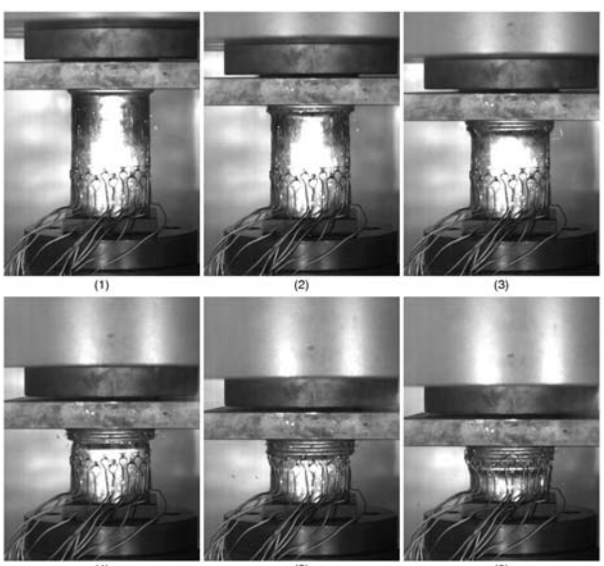

Figure 5. Progressive crush of a HSLA350 tube under constant velocity of 4 m/s. (Numbers below the photographs denote the relative time sequence).

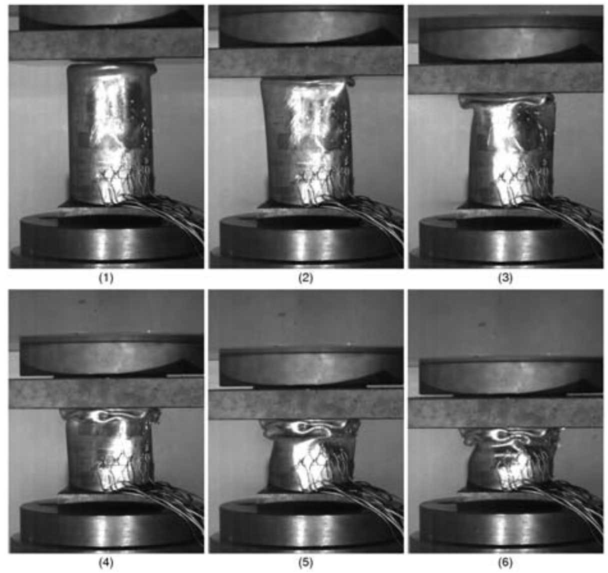

Figure 6. Progressive crush of a DP600 tube under constant velocity of 4 m/s. (Numbers below the photographs denote the relative time sequence).

The goal of the project is to measure and investigate the strain and strain-rate regimes that material experiences during the crush in order to improve predictive capabilities of the numerical models. The principal tools for strain-rate history measurement are electric resistance strain gages. The measured data for the first set of test materials is currently formatted and prepared for web-based data presentation.

A second set of advanced high-strength steel (AHSS) tubes are being tested. The materials included are transformation induced plasticity (TRIP), bake hardenable (BH), dual phase (DP), and interstitial free (IF) steels. The tests will be run under the same crush velocities. (0.06 m/s, 0.6 m/s and 4 m/s). The majority of materials were tested under 0.6 m/s and 4 m/s crush velocity. The remaining tests are scheduled to be completed during November of 2006.

Octagonal tubes made of spot welded profiles were manufactured and delivered for preliminary tests. The test specimen is shown in Figure 7.

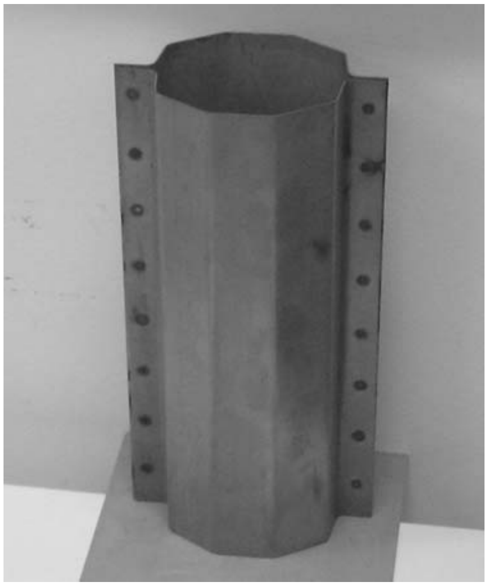

Figure 7. Octagonal tube crush specimen.

The tests will be conducted using the same regime of crush velocities. The measurement of load variation with impact speeds and investigation of corner strains will be the focus of these tests. These tests will be conducted on eight different AISI material grades: BH300, 440W, DP800, TRIP590, TRIP780, TRIP980, Hot Rolled Dual Phase, and TRIP600. For each of these materials, nine tests will be run, corresponding to three replicates at three different test velocities. In each case, two out of the three replicates will be instrumented with a maximum of nine strain gages. The geometry of all the tubes will be the same for all material grades to allow for comparison and common tube fixturing.

Conclusions

Three steel materials have been tested under constant crush velocities. The constant crush velocity and hydraulic-based testing systems provide unique tightly-controlled testing environments for structural and material characterization. The experimental data are used for validation and evaluation of modeling approaches, and for development of modeling guidelines for HSS materials and structures under impact loads.

Acknowledgments

Support from the Auto/Steel Partnership Strain-rate Characterization Team is acknowledged.

Future Work

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

1. Circular tube crush experiments in TMAC test machine for AHSS sheet materials (2^{nd} set)

2. Crushing of octagonal tubes in TMAC test machine. The geometry is characteristic of the front-end designs of new prototype vehicles.

3. Development of new coupon- and structure-level crash characterization experiments.

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[i] Denotes project 190 of the Auto/Steel Partnership (A/SP), the automotive-focus arm of the American Iron and Steel Institute. See www.a-sp.org. The A/SP co-funds projects with DOE through a Cooperative Agreement between DOE and the United Sates Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development. See www.uscar.org.