D. Composite Crash Energy Management

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Objective

- 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, 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.

Accomplishments

- Completed crash testing of square and rectangular braided carbon tubes to determine the effects of fiber type and architecture, tube shape, and temperature on energy absorption performance.
- Completed crash testing of circular and square tubes made of noncrimped fabrics (NCFs) to determine the effects of preexisting damage, laminate inserts and shape on static and dynamic energy absorption.
- Designed and used laboratory test fixture to determine effects of friction during sliding and bending.
- Conducted LS-DYNA analyses of adhesive material test specimens and modeled simple joints with nonlinear adhesive properties.
- Completed initial screening of 13 configurations of composite sandwich face/core.
- Modified a user subroutine originally developed for quasi-static analysis for dynamic analysis with the ABAQUS explicit finite-element (FE) code.

Carbon-Reinforced-Tube Performance

The objective of this project is to experimentally determine the effects of material, design, environment, and loading on carbon-fiber-reinforced tubes to guide automotive design and analysis development, including the development of analytical material models.

The carbon tube test program was completed in 2003. Braided tubes of square and rectangular cross sections were tested dynamically to evaluate their crush performance. A series of hot (82°C) and cold (–40°C) temperature tests were conducted on the drop tower, and these results were compared to the room temperature tests conducted previously. The tubes tested at hot temperature were also exposed to moisture. Mean crush force and specific energy absorption were compared for each class of materials. Table 1 shows the average mean crush force values at each of the temperatures tested. There was no significant difference in force levels between temperatures. Progressive crush was obtained for each architecture. An example of a 12k carbon tube is shown in Figure 1. This tube was tested at elevated temperature.

Table 1. Average mean crush as a function of temperature

Average Mean Crush Force (kN)						
Tube Dimensions	Tube ID	Fiber Type	Lay-up	**Cold Temp. (-40 C)**	**Room Temp.**	**Hot Temp. (82.2 C)**
50 x 100	4280-2	Grafil 12k Carbon	$(0/\pm30°)_2$	12.0	12.3	14.0
100 x 100	4290-2			18.8	22.8	24.9
50 x 100	4281-2	Fortafil 80k axial Grafil 12k off-axis	$(0/\pm45°)_2$	31.9	31.3	34.4
50 x 100	4283-2	Fortafil 80k axial 250 Yld. E-glass	$(0/\pm30°)_2$	44.0	40.4	49.1
100 x 100	4293-2			61.1	61.4	64.1
50 x 100	4284-2	Fortafil 40k axial Grafil 12k off-axis	$(0/\pm30°)_2$	20.1	22.9	20.5
100 x 100	4294-2			31.0	31.4	31.7

Figure 1. Elevated temperature crush sample.

Results from the room temperature tests continue to be utilized by the groups developing analysis methods for these braided carbon materials.

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. This study focuses mainly on braided carbon fiber materials where the tube tests showed a decrease in energy absorption of 50% when crushing dynamically. Strain rate effects in braided carbon fiber samples with notches have shown that under static three-point bend loading fiber bridging of cracks occurs. Fiber bridging is a well-known phenomenon in composites that leads to increased fracture toughness. In dynamic rates, there was almost no observable fiber bridging in the samples. Furthermore, the crack faces were smoother than those tested statically. The load and energy absorption capacity at dynamic rates were found to be much lower than those measured on the static tests. The intermediate strain rate testing machine designed to evaluate the crush performance of structures at constant elevated impact rates is fully operational at the National Transportation Research Laboratory at Oak Ridge National Laboratory (ORNL). The official dedication of the machine was in August 2003 (see 7C).

Effects of Preexisting Damage on Crash Behavior

The objective of this project is to provide an understanding of the effects of a range of material variability on the mode of crush and consequent energy absorption characteristics of generic and practical vehicle structure geometries. Specifically, the work focuses on the effect on energy absorption associated with delamination, through-thickness, and local point loading on generic circular and square tubular components. At the conclusion of the project, a generic guideline will be created that will help in designing more robust crash structures that are less sensitive to manufacturing and variability. In previous phases of this study, only circular cross sections using random chopped fibers were examined. In the present phase of the work, the effects of various damage modes were studied on tubes of NCF, circular and square cross sections, and interleaved inserts. Overall, NCF structures showed lower specific energy absorption (SEA) than random chopped structures. However, overall trends of sensitivity to damage were similar to those of random chopped materials. Specifically, the effect of damage was more pronounced at static rates. The study also showed the square geometries to be more sensitive to damage imparted at the corners, because these areas of the tube have higher crush stresses. Finally, the effect of adding thermoplastic interleaves was an increased resistance to damage; however, the overall SEA was reduced for undamaged structures when compared to noninterleaved structures.

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.

A test fixture, Figure 2, was designed and fabricated that allows the measurement of energy absorption due to matrix damage during bending and sliding friction and can isolate the sliding friction component of crush energy absorption. The fixture uses strip specimens that are commonly tested in a standard materials testing device such as an MTS machine. The test fixture can accommodate strips of varying width up to 1-3/4 in. and up to 3/16 in. thick. Preliminary testing results show that more that half of the energy absorbed during a strip test is attributable to friction. These results are presented in the Figure 3. Energy absorbed is the integrated area under the curve for each test specimen.

The top two curves in Figure 3 show the total energy due to sliding friction and matrix damage due to bending. The lower two curves show energy absorption attributable only to matrix damage due to bending and excludes energy absorption due to sliding friction.

Figure 2. Friction test fixture.

Material characterization testing has been completed for 0/±45 braided graphite/

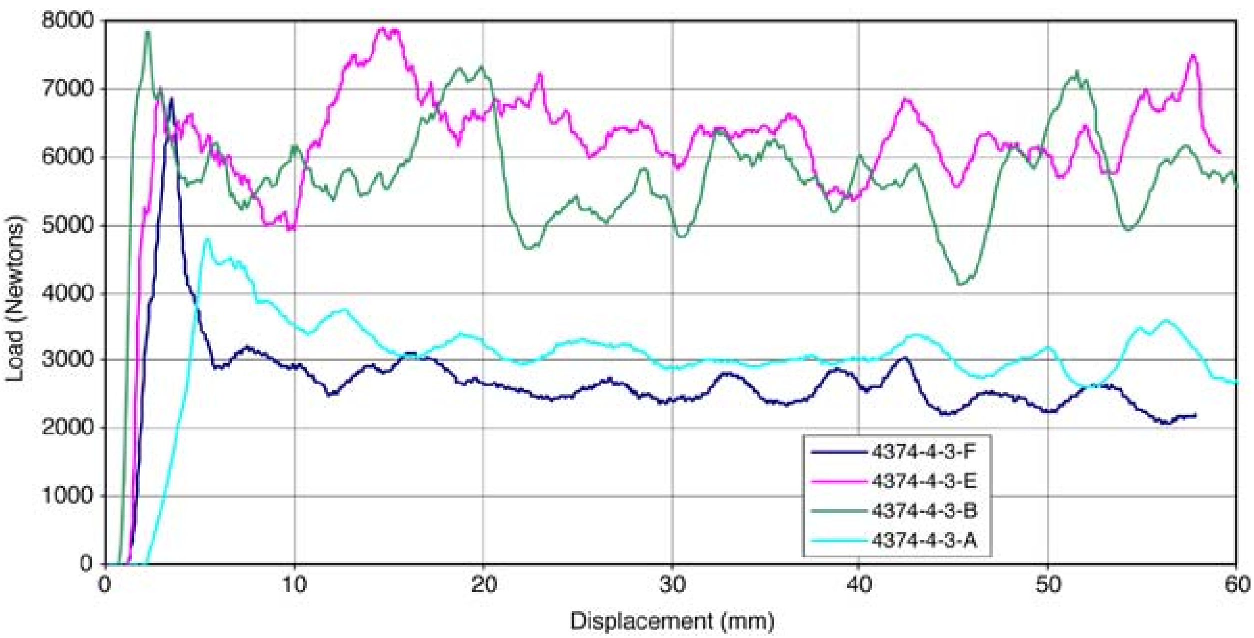

Figure 3. Strip test load deflection results as a function of loading mode.

vinyl ester composite. Standard 2-in. square graphite/vinyl ester test tubes have been quasi-statically tested using the standard crush trigger and the tapered 5° trigger described previously. Energy absorption modes observed were corner splitting, delamination, sliding friction, and matrix fracture due to bending.

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, environmental conditions, and other material issues; and (3) fabricate new molding tools to produce simulated automotive structures. This is a joint program with the ACC Joining Work Group and part of Focal Project 3 (FP3) design studies.

Visteon Corporation, a Tier I automotive supplier, is leading this effort jointly with FP3 and ACC Energy Management and Joining Work Groups. A comprehensive work plan was established to develop experimental and analytical methodologies to analyze and design adhesively bonded automotive composite structures that can sustain axial, off-axis, and lateral crash/impact loads. The key tasks of the work plan are

- selection of representative subcomponent geometry and substrate and adhesive material systems,
- generation of coupon level material data for substrate and adhesive materials for static and dynamic loading at various strain rates,
- fabrication and testing of the subcomponent geometry under quasi-static and dynamic impact loads at various strain rates,
- development of FE-based computational tools with adhesive material models and progressive damage/debonding algorithms,
- development of standard tests and procedures to characterize Modes I, II, and III and mixed-mode dynamic fracture in adhesively bonded joints,
- incorporation of the complete design methodology into a commercial FEA code such as ABAQUS or LS-DYNA, and
- validation computational tools with test results.

The current status of the key tasks follows.

Task 1: Select a Representative Subcomponent Geometry, Substrate, and Adhesive Material

Hexcel's HexMC® was selected as the initial substrate material for the project. HexMC®, a random chopped prepreg with carbon fibers in epoxy matrix, can be compression molded at about 1000 psi and 100°C to 150°C and has a 4- to 15-min cycle time. The molding, however, posed considerable challenges including,

- difficulty of molding plaques,
- variation in thickness and curvature,
- 20–30% coefficient of variation (COV) in preliminary testing results,
- difficulty molding hat sections, and
- concerns about compression molding closed-section, noncircular tubes.

The selection of the substrate material system was revisited, and a 3K high-tensile plain-weave fabric (aerial weight: 193 gsm) carbon/epoxy prepreg system from Advanced Composites Group was selected. The plain-weave system is designated ACG MTM 49/CF0501-42% Resin Weight. The carbon fiber is T300B 40B from Toray. Plaques of ACG MTM 49 carbon/epoxy material system have been manufactured and scheduled for static and dynamic material characterization by ORNL in FY 2004.

SIA 731SI, two-part toughened epoxy, was chosen as the adhesive. Standard surface preparation, for example, sanding with Scotch Brite and subsequently, using solvent wash, were used to prepare both bonded joint specimens and subcomponents.

Task 2: Generate Coupon-Level Material Data for Substrate, Adhesive Materials, and Single-Lap Joint Configurations for Static and Dynamic Loading

Characterization of bulk properties of SIA 731SI adhesive system at ORNL is in progress. Typical tension and compression stress/strain curves are shown in Figures 4 and 5.

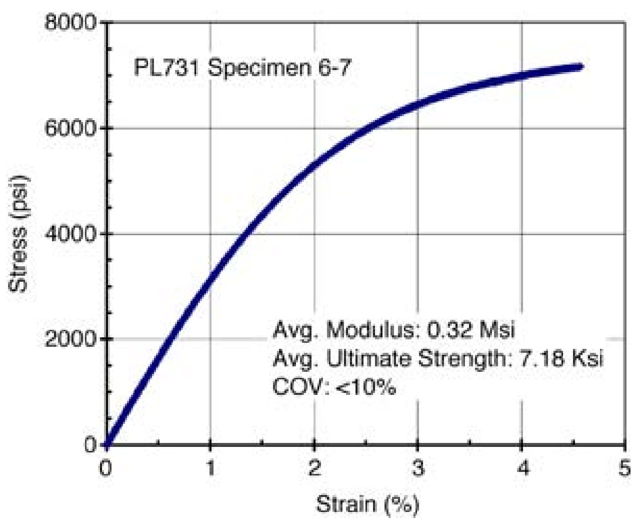

Figure 4. Adhesive tension test data.

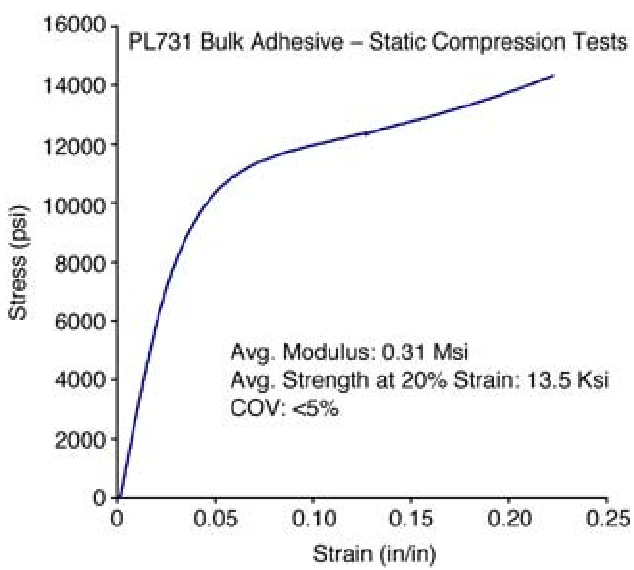

Figure 5. Adhesive compression test data.

Task 3: Build Unbonded and Bonded Subcomponents and Test Them Under Quasi-Static and Dynamic Loads

The tool for building square section tubes using the new plain-weave ACG MTM 49 carbon/epoxy material substrate system was fabricated. Both unbonded and bonded square tubes will be fabricated. The process of building the bonded tubes with two different overlap thicknesses and two types of bond lengths is currently being investigated.

Task 4: Develop Analytical Tools Incorporating Adhesive Elements, Material Models, and Progressive Damage Algorithms and Correlate Them With Coupon and Subcomponent Test Results

As part of the efforts on this task, the team

- initiated analysis of adhesive material test specimen using MAT 24 model in LS-DYNA,
- modeled a single-lap joint with nonlinear adhesive properties using true stress-strain curve derived from the uniaxial tension test data measured at ORNL, and
- partnered with Virginia Tech to develop material models and advanced computational techniques for predicting crash energy absorption of adhesively bonded automotive structures.

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.

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

Phase I resulted in the mechanical evaluation of 13 sandwich facesheet/core combinations. These were subjected to three types of testing, for example, flat-wise tensile, three-point bending, and edgewise compression. The configurations tested include both thermoset and thermoplastic facesheets. Five candidate configurations will be chosen from these combinations, based on the criteria of mechanical performance, manufacturing ease, and cost. These configurations will be subjected to an additional round of testing that will include edgewise impact, flexural impact, interlaminar shear, and flexure creep tests.

Energy Absorption of Triaxial Braided Composite Tubes

The objective of the project is to develop a predictive tool for crush analysis of triaxial braided composite structures based on a smeared micromechanics model. A smeared micromechanics model developed under an earlier contract is being further explored to extend it to dynamic analysis. The project will answer questions pertaining to the basis of the mathematical representation of the energy absorbing mechanisms, unit cell size relative to FE size, stress concentration effects on load sustaining ability, objectiveness of damage evolution assumptions, and micromechanics application to shell FEs.

The smeared micromechanics unit cell model code has been rewritten to improve its computational efficiency. The smeared micromechanics model can currently be run in a fraction of the time that was necessary in the previous project.

The effect of stress-concentration on damage evolution has been studied using X-rays and die penetration in tension specimens with holes and in square tubes. The effect of stress concentration has been modeled through the fiber bundle theory to capture the delay in bulk damage progression exhibited by square tubes.

The scissoring behavior of composite fiber tows has been experimentally observed, and the extent of rotations in tows due to missing matrix has been modeled using the micromechanics based code. Work related to calculating the load-carrying ability of jammed tows is ongoing.

The micromechanics model has been used with shell elements in an attempt to investigate if large-scale application to automotive structures would be feasible at low computational costs. Initial attempts did not lead to encouraging results. The demands of micromechanics approaches on accurate 3-D stress calculations are high, making shell elements inefficient for the purpose.

The user subroutine developed for quasi-static analysis has been modified for dynamic analysis with the ABAQUS explicit FE code. This subroutine will be evaluated against dynamic tube crush test results during the final year of the contract.

Lateral Impact Study

The objective of the project is to achieve a fundamental understanding of the energy-absorbing mechanisms in triaxial braided composites subjected to lateral bending. A combined experimental and analytical approach is planned for this purpose. The analytical study would use the smeared micro-mechanics material model developed in a previous ACC100 funded project, available as a user subroutine with ABAQUS. Based on the study of a simple test specimen, a specimen representative of an automotive component will be proposed. Because this is an initial investigation into energy absorption lateral bending of triaxial braided composites, the current project will be restricted to quasi-static loads.

The user subroutine for the smeared micromechanics model had been first checked for bugs by running circular tube problems on the user machine before it was implemented to composite strip lateral bending applications. Many issues relevant to the model usage and implementation, including scissoring effect, have been studied. Initial runs have been completed on a $[0_{80k}/\pm 45_{12k}]$ 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 including 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 that the material within the 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 the RUC as a certain scale of accumulated micromechanics damage zone has been reached. Experimental investigation into the composite strips for validating the model effectiveness is being carried out.