S. Strain Rate Characterization

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Contractor: U.S. Automotive Materials Partnership
Contract No.: FC26-02OR22910

Objectives

- Develop new experimental setups for characterization of crashworthiness and strain-rate sensitivity of both high-strength steels (HSSs) 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 crash-worthiness 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.

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 constant-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 1. Test machine for automotive crashworthiness.

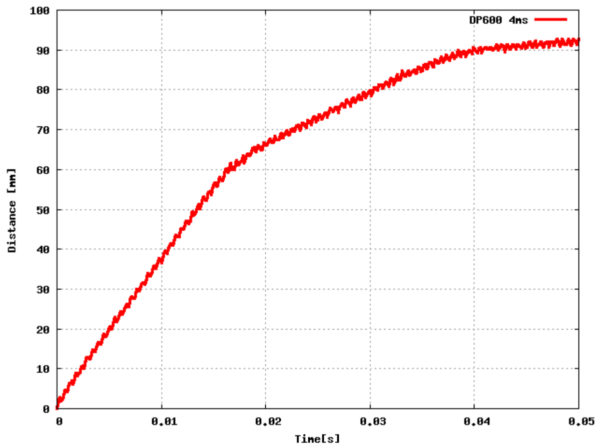

Figure 2. Displacement history for the 4 m/s tube crush

The Auto/Steel Partnership (A/SP) supplied experimental tube specimens. A relatively large diameter provides better bonding with the strain gages and relatively tight manufacturing tolerances alleviate uncertainties due to imperfection sensitivity of the circular tubes. Geometry of the tube specimens is defined by tube length, 178 mm (7 in), diameter, 50 mm (2 in), and wall thickness, 1.6 mm (0.063 in). 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.

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 material experiences large strains during progressive crush and, therefore, high elongation gages have to be used. The gage placement, bonding and data acquisition were determined in the previous studies. The tube force was measured by a set of load cells and a load washer. The data from load sensors, displacement trace, and high-speed camera are synchronized, and together provide comprehensive information about the progressive crush and crashworthiness.

Deformation modes of circular tubes are very imperfection-sensitive since the characteristic energy dissipation of different modes is very similar. Such uncertainty can also be exploited as different modes of deformation can be triggered with appropriate modifications of tube geometries and boundary conditions. We have considered several test configurations for inducing various symmetric and asymmetric deformation modes. Axially-symmetric crush in mild steel (DQSK) and High Strength Low Alloy (HSLA) tubes was triggered using the developed pre-crush adapter. The loading adapter generates symmetric deformation as shown in Figure 3.

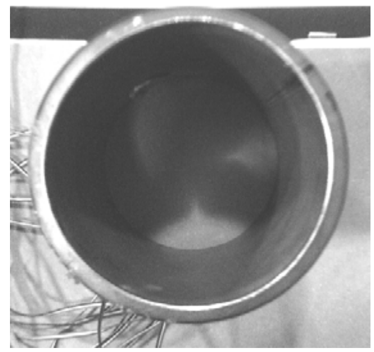

Figure 3. Pre-crush for mild steel tube

The pre-crushed specimens are then crushed with different test velocities. Axially-symmetric crush of a mild steel tube is shown in Figure 4.

Specimens tested with different velocities for the same crush length are shown in Figure 5.

The force-time histories for two different specimens crushed with 4 m/s are shown in Figure 6.

The effect of crush speed on the overall force levels can be analyzed by comparing force-distance signals for tests. Figure 7 compares the force levels for tests run at 2 velocities, 0.6 m/s and 4 m/s, respectively.

Asymmetric tube crush is more prevalent in automotive crush, as the structural component geometries have more complex shapes and loading conditions. Asymmetric crush modes in circular tube specimens were triggered by tube height modifications. This mode is also more likely in the high-strength steel structures.

The crush speed sensitivity of HSLA and DP steels is shown in Figures 8 and 9. The tubes were crushed in unsymmetric modes.

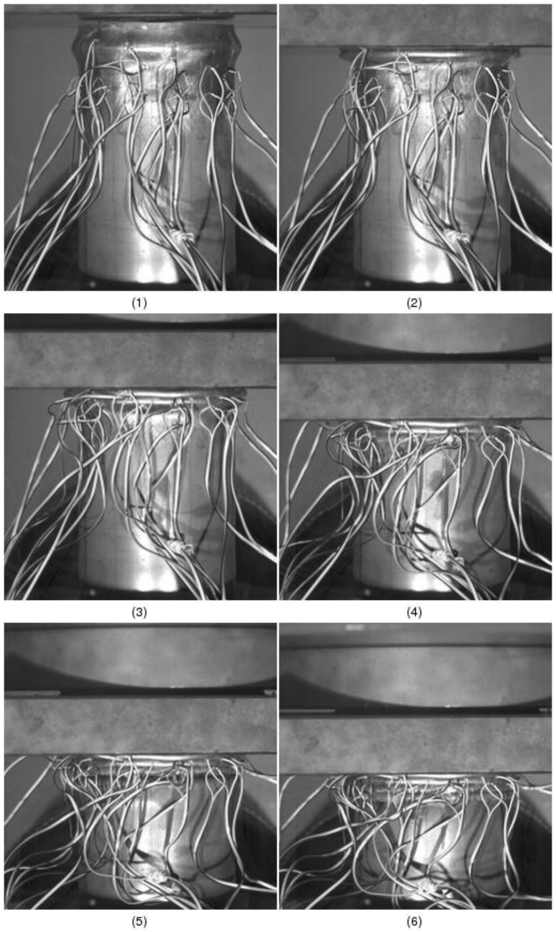

Figure 4. Progressive crush of a mild steel tube under constant velocity of 2 m/s. (Numbers below the photographs denote the relative time sequence)

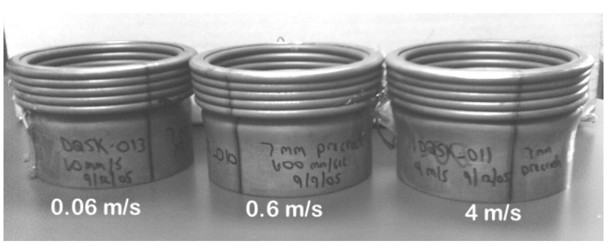

Figure 5. Specimens crushed under different velocities (Numbers in photograph denote crush speeds)

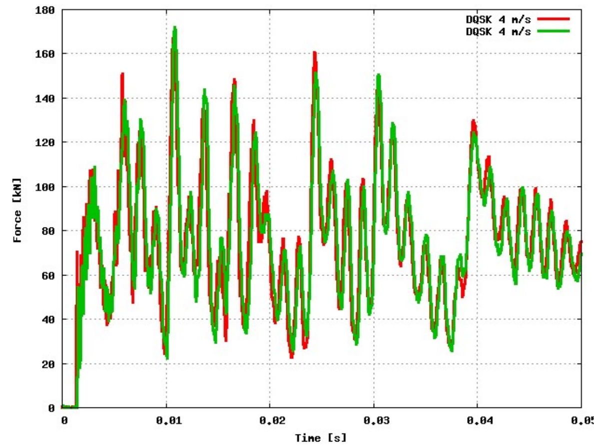

Figure 6. Crush force history of mild steel tubes for the symmetric crush at 4 m/s. (The overlap of the force traces indicates the repeatability of the test).

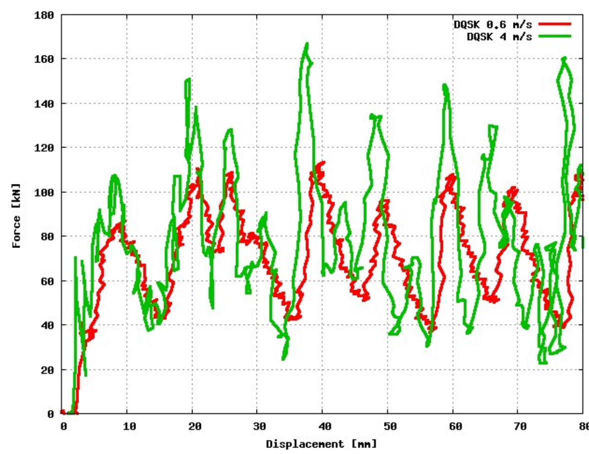

Figure 7. Force-crush distance data for crash tests at two velocities

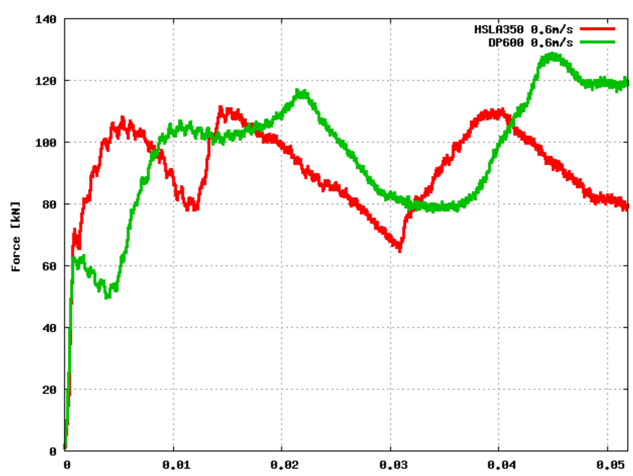

Figure 8. Crush test with 0.6 m/s

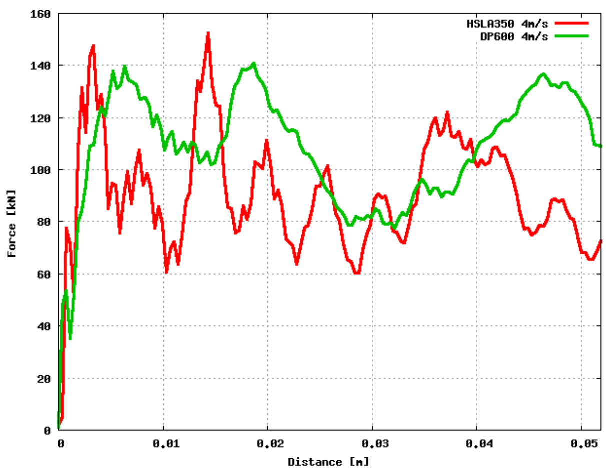

Figure 9. Crush test with 4 m/s

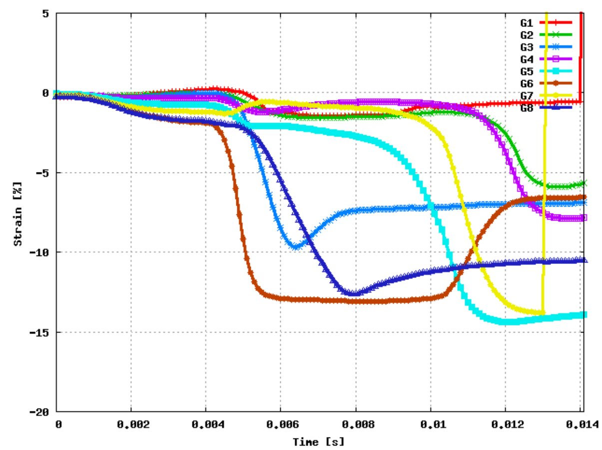

Figure 10. Strain history of axial strain gages for DP tube during 4 m/s crush

Figure 8 compares impact forces for HSLA 350 and DP 600 materials under crush speed of 0.6 m/s, whereas Figure 9 shows force traces less than 4 m/s crush. The results show different trends of the two materials and indicate higher crush speed sensitivity of DP 600 materials than can be deduced from the coupon-level uniaxial-loading data available in the literature. This, in turn, indicates that constitutive model modifications are necessary in order to account for this behavior as lower strain-rate sensitivity of DP 600 material in uniaxial configurations would result in corresponding force-level sensitivity in crush tests.

Each specimen is instrumented with multiple strain gages that record strain histories in axial and hoop directions of the tube. A typical recording of the axial strain gages during 4 m/s crush test is shown in Figure 10. Label numbers indicate gage identifiers that in turn are ordered away from the crushed end.

The strain histories of the gages positioned at the same location but for the different crush velocities can be compared in order to investigate loading conditions for different velocities. Figure 11 shows strain histories as functions of crush length for crash tests at 0.6 m/s and 4 m/s, respectively.

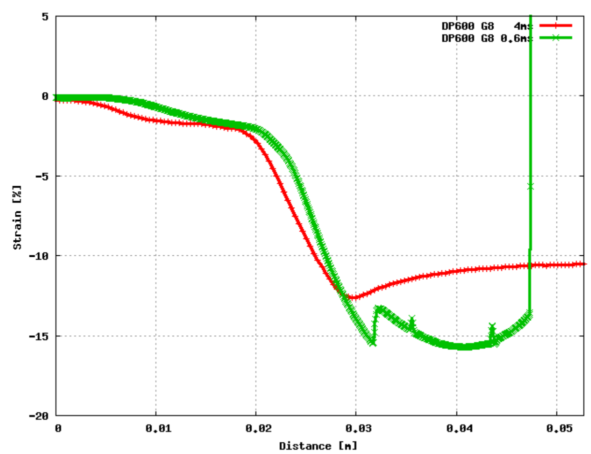

Figure 11. Axial strain gage data for crush tests at two different velocities.

The figure above indicates that the strain rate experienced by the material is proportional to the crush speed. The overall magnitude of the strain rate is recorded, as well. Such information is used to determine the range of testing conditions at the coupon level that are needed for material characterization.

A new analysis environment for tube crush data has been developed using DIADEM software from National Instruments. Computer programs were developed to synchronize multiple data channels to allow for simultaneous analysis of crush sequence, deformation, forces and velocities. The results are then viewed by a DIADEM viewer and distributed to the project participants. The results are shown in Figure 12.

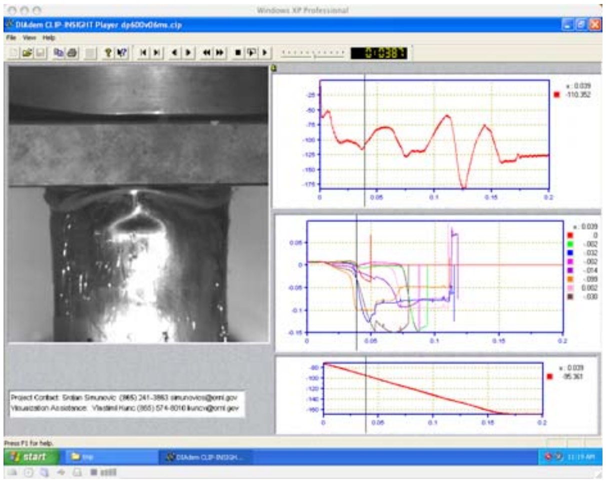

Figure 12. Tube crush data presentation

Such a coupled form of information has not yet been available in the automotive impact analysis and together with the unique experimental facility, provides new information for material analysis and benchmark for material and FEM model evaluation and development.

Conclusions

New experimental setups have been developed for characterization of crashworthiness of HSS. The experiments are based on hydraulic-based testing systems. The 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. The high-quality data is combined into a comprehensive viewing format.

Acknowledgments

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

Future Work

The future work on the project will focus on two remaining topics:

1. Circular tube crush experiments in TMAC test machine for various steel sheet materials.
2. Crushing of octagonal tubes in TMAC test machine. The geometry is characteristic to the front-end designs of new prototype vehicles.
3. Development of new coupon and structure-level crash characterization experiments.