B. Intermediate-Rate Crush Response of Crash Energy Management Structures

Principal Investigator: J. Michael Starbuck
Oak Ridge National Laboratory
P.O. Box 2009, Oak Ridge, TN 37831-8048
(865) 576-3633; fax: (865)-574-8257; e-mail: starbuckjm@ornl.gov

Project Manager, Composites: C. David Warren
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6065
(865) 574-9693; fax: (865) 576-4963; e-mail: warrencd@ornl.gov

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

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Contractor: Oak Ridge National Laboratory
Contract No.: DE-AC05-00OR22725

Objective

- Develop unique characterization facility for controlled, progressive-crush experiments, at intermediate rates, of automotive materials (polymer composites, high-strength steels, and aluminum) and structures.
- Study the deformation and failure mechanisms of automotive materials subjected to crush forces as a function of impact velocity.
- Obtain specific energy absorption and strain data, and correlate with deformation and failure mechanisms to describe the unknown transitional effects from quasi-static to high loading rates for polymer composites.
- Characterize the strain-rate effects for metallic materials and components.
- Provide access to this unique test capability to university, industry, and government users for collaborative research.

Approach

- Develop a unique, high-force (270-kN), high-velocity (8-m/s) servo-hydraulic machine to conduct progressive crush experiments on structural components at intermediate rates.
- Use high-speed imaging to observe and document deformation and damage mechanism during the crush event.
- Conduct strain measurements at discrete locations and explore full-field measurements of strains and curvatures.
- Coordinate polymer composites investigations with the Automotive Composites Consortium (ACC) Energy Management Group.
- Coordinate steel investigations with the Auto/Steel Partnership.

Accomplishments

- Procured high-speed video system.
- Completed glass-fiber-reinforced composite-tube testing that clarified the transition region from static to dynamic.
- Completed tube testing under Stanford University User Proposal,
- Completed preliminary testing on sandwich panels for University of Utah. (See report 4.I.)
- Completed preliminary testing on magnesium tubes for Swinburne University of Technology, Australia.
- Completed tube testing in support of Crash Analysis of Adhesively Bonded Structures (CAABS) Project. (See report 4.J.)
- Completed tube testing in support of the Auto/Steel Partnership Strain-Rate Characterization project. (See report 2.S.)
- Developed improved data acquisition software for strain-gage measurements.
- Developed streamlined software for interfacing force-displacement data with high-speed video.

Future Direction

- Explore techniques for full-field measurements of strains and curvatures.
- Develop User Interaction Plan.
- Support user collaboration as required.

Introduction

Progressive crush is an important mechanism by which the kinetic energy of a traveling automobile is dissipated in a collision to protect the safety of occupants. Unfortunately, the mechanisms governing the progressive-crush response of some emerging automotive materials are not well understood. Additionally, many of these materials are known to exhibit responses that are sensitive to rate of loading.

Understanding the influence of impact velocity on the crush response of materials and structures is critically important for crashworthiness modeling inasmuch as collisions occur at a range of velocities. Additionally, from a structural standpoint, the deformation (or strain) rate is generally not unique from either a spatial or temporal standpoint. Consequently, it is important to quantify the behavior of materials at various strain rates.

Test Machine for Automotive Crashworthiness (TMAC)

Typically, standard test machines are employed for experiments at quasi-static rates, whereas drop towers or impact sleds are the convention for dynamic rates. These two approaches bound a regime within which data, for experiments at constant impact velocity, are not available by conventional experimental practice. This regime is termed herein the intermediate-rate regime and is defined by impact velocities ranging from 1 m/s to 5 m/s. Investigation of rate effects within this regime requires experimental equipment that can supply a large force with constant velocity within these rates. Using a drop tower or sled at intermediate rates, although technically possible, is problematic due to the prohibitively large mass required to maintain constant velocity during the crush. Consequently, the Oak Ridge National Laboratory (ORNL) and the Automotive Composites Consortium (ACC) collaborated to define specifications for a unique experimental apparatus that mitigates the shortcomings of existing equipment. MTS Systems Corporation designed and built the servo-hydraulic test machine, referred to as the TMAC. TMAC is uniquely capable of conducting controlled, progressive-crush tests at constant velocity in the intermediate-velocity range (i.e., less than 5 m/s) because of the large energy available at those rates and to the sophisticated simulation and control software that permits velocity uniformity to within 10%.

The new experimental facility is being used to understand the crush behavior between the static and dynamic (8-m/s) conditions. The installation of the TMAC at its National Transportation Research Center (NTRC) Knoxville, Tennessee, location is shown in Figure 1.

Figure 1. Installation of TMAC in the NTRC Composite's Lab.

Status

Since the last reporting period, activities have focused on supporting users, developing and promoting user interactions, and improving data acquisition.

In FY 2004, a test matrix on glass-fiber-reinforced composite tubes was completed and the experimental data were supplied to the ACC. The tubes were approximately 50 mm x 50 mm square and used an internal plug with a radius as an initiator. A total of 60 tests were initially conducted: six specimens/velocity/material; five velocities (5 mm/sec, 1000 mm/sec, 2000 mm/sec, 3000 mm/sec, and 4000 mm/sec); and two materials (one braided and one fabric). The results showed that the transition between static and dynamic was below the 1000-mm/sec test velocity. In FY 2005, additional tests were run at 250 mm/sec and 500 mm/sec. The results are shown in Figure 2 and clearly indicate that a transition exists. The test specimens have been sectioned and photographed to determine if a physical phenomenon exists that correlates with the transition from static to dynamic test velocity. Complete documentation of this work is in preparation and is being coauthored by Ford Motor Company.

In addition to the glass-fiber-composite tubes tested there were carbon-fiber tubes tested for Ford Motor Company under a user proposal. The objective of this project was to collect experimental data that

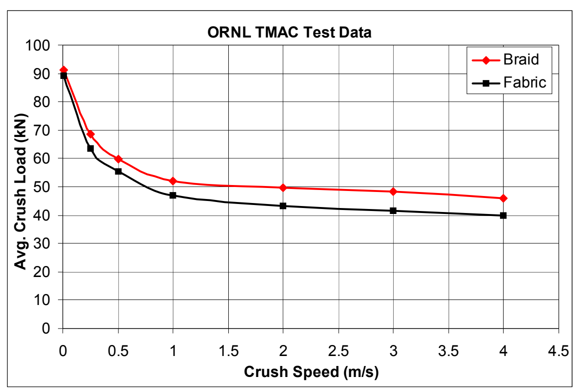

Figure 2. Average crush load versus speed for glass-fiber-reinforced composite tubes.

would help in quantifying the contribution that different failure mechanisms have on the total energy absorbed. This work was completed and the results are to be presented at the 2006 SAMPE Conference.

Stanford University, under ACC Cooperative Agreement funds, has a research project to create a finite element material model that describes the response and failure behavior of braided composite materials. These materials can be used to absorb energy in automotive, aerospace, or other crashes. In order to model the material and to verify numerical predictions, crush tests must be conducted on representative samples, in this case, triaxially-braided composite tubes crushed at several rates using a plug initiator. It is expected that the energy absorption of dynamically-crushed tubes will be lower than statically-crushed tubes that have been crushed previously and that the energy absorption will be sensitive to braid angle.

The scope of work for Stanford University's User Facility proposal included testing of composite tubes to provide essential data for verification of their finite element models. The following tube configurations and velocities were tested.

Square tube

- 30° Braid angle
  - 3 tubes at 1 m/s
  - 3 tubes at 4 m/s
- 45° Braid angle
  - 3 tubes at 1 m/s
  - 3 tubes at 4 m/s
- 60° Braid angle
  - 3 tubes at 1 m/s
  - 3 tubes at 4 m/s

Circular tube

- 30° Braid angle
  - 3 tubes at 1 m/s
  - 3 tubes at 4 m/s
- 45° Braid angle
  - 3 tubes at 1 m/s
  - 3 tubes at 4 m/s
- 60° Braid angle
  - 3 tubes at 1 m/s
  - 3 tubes at 4 m/s

The force and displacement versus time traces, and high-speed video for each test were provided to Stanford University for analysis. This work was part of a graduate student's Ph.D. dissertation. The student has successfully defended his work and publication of these results is in progress. Preliminary tests were completed on sandwich panels for the University of Utah (see report 4.I) and on magnesium tubes for the Swinburne University of Technology, Australia. These tests were conducted to determine appropriate specimen geometries and fixture requirements for future potential user proposals. Examples of these tests are shown Figures 3 and 4 where snap-shot images from the high-speed video were taken. Figure 3 shows a carbon-fiber facesheet with balsa wood core sandwich panel being compressed along one edge. This image captures the sandwich panel failing by buckling and core shear failure. A progressive-crush mode could not be achieved using this specimen geometry and fixture. The University of Utah has redesigned their test fixture and is currently drafting

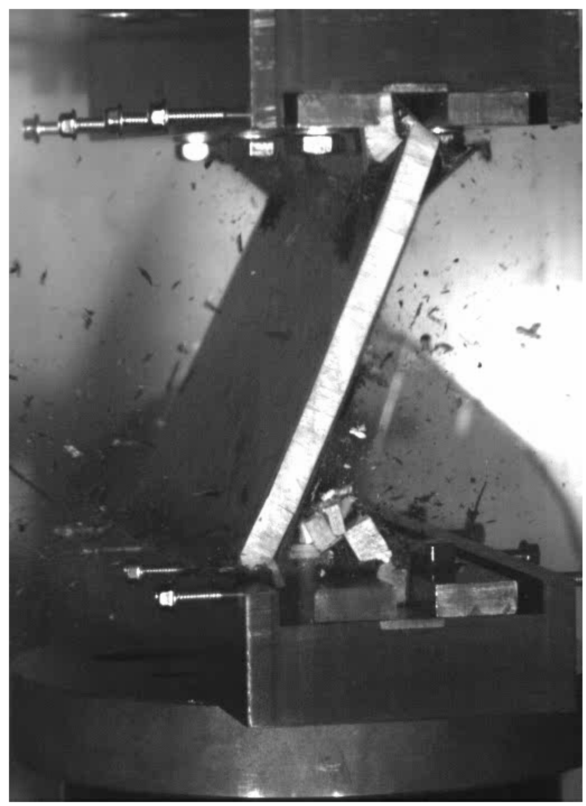

Figure 3. End-loaded compression test on composite sandwich panel having a balsa wood core.

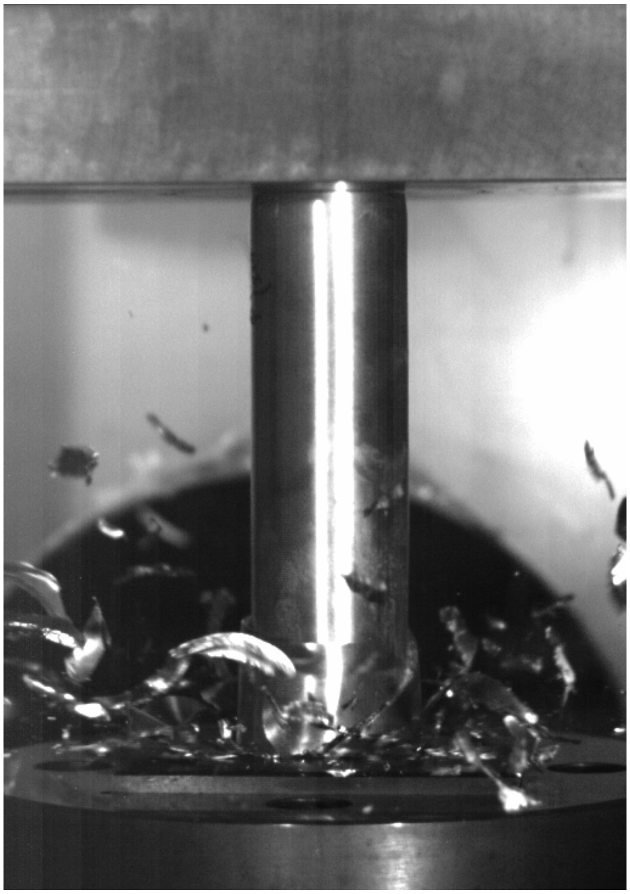

Figure 4. Progressive crush of a magnesium tube.

a new User Facility proposal. A magnesium tube being crushed is shown in Figure 4. This tube underwent a tremendous amount of elastic deformation before failing via multiple fractures. The data from the magnesium tubes tests were provided to the research professor at Swinburne University for his review.

Other interactions with potential users have taken place with Rutgers, Massachusetts Institute of Technology, SAE High Strain Rate Plastics Consortium, General Motors, and Imperial College (London, England).

Project Support Activities

Extensive testing was completed on TMAC in support of both the ACC Crash Analysis of Adhesively Bonded Structures (CAABS) project (see report 4.J) and the Auto/Steel Partnership (A/S-P) Strain-Rate Characterization project (see report 2.S). For the CAABS project, 30 tubes were tested that quantified the effect that adhesive bonds have on energy absorption. In support of the A/S-P project, 30 tubes were tested for determining strain-rate sensitivities in high-strength low-alloy steels and dual-phase steels. Strain gages were used in these tests to locally measure the strains associated with plastic hinge formation in metal tubes undergoing progressive crushing.

Conclusions

TMAC provides a unique capability to measure the specific energy absorption on crush tubes and other specimen geometries as a function of (constant) impact velocity within a range from quasi-static to 8 m/s.

During the past reporting period, tests were conducted to further characterize glass-fiber-composite tubes at 2 velocities below 1000 mm/sec. These tests provided critical data that definitely showed the transition from static to dynamic response that was previously unavailable using other test methods. Also, braided-carbon-fiber tubes were completed for Stanford University under a User's Facility proposal. Additional scoping tests were conducted for the University of Utah and for Swinburne University of Technology, Australia, in support of developing future user proposals. TMAC was also instrumental in meeting project objectives for the CAABS and A/S-P projects. In all of these tests, high-speed video was recorded to document the failure mechanisms using a state-of-the-art CMOS camera that was procured for the TMAC installation.

Presentations/Publications/Patents

None