2002-01-1954

A Novel Capability for Crush Testing Crash Energy Management Structures at Intermediate Rates

Raymond G. Boeman
Oak Ridge National Laboratory

Ari G. Caliskan
Ford Motor Company

ABSTRACT

The crush performance of lightweight composite automotive structures varies significantly between static and dynamic test conditions. This paper discusses the development of a new dynamic testing facility that can be used to characterize crash performance at high loads and constant speed. Previous research results from the Energy Management Working Group (EMWG) of the Automotive Composites Consortium (ACC) showed that the static crush resistance of composite tubes can be significantly greater than dynamic crush results at speeds greater than 2 m/s. The new testing facility will provide the unique capability to crush structures at high loads in the intermediate velocity range. A novel machine control system was designed and projections of the machine performance indicate its compliance with the desired test tolerances. The test machine will be part of a national user facility at the Oak Ridge National Laboratory (ORNL) and will be available for use in the summer of 2002.

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 passengers. Unfortunately, the progressive crush response of some emerging lightweight materials is not well understood. Additionally, many of these materials are known to exhibit responses that are sensitive to strain rate.

One candidate material for lightweight impact structures is polymer composites. This class of materials offers one of the highest strength to weight ratios. Furthermore, the anisotropic nature of these materials allows one to design at the microstructural as well as the macrostructural level. However, because of this anisotropy, the failure mechanisms associated with these materials are very complex. These mechanisms include fiber and matrix fracture, debonding, and delamination. The presence of specific failure mechanisms and perhaps their sequence of occurrence may be influenced by the rate of loading. These issues arise not only for complex crush forces, but also for simple one-dimensional loading conditions. The ultimate challenge is to predict accurately the crush energy absorption of such structures so that they may be used as alternative materials in designing impact structures. This cannot be done without understanding and inclusion of rate effects.

For steels, it is known that the strength of the material increases with increasing deformation rates. Rate-sensitive material data is not currently available for the rates consistent with vehicle crashes. Current conventional analysis relies on the use of assumed parameters to represent the rate-dependency.

Unlike steels, the effects of loading rate for aluminum alloys are small within the speeds experienced during vehicle impacts. The difference in load response is important for crashworthiness since accidents can occur at various velocities. As a result, it is important to understand the behavior of materials at various loading rates, so that a given structure can be designed to absorb impact energy at both low and high speeds.

Typically standard test machines are employed for tests 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 tests at constant impact velocity, is not currently available. 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 test equipment that can supply a large force with constant velocity within these rates. Using a drop tower or sled at intermediate rates, although feasible, 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) are developing a unique testing capability to conduct tests on automotive materials within the intermediate rate regime.

BACKGROUND – A COMPOSITES CASE STUDY

The need to test within this intermediate rate regime can be established by considering the following case study on composites. There are many factors that can affect the crush behavior of composites. Some of the more significant factors include the material type, geometry, fiber orientation, and impact speed. Among these factors, the effects of impact speed have been the most difficult to understand. In a previous study, hollow square tubes with a 50 mm x 50 mm outside dimension made of various fiber types and thickness were tested quasi-statically and dynamically. A typical specimen with a plug-type initiator is shown in Figure 1. Results indicate that identical tubes tested under dynamic conditions absorbed dramatically less energy than those tested quasi-statically [1,2] as can be seen in Figure 2.

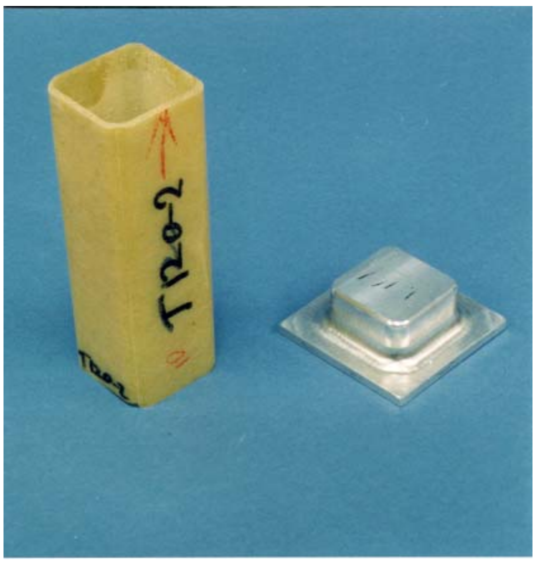

Figure 1. Typical composite hollow-section tube with plug-type crush initiator.

A subsequent examination of these tubes showed some differences in crush mode between the dynamically and statically tested tubes as shown in Figure 3. In general, tubes that were crushed dynamically showed more delaminations than those tested statically [3]. One of the assumptions during the initial set of tests was that impact speed would not affect the crush behavior. As a result, the impact speed was not kept constant for all tests. In addition, during the impact tests, the impactor speed naturally decreases as the tube absorbs more energy. Because of these factors an explanation as to why the decrease in energy absorption could not be made.

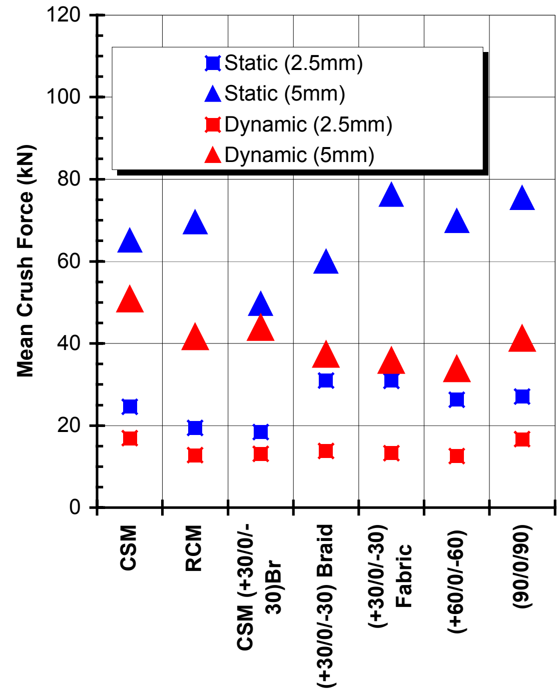

Figure 2. Mean crush force for various fiber types at 2.5 mm and 5 mm wall thickness. [1,2]

a) Quasi-static

b) Dynamic

Figure 3. Sectioned (0/±30) braided tubes tested at quasi-static (a), and dynamic (b) rates. Dynamically tested tube experienced significant delamination. [3]

After these studies, a new research program was put in place to examine the effects of impact speed on crush performance. Both (0/±30) braid and fabric tubes were chosen as the specimens. Previous studies showed these material types to have the greatest difference between static and dynamic loading conditions. As a part of investigating the effect of impact speed, the study also aimed at determining if there is a threshold speed at which a change in the failure mode occurs that leads to the differences between static and dynamic crush loads. The tubes were crushed at speeds from quasi-static to 10 m/s at constant or nearly constant velocity. The quasi-static tests were performed on a conventional servo-hydraulic material testing machine at 0.083 mm/sec. The tests between 3–10 m/s were performed on an impact sled with enough kinetic energy to crush the specimens at (essentially) constant velocity. For decreasing speeds, a near zero change in velocity during crush requires an increasing amount of sled mass. However, the sled that was used in this study did not have the capacity to hold an ever-increasing amount of weight. Furthermore, it is practically impossible to achieve a near zero velocity change within this speed range since the mass requirements are outside any known testing apparatus. From Figure 4 it is apparent that for rates ranging from 3–10 m/s there is virtually no change in the energy absorption. Similarly, results within the quasi-static rates are uniform within the confines of material variability. Currently, it is unknown what rate-influenced mechanisms within the material or geometry are responsible for the large difference between static and dynamic energy absorption seen in Figure 4. Data for quasi-static rates are connected to data for dynamic rates by a dotted straight line in Figure 4. It is unknown how the actual mean crush force varies as a function of impact velocity within this intermediate rate regime. The new test facility will be used to understand the crush behavior between the static and dynamic (2m/s) conditions.

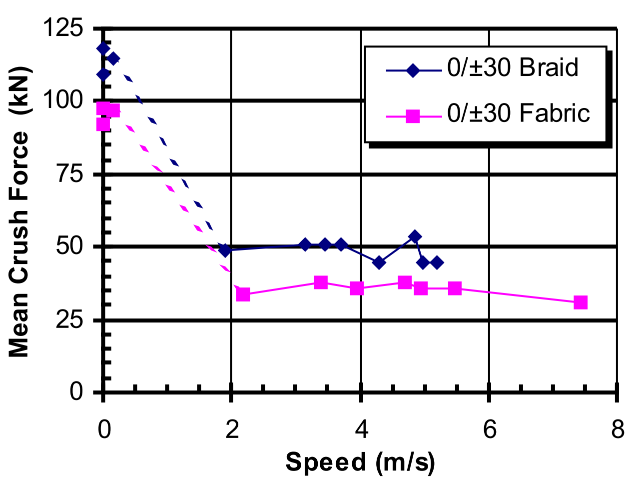

Figure 4. Mean crush force as a function of crush speed for (0/±30) fabric and braided tubes. [3]

LARGE-FORCE, INTERMEDIATE-RATE TEST CAPABILITY

As documented in the case study above, a test capability that can provide crush data – at constant velocity – is required to gain an understanding of the rate dependence of many materials. Consequently, inquiries were extended to the technical community in search of suitable equipment to conduct such tests. No known equipment was in existence or commercially available that could handle the test requirements established by the ACC. High-rate servo-hydraulic test machines generally have low force capacity (on the order of 5 kN) and rely on poppet valves to initiate the pulse. For low energy test conditions, poppet valves work well, but for component crush tests significant velocity degradation would occur as the energy is absorbed. Drop towers and impact sleds are the convention for dynamic rates. However, using a drop tower or sled at intermediate rates is problematic due to the prohibitively large mass required to maintain constant velocity during the crush. Consequently, the ACC and ORNL partnered to define specifications for a unique test machine that mitigates the shortcomings of existing equipment. MTS Systems Corporation was selected to design and build a high-rate, large-force test machine to meet the specifications.

REQUIREMENTS – The performance requirements for the machine were set as follows:

- *No-Load Operation:* Stroke greater or equal to 220 mm at velocities greater or equal to 6 m/s. Velocity constant to within ±10% for 115 mm.
- *133 kN Mean Crush Force:* Stroke greater or equal to 240 mm at velocities greater or equal to 4 m/s. Velocity constant to within ±10% for 115 mm.
- *267 kN Mean Crush Force:* Stroke greater or equal to 115 mm at velocities greater or equal to 4 m/s. Velocity constant to within ±10% for 115 mm.

It should be noted that these mean crush forces are considerably higher than expected under normal test specimen configurations. Additionally, the design was required to support axial testing of long specimens by providing a minimum daylight of 900 mm and which could be reduced with spacers and fixtures for shorter samples. No machine meeting these requirements is known to exist in the world.

MTS's solution was to integrate and enhance technology serving three of their product areas: materials testing, automotive testing, and metals forming. The hardware design is largely based on a unique research forging press recently developed for the University of Gent in Belgium. Software is based, in part, of MTS's dynamic vehicle simulation software. Machine control is based on their materials testing systems.

The design, as seen in Figure 5, is a closed-loop servo-hydraulic machine operating in open-loop mode for dynamic testing. It features unique hardware and software components for control and simulation. The system provides an integrated hardware and software solution for crush experiments as described below.

HARDWARE FEATURES – The machine features a four-column, fixed-crosshead design, providing exceptional stiffness. An actuator rated at 490 kN with a 250 mm stroke and an integral LVDT displacement transducer is mounted in the crosshead with a hydrostatic bearing to provide side-load capacity of 450 kN. Four, three-stage servovalves rated at 1500 L/min provide a total flow capacity of 6000 L/min with the aid of top-mounted accumulators with capacity of 110 L. An additional low flow rate servo valve is provided for slow-speed operation and positioning. An actuator-mounted mass of 450 kg is provided to store additional energy to mitigate influences of peak forces and specimen variations. MTS's TestStar controller and electronics provides digital servo control, function generation, machine required data acquisition, hydraulic control, and digital I/O. Function generation is provided by a 32-bit processor. Data acquisition within the TestStar system provides 16-bit resolution at 5KHz for one to 14 channels. Dedicated DAQ cards and the LabVIEW Virtual Instrument software will provide additional high-speed data acquisition.

SOFTWARE FEATURES – Software components of the system consists primarily of the following three interacting components:

- *TestStar Software*: This software provides the real-time software interface to the electronics and hardware for machine control.

- *Advanced Drive File Generation: (ADFG):* This component is required since the response time of the feedback signal is not sufficient for closed-loop operation. From input data on machine characteristics and anticipated specimen response it generates a complex servo drive file to be used by TestStar to control the machine response. Prior to a physical test it is used in conjunction with the IDM to iterate until convergence is obtained for the input parameters given.

- *Interactive Dynamics Model:* (IDM): This component takes the drive file generated by ADFG and runs a simulation of the machine response. Prior to a physical test it is used in conjunction with the ADFG to iterate until convergence is obtained for the input parameters given.

Figure 5. High-rate, large-force test machine for intermediate-rate, progressive-crush testing.

The software interaction is shown schematically in Figure 6. Based on a desired velocity and an anticipated force-crush response from the specimen, the ADFG module defines a drive file for TestStar. The force-crush response is what is actually desired from the test – it is not known *a priori*. Therefore, a reasonable estimate, in terms of average crush force, must be assumed. Next the IDM module is used to simulate the machine response in a virtual test. Iteration between the ADFG and IDM modules is performed until the convergence criteria are met. Then a physical test can be conducted. The measured machine response is compared to the programmed response to determine whether the test was satisfactory. If not, the ADFG can "learn" from the test by using the actual force-crush data of the first test as input to ADFG and IDM for iteration. Obviously, the simulation iteration step could be eliminated in favor of direct learning from specimen data. This is likely to require a few, if not several iterations, consuming many potentially expensive specimens. The IDM module minimizes the number of specimens consumed.

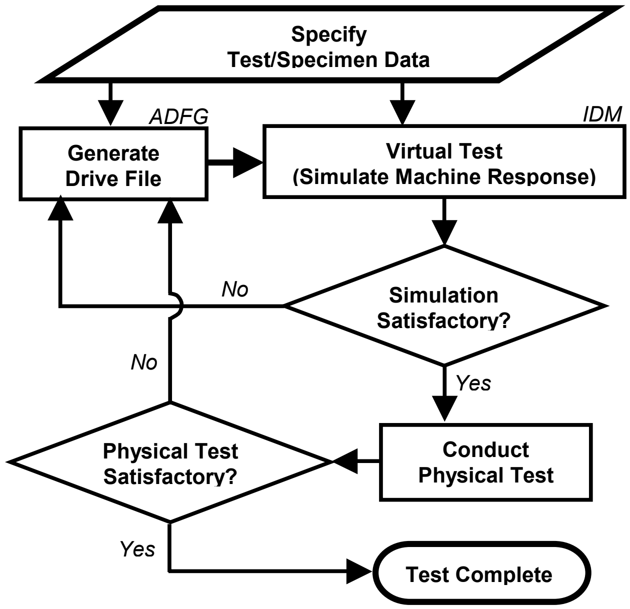

Figure 6. Test procedure and software interaction for the large-force, high-rate test machine.

<u>Simulations</u> – As part of the design process, simulations were conducted to assess the systems performance. The ability of the machine to meet performance requirements was evaluated as well as the sensitivity of the machine response, i.e. velocity, to variations in average crush force. The former factor is largely controlled by the ability to move large volumes of oil rapidly and the sophistication of the simulation and inverse models, and their interaction. Simulations suggest that the machine should perform nicely within the performance requirements. Recalling that the system has an extremely high flow rate of oil upon the actuator, it is important to note that the force and velocity capacity is dependent on the flow in a compromise scenario. That is, higher force results in lower velocity. Higher velocity reduces force capacity. Since the performance requirements were set conservatively for both mass and velocity, there is high confidence that the actual machine performance will exceed the testing needs.

The latter factor, specimen variation, is effectively mitigated by the 450 kg added mass. Considerable energy is stored by the mass such that small variations within a specimen or from specimen to specimen would not affect the machine response. For example, Figure 7 depicts the results of a simulation for a specimen in which the drive file was generated for a mean crush force of 22.5 kN and a velocity of 4 m/s. For a drive file generated with limited iteration, the mean simulated velocity is within 13% of target and the velocity varied approximately 5% over more than 200 mm of stroke. These results would improve with additional iteration. Figure 8 depicts the results for a test using the same drive file but on a specimen with a mean crush force 15% greater without additional optimization. The mean simulated velocity is with 8% of target and the velocity varied approximately 3% over the stroke. This illustrates the robustness of the system, which is attributable to the high kinetic energy stored in the 450 kg mass. It should be noted that velocities in Figure 8 are closer to target than those of Figure 7 as a result of using a drive file not fully optimized and are not anticipated to be a general result.

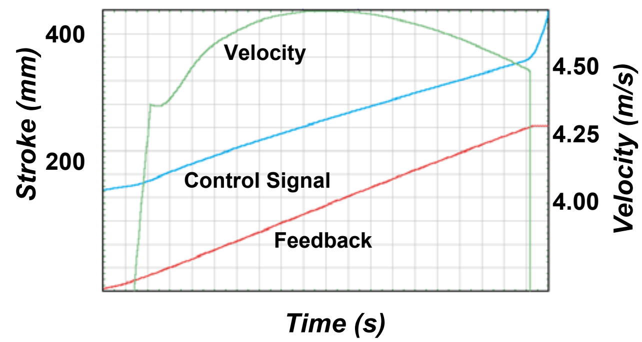

Figure 7. Simulation of machine response controlled by a drive file generated for a specimen with a mean crush force of 22.5 kN and a target velocity of 4.0 m/s. The drive file was generated with minimal iterations and thus is not fully optimized.

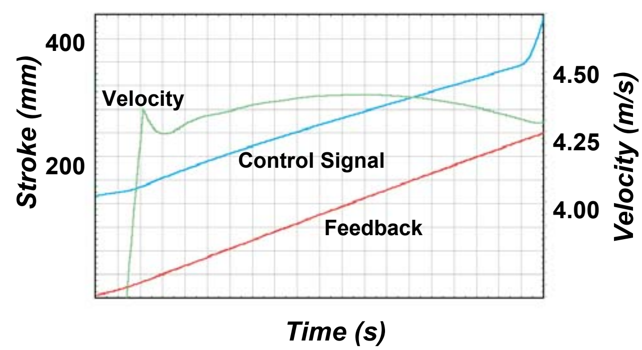

Figure 8. Simulation of machine response for a specimen with a mean crush force 15% greater than that used to generate the drive file. The drive file is the same as in Figure 7. The drive file was generated with minimal iterations and thus is not fully optimized.

STATUS – The test machine is in final assembly at the writing of this paper (February 2002). After completion, a set of acceptance crush tests on aluminum honeycomb specimens will be conducted at MTS to verify machine performance. The machine will then be shipped to the National Transportation Research Center (NTRC) in Knoxville Tennessee. NTRC; an alliance between Oak Ridge National Laboratory, The University of Tennessee, The U.S. Department of Energy, The Development Corporation of Knox County, UT-Battelle, and NTRC, Inc; is a National User Facility. The machine will be operational in early summer 2002 and will be available for collaborative research.

FUTURE WORK

In the long term, such a machine can be utilized not only for crush tests but for other basic material tests that require various loading rates. In addition to impact properties, basic material properties of all classes of materials (metals, plastics, ceramics, etc.) also vary as a function of loading rates. Another area of work where such a machine would be useful is also for determining the dynamic behavior of adhesively bonded structures, both composite and metallic. Furthermore, interior materials such as foams can also be tested to better understand their behavior at high strain rates. Such a machine will provide an understanding of fundamental material properties/behavior for a range of speeds. This knowledge will provide vital data to designers and CAE analysts to aid in the application of these materials in vehicles.

CONCLUSION

A unique test capability featuring an integrated hardware and software solution is being established which will provide data within an intermediate-rate regime that is not practically obtainable with existing equipment. The servo-hydraulic based mechanical test machine will provide data for specimens with mean crush forces up to 267 kN at constant velocities up to 4 m/s in a very controlled and predictable manner. A 450 kg added mass provides robustness of the test capability to mitigate variations within specimens and from specimen to specimen.

ACKNOWLEDGMENTS

Data represented in Figure 4 was generated by Sukru Fidan, formerly of the Ford Motor Company, for the ACC.

The authors would like to thank the Board of the Automotive Composites Consortium and the DOE Office of Advanced Automotive Technologies for providing funding for the equipment. Richard Jeryan, Chair of the ACC EMWG, is acknowledged for providing direction and support in developing the performance requirements for the test machine. Venki Agaram of DaimlerChrysler, ACC EMWG, and the Auto/Steel Partnership is acknowledged for providing critical assessment of the capability for composites and steel research.

The work of the first author was sponsored by the U. S. Department of Energy, Office of Transportation Technologies, Office of Advanced Automotive Technologies, Lightweight Materials Program. Oak Ridge National Laboratory is operated by UT-Battelle, LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725.

REFERENCES

1. Browne, A.L., Houston, D.Q., Watling, P.J., and Lalik, L., "Automotive Composites Consortium Generic Tube Crush Program: Resin Transfer Molded Tubes," Crashworthiness, Occupant Protection and Biomechanics in Transportation Systems - 1998 -, ASME Publication AMD-Vol. 230 BED-Vol. 41, pp. 75-94, Nov. 1998.

2. Johnson, N.L., Houston, D.Q., Watling, P.J., and Lalik, L.,"Generic Tube Crush Program: Structural Reaction Injection Molded Tubes,"Crashworthiness, Occupant Protection and Biomechanics in Transportation Systems - 1998 -, ASME Publication AMD-Vol. 230 BED-Vol. 41, pp. 53-73, Nov. 1998.

3. Caliskan, A.G., Chadwick M.M., Han X., Favro. L.D., “Static and Dynamic Crush of Composite Tubes”, ASME Mechanics & Materials Conf., Session on Recent Developments in the Study of Impact of Composite Materials, Blacksburg, VA, June 28-30, 1999.

CONTACT

For further information, please contact Ray Boeman, at 248-452-0336 or BoemanRG@ORNL.GOV.