E. Composite Crash Energy Management

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Objectives

- Determine experimentally the effects of material, design, environment, and loading on macroscopic crash performance to guide the design and the development of predictive tools.
- Determine the key mechanisms responsible for crash energy absorption and examine microstructural behavior during crash to direct the development of material models.
- Develop analytical methods for predicting energy absorption and crash behavior of components and structures.
- Conduct experiments to validate analytical tools and design practices.
- Develop and demonstrate crash design guidelines and practices.
- Develop and support design concepts for application in demonstration projects.

Approach

- Conduct experimental projects to increase understanding of the global and macro influences of major variables on crash performance.
- Use the data from these experiments to create crash intuition, guidelines, and rules of thumb and data for the validation of analysis developments.
- Conduct microscopic experimental characterization to define the mechanisms that occur during and as a result of the crash process.
- Develop and validate analytical design tools to predict structural crash performance based on both phenomenological and micromechanical approaches to material and crash mechanism modeling.

Accomplishments

- Completed high-rate compression tests to demonstrate that shear transfer between fiber tows and matrix is reduced at higher strain rates.
- Completed static and dynamic tests to determine effects of friction during sliding and bending.
- Completed static and dynamic tests to determine Mode I and Mode II adhesive fracture properties.
- Completed down-selection of composite sandwich face/core configurations and initiated second phase of testing.
- Implemented cohesive zone models into finite-element analysis codes and demonstrated good agreement with experimentally determined behavior of bulk adhesive.
- Characterized in-situ and bulk composite matrix material properties and examined details of the fiber architecture of molded specimens to understand anomalies in material properties and energy absorption of braided composites.
- Completed the analysis of the fracture of a composite strip under a combined bending and compression load. Experiments are being conducted to validate the analytical results.

Future Direction

- Continue the development and validation of both micromechanical and phenomenological analytical design tools to predict structural crash performance.
- Expand micromechanical approaches to model material and crash mechanisms and explore novel multiscale approaches.
- Expand focus on design tools suitable for use with random chopped carbon-fiber-reinforced composites.
- Continue the characterization of the energy absorption mechanisms of carbon-fiber-reinforced composites.
- Characterize the critical physical parameters required for analytical model development. Develop test methods to obtain the stress-strain response beyond the peak stress of the materials and expand the current experimental methods to more fully characterize the dynamic material and physical properties needed to advance the modeling capability.
- Determine the effects of manufacturing features and environmental and loading factors, for example, minor field damage, abrasion, fatigue, and cumulative effects, on the macroscopic crash performance of carbon and carbon/glass hybrid reinforced composites. These results will establish design guidelines and guide the development of predictive tools.
- Develop relationships to implement analytical tools for commercial use.

Introduction

The purpose of the Crash Energy Management Program is to develop and demonstrate the technologies required to apply production-feasible structural composites in automotive crash and energy management applications. Projects within the program are intended to understand the mechanisms of polymer composite crash, develop analytical tools for use in vehicle design, and build a knowledge base for the vehicular application of lightweight polymer composites. The projects relate to materials, molding, and assembly process and design configurations that are useful in realistic applications. Design analysis methods will be developed that can be used at the several different steps in the design process. These steps require different levels of precision and speed of use, and the appropriate tools are expected to include both micro-mechanical and phenomenological approaches.

Static vs Dynamic Performance

This project's objectives are to experimentally determine the microstructural factors and behaviors that lead to decreased energy absorption when crushing tubes dynamically. In this study, the strain rate effects of a braided carbon fiber composite are investigated at the specimen level. The goal is to determine the source of rate effect using specimen-level tests and develop experimental methods by which candidate materials for energy absorption can be evaluated for their rate sensitivity. The results of this study will be used to develop and enhance analytical models that will need to take into account rate-sensitive material behavior.

Material properties of the two composite material systems were measured. This included the virgin and the in-situ properties (i.e. matrix properties within the composite) of the resins. The results showed that in-situ properties were much lower than the virgin properties. This suggests that virgin properties of the resins are not useful for characterizing the composite material properties or behavior. Mode I and II fracture toughness tests were carried out on thick specimens at both static and dynamic loading rates, Figures 1 and 2. The results showed that for both Mode I and II, increasing loading rates resulted in lower fracture toughness. In addition, high-rate compression tests were conducted to characterize the rate-dependent inelastic response. The results showed that shear transfer between the fiber tows and matrix was reduced at higher strain rates. This implies that the load carrying capacity of the fibers is lower at high strain rates.

Friction Effects on Crash Performance

The objectives of this work are to (1) experimentally determine the relative energy absorption due to each mode of a progressively crushed composite tube and isolate that portion of energy absorption due to friction and (2) evaluate differences in friction energy absorption between quasi-static and dynamic crush.

All dynamic and static testing has been completed for tubes and strips. The dynamic testing was performed on the National Transportation Center Test Machine for Automotive Crashworthiness (TMAC). The specific energy absorption (SEA) was 23% lower for dynamic loading than static loading. Results show that for static loading friction accounted for 30% of SEA and only 13% when tested dynamically. More than 80% of the difference in SEA between static and dynamic loading is attributable to friction.

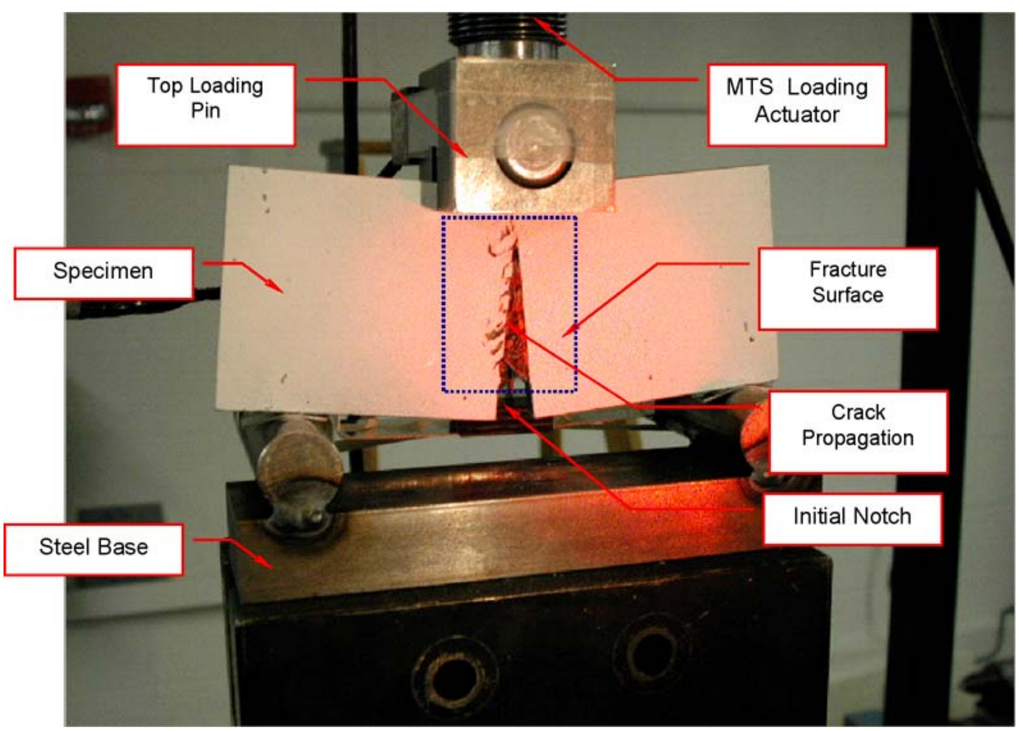

Figure 1. Three-point bending test setup for Mode I fracture toughness measurement.

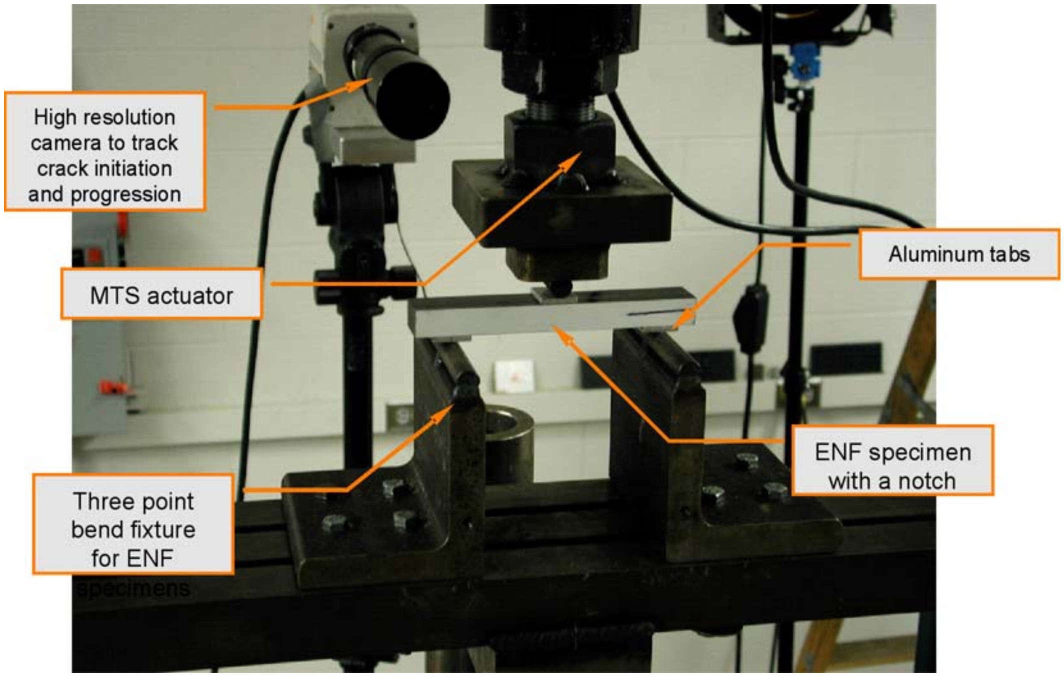

Figure 2. End-notched fracture (ENF) test setup for Mode II fracture toughness measurement.

Impact Performance of Bonded Structures

The objectives of this effort are to (1) evaluate the performance of bonded structures under crash loads; (2) examine the influence of bond design concepts, impact velocity, and other material issues; and (3) fabricate new molding tools to produce simulated automotive structures. Visteon Corporation, a Tier I automotive supplier, is leading this effort jointly with Focal Project 3 and the Automotive Composites Consortium (ACC) Energy Management and Joining Work Groups.

An integrated computational and experimental study of the dynamic response and behavior of an adhesively bonded, automotive substructural component under impact loading is undertaken here. The approach consists of characterizing the dynamic fracture of the adhesive material under various mode mixities. Numerical constitutive models of the adhesive are developed and validated. The numerical constitutive model of the adhesive will be implemented in the LS-DYNA software package to simulate the tube crush tests. Corroboration of the test results with the simulation will be used to assess the computational modeling methodology.

In the experimental part, the test methods for measuring the fracture parameters under dynamic Mode I, II, and mixed-Mode I/II, loading were established. Data analysis methods for Mode I and II were developed. Static and dynamic fracture tests, Figure 3, were conducted using both aluminum and composite adherends. The results for Mode I and II tests are presented in Figure 4 and Table 1.

In the computational effort, the CZM (cohesive zone model) constitutive law was used to study the dynamic crack propagation in adhesively bonded structural joints. There is a nonlinear relationship between the interfacial tractions and the relative displacements of the upper and lower surfaces of a crack. The law for mode I fracture initiation and crack propagation is shown in Figure 5, where T1 denotes the normal traction component, or peel component, and Δ denotes the opening displacement. The CZM law was implemented in an interface finite element, which is located between either two-dimensional (2-D) or three-dimensional (3-D) bulk material elements. In 2-D models the interface element is a line in the undeformed geometry, and in 3-D models it's a surface. The element level matrices were formulated, and the element was incorporated into ABAQUS® using the User-defined Element (UEL). The CZM law was further modified to incorporate rate-dependent behavior in the interface element. The comparison of the numerical results, using both rate-independent and rate-dependent CZM laws and experimental data for

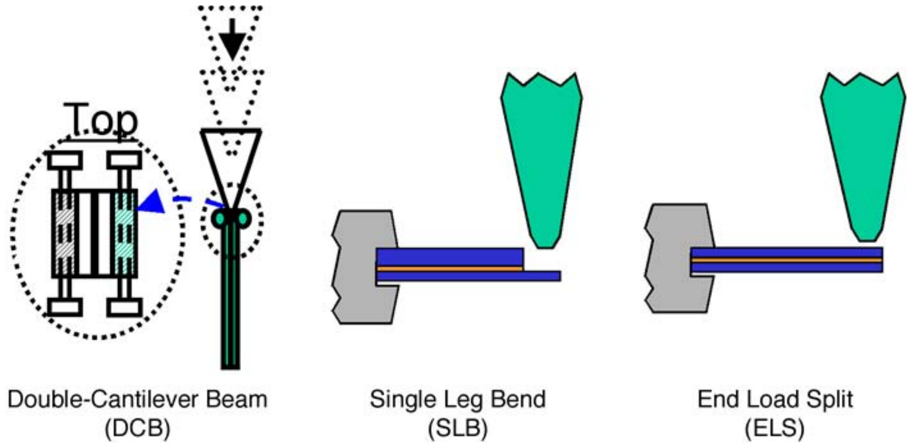

Figure 3. Static and dynamic fracture test configurations.

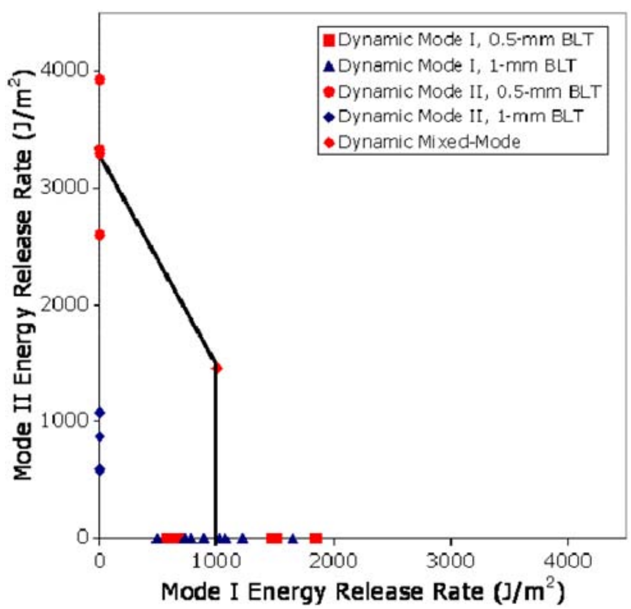

Figure 4. Mode I and II fracture test envelop for the adhesive.

Table 1. Mode I and II energy release rates for adhesive

Mode I/II energy release rates			
Adherent		Peak/initiation (J/m^2)	Average (J/m^2)
6.4-mm aluminum DCB	Static	1800	610
	Dynamic	1900	N/A
36-ply composite DCB	Static	1200	440
12-ply composite DCB	Static	2700	510
	Dynamic	1400	N/A
12-ply composite DCB	Dynamic	3100	N/A
12-ply composite SLB	Mode I	1000	N/A
	Mode II	1400	N/A

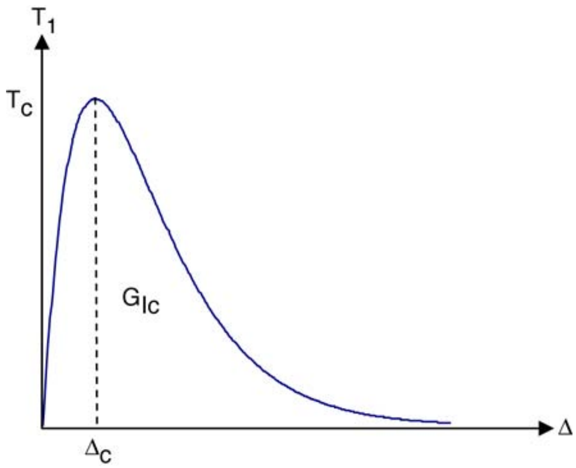

Figure 5. Nonlinear behavior of the traction opening displacement curve.

double-cantilever beam (DCB) specimens is shown in Figure 6.

Next, the interface element was implemented in LS-DYNA using the user-defined material (UMAT) option. The traction-displacement law from the interface element has been modified to a stress-strain law for use in the UMAT subroutine. The UMAT was implemented using the standard library 8-noded solid brick element. Preliminary results for a DCB analysis were obtained using the newly implemented CZM law in LS-DYNA analysis and are compared with ABAQUS® as shown in Figure 7.

Performance of Novel Sandwich Composites

The objective of this project is to investigate the viability and crashworthiness of novel sandwich composite concepts for automotive applications.

Topics such as wrinkling, face-sheet debonding, Poisson's effects and core-skin property mismatch, load rate effects, impact damage modes, and energy absorption were identified as part of the research effort. The research work being performed at the University of Utah is split into three phase-specific objectives:

Phase I: To evaluate candidate materials, concepts, and manufacturing methods for automotive sandwich composites. This two-round experimental evaluation of energy absorption, damage mechanisms, and mechanical properties will be used to identify the best-suited sandwich composite concepts for further investigation in the second phase.

Phase II: To develop an understanding of the structural response of selected sandwich composite concepts identified in Phase I. This investigation will focus on damage modes and energy absorption mechanisms during impact loading as well as static loading.

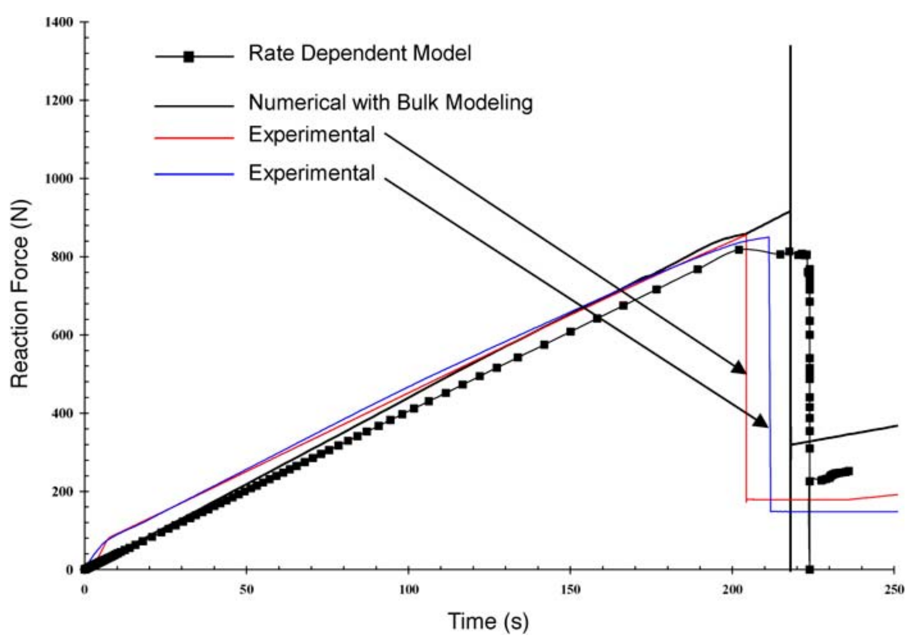

Figure 6. Tip reaction forces for DCB specimen using rate-dependent law and bulk adhesive modeling.

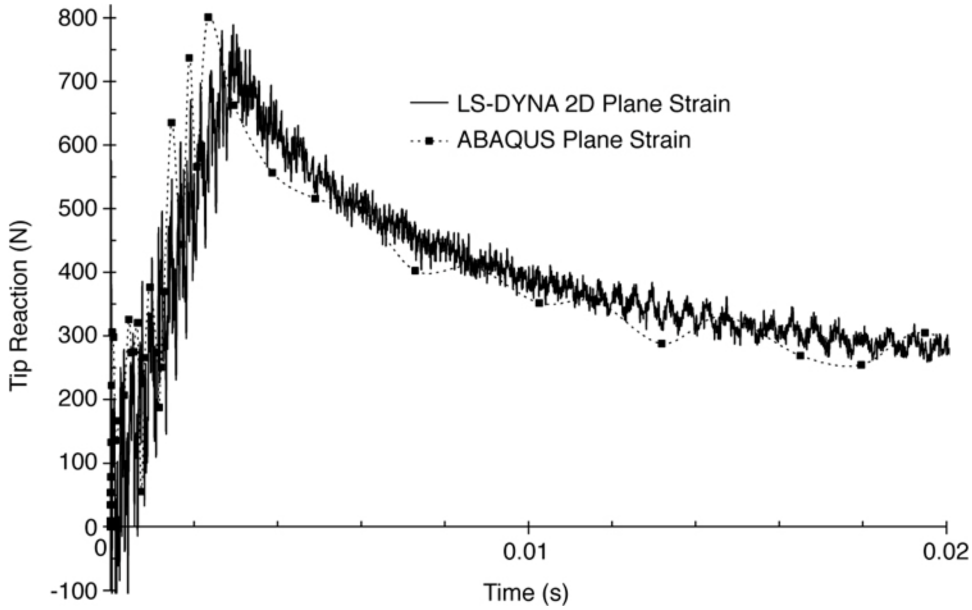

Figure 7. Comparison of results for DCB analyses using CZM law as implemented in LS-DYNA and ABAQUS.

Phase III: To develop and validate finite-element (FE) based methodologies for predicting damage formation and energy absorption in candidate sandwich composite concepts identified in the first two phases of the program.

The Phase I has been completed. Thirteen different sandwich configurations were subjected to three types of testing viz., flat-wise tensile, three point bending, and edgewise compression. The configurations tested included both thermoset and thermoplastic facesheets and had an overall thickness of 15 mm. Five sandwich configurations were chosen for the second round of tests including flexural creep, edgewise impact, flexural impact, and interlaminar shear tests. Four configurations were selected for evaluation in Phase II based on the criterion of mechanical performance, manufacturing ease, and cost. These facesheet/core configurations were Carbon-Epoxy/Balsa, Carbon-Epoxy/ Polyurethane foam, P4 Carbon-Epoxy/Polyurethane foam, and P4 Carbon-Epoxy/Balsa.

Postpeak Response Characterization of 2-D Triaxially Braided Composites

The objectives of this project are to (1) computationally demonstrate postpeak softening (PPS) observed with single unit cell structural models on multicell structural models; (2) computationally investigate how the hierarchy of behavior modes and the number/arrangement of unit cells affect PPS predictions; (3) computationally investigate how the variation in degree of imperfection in the microarchitecture affects the derived structural properties of the 2-D Triaxially Braided Composite (2DTBC); and (4) experimentally test multiunit cell structural specimens to reflect, refute, or support the findings of the above objectives.

In the approach to this project, scalability of macroscopic structural stress-strain relations in 2DTBC will be investigated and studied. Computational models will be employed to demonstrate PPS observed with single-unit cell structural models on multicell unit structural models. The results of such analyses are directly applicable to the development of structural properties of 2DTBC for large-scale FE simulations that are needed to assess energy absorption in 2DTBC structural components. Using laser extensometer and speckle photography (for full field strain measurements), experimental tests to measure PPS on single and multicell 2DTBC will be performed. Further, computational models that incorporate cohesive zones (CZs) within the cell in order to capture experimentally observed tow/matrix separation will be developed and analyzed including the effect of CZ on PPS. Finally, the computational analyses will be carried further to study and characterize the effects of measured architecture imperfections on the single-unit cell and multicell structural stress-strain properties of 2DTBC, including the effects of different types and distribution of imperfection on PPS.

The primary materials (Hetron and Epon) were experimentally characterized by measuring their pure (virgin) properties, performing coupon tension tests (with 0, +45/–45 tow orientations), and then using data reduction techniques back-calculated to in-situ material properties. It was found that in-situ matrix properties differ from pure matrix properties, and hence, the in-situ properties (not pure) should be used for subsequent FE analyses.

Because axial fiber tows are the dominant load-carrying component of the braided composite architecture, statistical scanning electron microscopy (SEM) in conjunction with photo-stitching techniques were performed on the Hetron- and Epon-based composites. From the detailed specimen preparation and subsequent SEM images, it was found that unwetted regions inside the tows needed to be accounted for (e.g., FE analysis) by a reduction in tow cross-sectional area and/or material constants. Such regions that reduce the fiber volume fraction exist in the Hetron-based composite and are usually associated with microcracking. However, detailed SEM images of Epon-based composite show that the tows are fully wetted and microcracks are minimal. Such a difference might explain (at this early stage in the study) the higher energy absorption capacity of the Hetron-based system as compared with the Epon-based one as reported in the literature.

A detailed FE model has been developed encompassing several unit cells of the above braided architectures and material systems and is currently being analyzed and compared with experimental data.

The Principal Investigator and his team have investigated and tested several laser extensometers and are in the final stages of making the purchase decision. This will be used in tracking deformations that are intra-unit cell as well as inter-unit cells (in specimen with several unit cells).

Energy Absorption of Triaxially Braided Composite Tubes

The objective of the project is to develop a predictive tool for the crush analysis of triaxially braided composite structures under dynamic loads based on a smeared micromechanics model developed in an earlier project that specifically targeted static loading. The smeared micromechanics model meant for static analysis was simplified to improve computational efficiency, without loss of precision.

The effects that were considered as significant role players were stress concentration, fiber tow scissoring, and rate dependency. The scissoring was introduced based on the assumption that once the matrix fractured in a unit cell, the tows could scissor under a constant tow load until the tows jammed against one another. This phenomenon was observed experimentally, and the tow rotation measured in the experiments was predicted using the FE analysis in a static mode. The effect of delay in damage propagation as a result of stress concentration was captured using the fiber bundle theory of Tsai and Hahn specialized for the triaxial braid situation.

The effect of stress-concentration was demonstrated by comparing experimental and numerical results in case of a tensile specimen with a hole. The critical damage area approach based on Tsai-Hahn fiber bundle theory was found to be very effective. The effect of strain rate on the damage evolution was introduced based on Sun et al.'s approach of anisotropic viscoplasticity. It was demonstrated on dynamic crushing of square tube with ±45° layup.

The constitutive model with scissoring, stress-concentration, and rate dependency has been implemented as a user material subroutine in the explicit version of ABAQUS. The user material needs to be tested thoroughly against several tube tests at different rates of loading.

Lateral Impact Study

The objective of the project is to achieve a fundamental understanding of the energy-absorbing mechanisms in triaxially braided composites subjected to lateral bending and impact. A combined experimental and analytical approach has been planned and implemented for this purpose. The analytical study has applied the smeared micromechanics material model previously developed in the Energy Management Program, available as a user subroutine with ABAQUS®. Based on the study of a simple test specimen, a specimen representative of an automotive component such as a B-pillar will be proposed.

The overall study involves three distinct phases: smeared micromechanics material model of composite strips under lateral bending, validation of the model using experimental data, and extension of the model for designing automotive components such as the B-pillar of a passenger compartment. Phase I of the project has been finished with modeling and analysis of a $[0_{80k}/\pm45_{12k}]$ triaxial carbon fiber braided composite strip subjected to off-axis compressive loading. Damage initiation and accumulation at the midlength of the strip have been observed with identification of many energy absorption modes. Principle modes observed include tow splitting—in-plane and out-of-plane, axial tow compression, matrix cracking, and interply delamination, which all contribute to some degree to material degradation/softening in the strip subject to lateral bending. The axially braided composite exhibits, as observed in the micromechanics model, a phenomenon in which the material within Representative Unit Cell (RUC) can regain a prominent stiffness even after a peak load point. This would be caused by a dramatic change of stiffness distribution in a RUC as a certain scale of accumulated micromechanics damage zone has been reached

Project activity in Phase II is being carried out to pursue experimental investigation into the composite strips for validating the model effectiveness and competitiveness, including model capabilities for characterizing mechanical properties of the unit cell structure in the braided composite. Atkins & Pierce was selected to provide the braided raw materials (production code 4374-2) for plaque molding. The molded plaques were then provided to the university contractor for specimen cutting and testing in July 2004. Guidelines on procedures for all the tests, including material test matrix and specimen cutting layout were established for research contractors to follow to acquire proper experimental data for validation. Total of 90 specimens were planned on characterizing properties of triaxially braided composites in tensile, compression, pure bending, and lateral bending. The tests started in the fourth quarter of FY 2004 and are projected to be finished in the first quarter of FY 2005.

Summary

The Crash Energy Management Program develops and demonstrates technologies that are required to apply production feasible structural composites in automotive crash and energy management applications. Projects within the program are intended to understand the mechanisms of polymer composite crash, develop analytical tools for use in vehicle design, and build a knowledge base for the vehicular application of lightweight polymer composites. The FY 2004 experimental projects follow:

- High rate compression tests were completed to demonstrate that shear transfer between fiber tows and matrix is reduced at higher strain rates.
- Static and dynamic laboratory tests were completed to determine effects of friction during sliding and bending.
- Mode I and Mode II adhesive fracture properties were determined in both static and dynamic tests.
- Composite sandwich face/core configurations were evaluated, and the down-select was completed to initiate the second phase of testing.
- In-situ and bulk composite matrix material properties were characterized, and details of the fiber architecture of molded specimens were examined to understand anomalies in material properties and energy absorption of braided composites.

The analytical studies indicated the following:

- Cohesive zone models were implemented into FE analysis codes and demonstrated good agreement to experimentally determined behavior of bulk adhesive.
- The analysis of the fracture of a composite strip under a combined bending and compression load was completed using a code previously developed in the program. Experiments were initiated to validate the analytical results.

Presentations and Publications

1. A. G. Salvi, A. M. Waas, and A. Caliskan, "Rate-Dependent Compressive Behavior of Unidirectional Carbon Fiber Composites," *Polymer Composites*, **25**(4), 397–406 (August 2004).
2. A. G. Salvi, A. M. Waas, and A. Caliskan, "Specimen Size Effects in the Off-axis Compression Test of Unidirectional Carbon Fiber Tow Composites," *Composites Science & Technology*, **64**(1), 83–97 (January 2004).
3. R. K. Kapania, D. P. Makhecha, E. R. Johnson, J. Simon, and D. A. Dillard, "Modeling Stable And Unstable Crack Growth Observed In Quasi-Static Adhesively Bonded Beam Tests," IMEC204-59765, *Proceedings of IMECE'04*, 2004 ASME International Mechanical

Engineering Congress and Exposition, Anaheim, California, U.S.A., November 13–16, 2004
4. J. C. Simón, D. A. Dillard, and E. R. Johnson, “Characterizing the Impact Fracture Properties of Structural Adhesives,” Presented at the 27th Annual Meeting of Adhesion Society, Wilmington, North Carolina, U.S.A., February 15–18, 2004.
5. A. L. Van Otten, N. S. Ellerbeck, D. O. Adams, C. L. Nailadi, and K. W. Shahwan, “Evaluation of Sandwich Composites for Automotive Applications,” *Proceedings of the 2004 SAMPE Conference, Long Beach, California*.
6. N. D. Flesher and F-K. Chang, “Modeling the Response of Braided Composites with Stress Concentrations,” 11th U.S.-Japan Conference on Composite Materials, September 9–11, 2004, Yonezawa, Japan.
7. N. D. Flesher and F-K. Chang, “Effect of Cross-Section Configuration on Energy Absorption of Triaxially Braided Composite Tubes,” 18th Annual Technical Conference American Society for Composites, October 19–22, 2003, University of Florida.
8. N. D. Flesher and W. Cheng, “Evaluation of STCrush for Characterization of Crushing Behavior of Composite Tubes, 10th U.S.-Japan Conference on Composite Materials,” September 16–18, 2002, Stanford University.
9. S. C. Quek, A. M. Waas, K. W. Shahwan, and V. Agaram, “Compressive response and failure of braided textile composites: Part 2—computations,” *Int. J. Nonlinear Mech*., **39**(4), 650–663 (June 2003).
10. S. C. Quek, A. M. Waas, K. W. Shahwan, and V. Agaram, “Compressive response and failure of braided textile composites: Part 1—experiments,” *Int. J. Nonlinear Mech*., **39**(4), 635–648 (June 2003).
11. S. C. Quek, A. M. Waas, K. W. Shahwan, and V. Agaram, “Analysis of 2D Flat Triaxial Braided Composites,” *Int. J. Mechanical Sciences*, **45**(6–7), 1077–1096 (2003).
12. S. C. Quek and A. M. Waas, “Micromechanical Analyses of Instabilities in Braided Glass Textile Composites,” *AIAA J*, **41**(10), 2069–2076 (October 2003).