

## I. Composite Crash Energy Management

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### Objective

- Experimentally determine 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.

### FCVT R&D Plan: Task 7; Barrier C

#### 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 micro-mechanical approaches to material and crash mechanism modeling.

## Accomplishments

- A computational model employing a discrete cohesive zone representation of the fracture plane was used to evaluate the performance of composites with two different polymer matrices. The analyses showed that fracture toughness is more critical than material strength when energy absorption is to be maximized.
- The effects of friction on the energy absorption of composites, including the differences between quasi-static and dynamic behavior, have been characterized and reported.
- A novel driven-wedge test technique was developed to effectively determine the stick-slip behavior of bond fractures including the adhesive bond crack initiation and arrest fracture energies.
- The damage evolution testing of sandwich structures has been completed. The testing included Mode-I (DCB), Mode-II (ENF) and Mixed Mode tests.
- A rate-dependent plasticity model, incorporated into the ABAQUS® code, was used to predict the dynamic crush behavior of square and circular tubes with good correlation to experimental results.
- A Schapery-like, thermodynamically-based theory was developed to characterize post-peak progressive (inelastic) damage. The methodology encompasses a mechanism-based damage/fracture model in order to represent degradation at both the micro and macro (structural) levels.
- The modeling and analysis of a [0° 80k / ±45° 12k] tri-axial carbon-fiber braided composite strip subjected to off-axis compressive loading has been completed.
- A rate-independent damage material model was developed under a multi-scale framework based on the mathematical homogenization theory and a novel model reduction technique that represented the damage-induced fields by influence functions. The multiscale model was implemented for two and three-dimensional problems and incorporated into ABAQUS® Explicit using the user material utility.

## Future Direction

- Continue the development and validation of both micro-mechanical and phenomenological analytical design tools to predict structural crash performance.
- Expand micro-mechanical approaches to model material and crash mechanisms and explore novel multi-scale 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, e.g. 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.

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## 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 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 material specimen level. The goal is to determine the source of rate effects 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.

In this period, parametric studies using the Discrete Cohesive Zone Model (DCZM) were conducted with regard to fracture toughness. In addition, the DCZM code was used to predict the fracture behavior of Epon and Hetron resin matrix composites. Parametric studies showed that under Mode I conditions when the fracture toughness of the matrix increases, the overall energy absorption capacity of the composite increases. By keeping the fracture toughness as a constant and varying the cohesive strength (i.e., ultimate strength of the material), it is shown that the peak load of initial fracture increases as the strength increases, however, post-peak energy absorption remains the same. These results are important for the design of energy-absorbing structures since it shows that fracture toughness is more important than the strength of the composite when energy absorption is to be maximized. Experimental results using Epon and Hetron composites showed that in the case of Epon specimens, there is less energy dissipation. This was found to be linked directly to the lower fracture toughness of Epon composite compared to the Hetron composite. The conclusion of the study is that the matrix material toughness is a very important factor when designing for energy absorption. A simple DCZM model that takes into account the material strain energy release rate and strength can be used as a tool to design appropriate composite materials for energy-absorbing 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.

All dynamic and static testing has been completed and the documentation of the results and conclusions is complete. The results are published by Michigan State University in a Ph.D. dissertation titled "Friction Energy Absorption in Fiber Reinforced Composites" by Thomas J. Brimhall, August 2005. The results are summarized as follow:

Experiments seem to suggest that sliding friction played an important role in the energy absorption of composite crush tubes. In order to separate the sliding friction Specific Energy Absorption (SEA) from the SEA attributable to matrix damage due to bending, an innovative strip testing fixture was designed, fabricated, and tested. When loaded quasi-statically, the SEA of round-cornered square carbon-fiber-reinforced composite tubes was measured to be 30.4 J/g. The SEA of identical crush tubes when tested dynamically (2 m/sec), was measured to be 23.8 J/g, a decrease in SEA of 6.6 J/g. These results are presented in Table 1 along with the individual energy absorption modes and are described below.

Simple mechanical tests were used to isolate and measure four modes of energy absorption: axial corner splitting, delamination, matrix damage due to bending, and sliding friction. The first two of these modes accounted for a low percentage of energy absorption. Fracture energy values were obtained

**Table 1.** Quasi-static vs. dynamic loaded carbon composite tube crush dynamic load rate (2.0 m/sec).

| Energy Mode           | Quasi-Static |      | Dynamic |      | Difference |     |
|-----------------------|--------------|------|---------|------|------------|-----|
|                       | J/gm         | %    | J/gm    | %    | J/gm       | %   |
| Delamination          | 0.84         | 2.8  | 0.84    | 3.5  | 0          | 0   |
| Bending               | 18.9         | 62.2 | 18.6    | 78.1 | -0.3       | 5   |
| Friction              | 10.6         | 34.8 | 4.3     | 18.1 | -6.34      | 96  |
| Tube Corner splitting | 0.063        | 0.2  | 0.06    | 0.3  | 0          |     |
| Total                 | 30.4         | 100  | 23.8    | 100  | -6.6       | 100 |

from simple tensile testing and used to calculate SEA attributable to tube corner splitting. End notch flexure testing data was used to calculate SEA attributable to composite delamination.

The strip testing fixture was used to measure SEA attributable to matrix damage due to bending and sliding friction. The strip testing fixture has two test configurations that permit the isolation of SEA attributable to sliding friction. Under quasi-static loading, SEA attributable to matrix damage due to bending was found to be 18.9 J/g or 62.2% of the total tube SEA. Under dynamic crush, the SEA attributable to matrix damage due to bending was found to be 18.6 J/gm or 78.1% of the total tube SEA. Carbon-fiber-composite SEA attributable to sliding friction under quasi-static compression was found to be 10.6 J/gm or 34.8% of the total tube SEA. Under dynamic crush, the SEA attributable to sliding friction was found to be 4.3 J/gm or 18.1% of the total SEA. The decrease in sliding friction SEA of 6.3 J/gm accounted for nearly all of the decrease in tube SEA of 6.6 J/gm between dynamic crush and quasi-static compression. Sliding friction was concluded to be responsible for the decrease in tube SEA from quasi-static compression to dynamic crush.

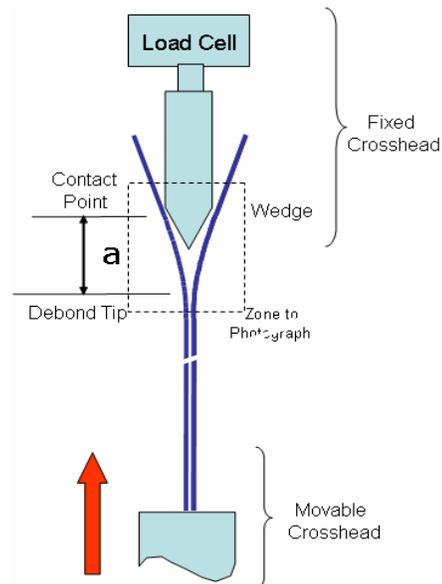
### **Impact Performance of Bonded Structures**

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, an automotive supplier, is leading this effort jointly with Focal Project 3 and ACC Energy Management and Joining Work Groups.

An integrated computational and experimental study of the dynamic response and behavior of an adhesively-bonded, automotive sub-structural 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.

### **Experimental work:**

A driven-wedge technique has been developed and implemented at the Oak Ridge National Laboratory (ORNL). Tests have been conducted on 12-ply composite adherends, bonded with the SIA adhesive. A special frame, developed to hold a small wedge, was attached to a 1000 lb load cell mounted on the upper crosshead. The lower end of the bonded beam specimen rests on the hydraulic actuator, which is able to force the specimen past the wedge. The setup is illustrated in Figure 1 below.



**Figure 1.** Illustration of driven wedge test configuration.

Tests were conducted over a range of loading rates, up to 1 m/sec, with similar results. This approach has been a major step forward for testing adhesives, showing the substantial stick-slip behavior that is typical of the SIA adhesive material. Rather than obtain only two data points per 12" long double-cantilever beam (DCB) specimen, we are now able to obtain 10 or more data points per specimen. This improves the amount of useful data that can be obtained from a set of specimens, and is believed to offer advantages for future testing needs. Figure 2 illustrates typical results obtained from one specimen that was tested at both 3 and 30 m/min. No significant differences were seen for these rates.

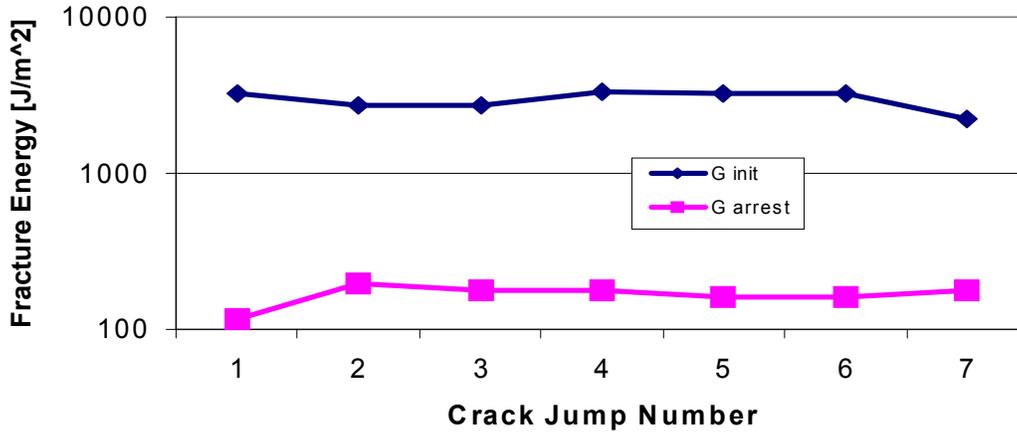


Figure 2. Initiation and arrest fracture energies for bonded 12 ply composite specimens.

Testing of compact tension  $K_{Ic}$  specimens at sub-ambient temperatures was continued. When tested cold at 1 m/s, fracture toughness values were on the order of  $0.5 \text{ MPa m}^{0.5}$ , similar to what had been obtained for specimens tested at this rate at ambient conditions. Sub-ambient tests conducted over a range of quasi-static crosshead rates, however, resulted in fracture toughness values that were well above the 1 m/s test results. When tested at slower crosshead speeds at temperatures of  $-40, -80, -120,$  and at  $-160^\circ\text{F}$ , fracture toughness of about  $1.5 \text{ MPa m}^{0.5}$  was obtained. The results are being analyzed, but application of the time-temperature superposition principle (TTSP) to fracture toughness values does not appear feasible. It is possible that the multiphase components within the formulated adhesive are complicating the time-temperature relationship.

**Rate-Dependent Modeling in LS-DYNA:**

The preliminary tests on the compact tension test specimens carried out at ORNL showed that the fracture toughness was dependent on the test speeds. A rate-dependent model was formulated to incorporate this behavior in terms of the strain energy release rate and the rate of the opening displacement. The rate-dependent law was implemented in the adhesive elements in the LS-DYNA simulation of the DCB configuration used in the drop-tower tests.

Figure 3 shows the crack length history obtained using the rate-independent and the rate-dependent analysis of a 12-ply composite DCB. The results are obtained using the Tsai and Wu model for the

composite damage, which is part of the LS-DYNA material model library (\*MAT\_054-055). Softening parameters for the progressive damage were not incorporated and are currently being investigated. The results from this preliminary analysis can be considered to be in fair agreement with the experimental result.

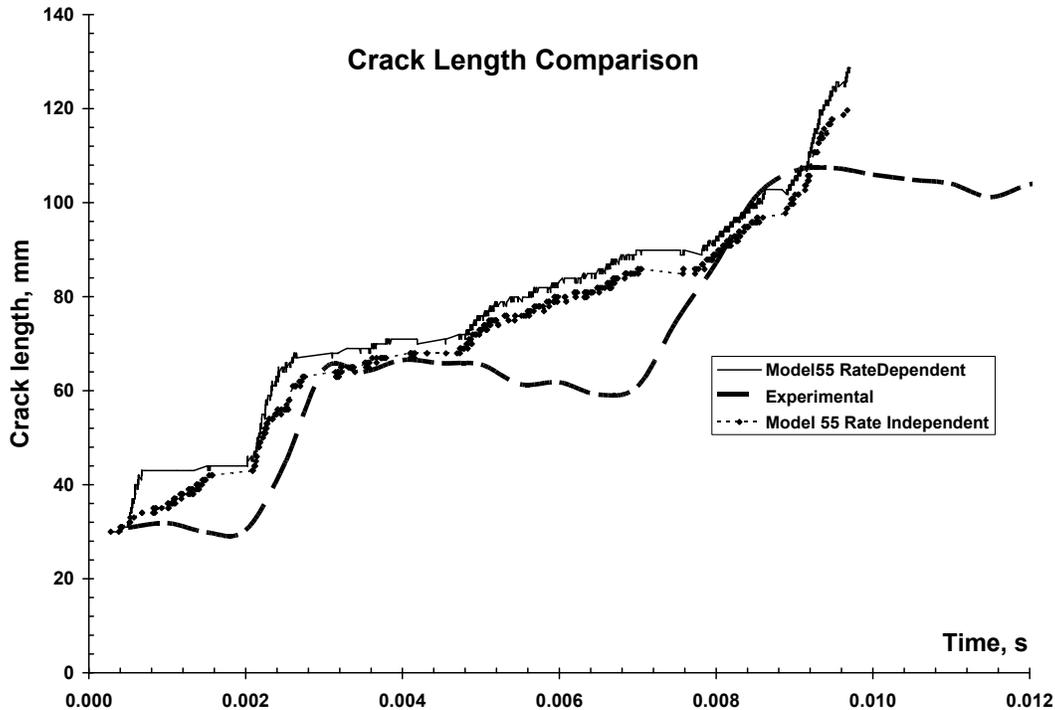
**Mode II Modeling in LS-DYNA:**

Even though the experimental data on Mode II is preliminary, the end-load-split (ELS) falling-wedge test was modeled with the data obtained thus far including some of the Mode I fracture parameters for the SIA adhesive. Also, since the test is dynamic, the force histories from the experiment were not monitored. The simulation matches the experimental results qualitatively. Investigations to obtain a quantitative comparison between the experiments and the simulations are continuing.

**Tube Modeling in LS-DYNA**

Simulation of the composite tube axial-crush test is being conducted at ORNL using the element deletion scheme in LS-DYNA. These tests are unique in that the crush is performed at a constant velocity, intermediate between quasi-static test speeds and typical impact-sled speeds. Experiments done for the axial crushing of the square composite tube at ORNL were simulated using LS-DYNA. The experiments showed that the composite tubes exhibited extensive material fracture upon impact.

To simulate this kind of fracture in LS-DYNA, shell elements were used to model the composites along



**Figure 3.** Crack length histories for the SIA-bonded, twelve-ply composite DCB from the falling wedge test, and from rate-independent and rate-dependent LS-DYNA simulations.

with the material model for enhanced composite damage (\*MAT\_054-055). The built-in criterion for the material model, TFAIL, was used. TFAIL is defined as the time-step criteria for element deletion. The cross-section of the square tube is 100 mm x 100 mm x 2.5 mm. The fracture pattern as well as the peak loads and the load history were compared. The unbonded tube was tested at ORNL at an impact velocity of about 4 m/s. Figure 4 compares the reaction force from the experimental and numerical simulations. The peak loads for each of the time histories are given in parentheses in the legend. Comparison of the two load histories shows that LS-DYNA simulation is not only capable of capturing the right crush mode, but also predicts the peak load reasonably well.

### **Performance of Novel Sandwich Composites**

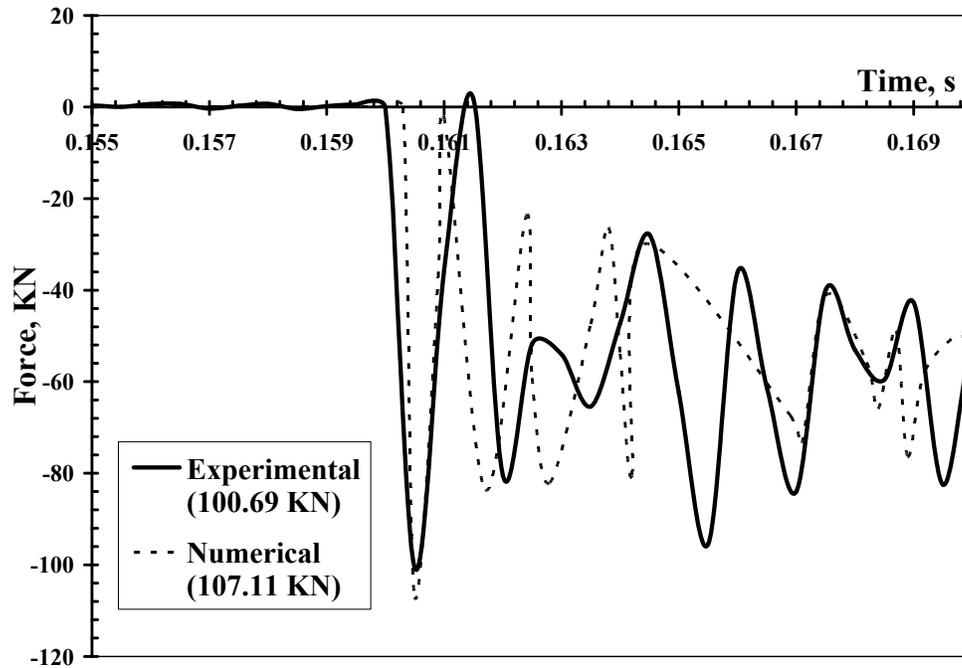
The objective of this project is to investigate the viability and crashworthiness of novel sandwich composite concepts for automotive applications.

Topics such as wrinkling, face-sheet de-bonding, Poisson's effects and core-skin property mismatch, load-rate effects, impact damage modes, and energy absorption were identified as part of the research

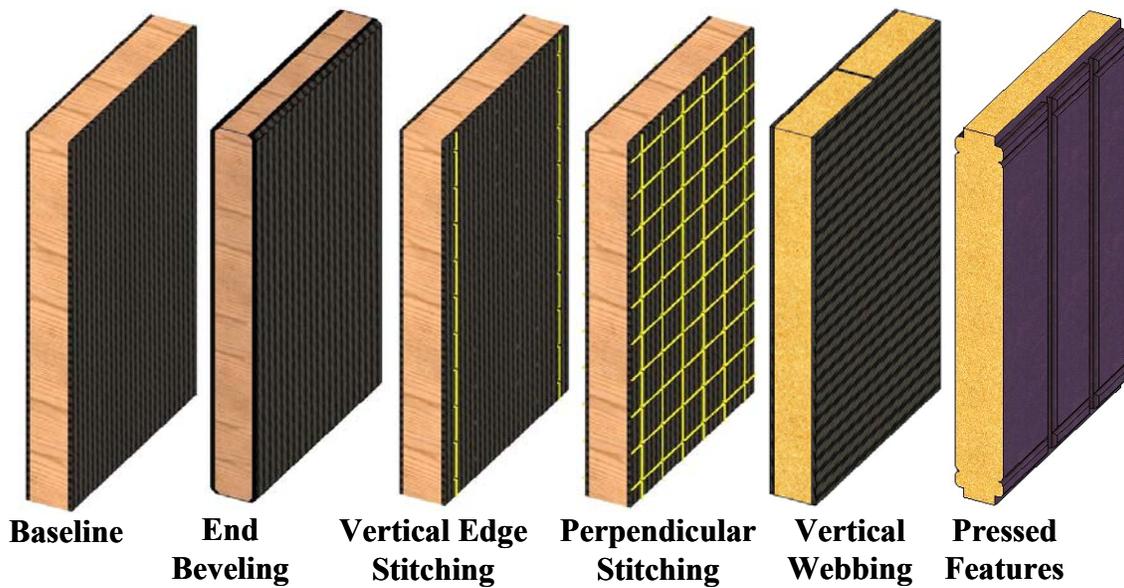
effort. The research work being performed at the University of Utah is split into three, phase-specific objectives, of which the first phase has been completed. The current phase involves developing an understanding of the structural response of four selected sandwich composite concepts identified in Phase I. These configurations are:

- Carbon-Epoxy/Balsa
- Carbon-Epoxy/Polyurethane Foam
- P4 Carbon-Epoxy/Polyurethane Foam
- P4 Carbon-Epoxy/Balsa

Numerous structural enhancements have been investigated in the current phase, Figure 5. They include end beveling, vertical edge stitching, perpendicular stitching and vertical webbing. In addition, the current work is also focusing on the details needed in the test fixture to obtain not only high energy absorption in the structural specimens but also consistent test results. The progress thus far has resulted in significant increases in the energy absorption of the above-mentioned configurations, Figure 6. Work is also currently underway to obtain fracture toughness measurements of the face-sheet/core interface. These measurements are input



**Figure 4.** Comparison of force histories for the unbonded tube under an impact velocity of 4m/s.



**Figure 5.** Structural Enhancement Features Being Explored in Phase II.

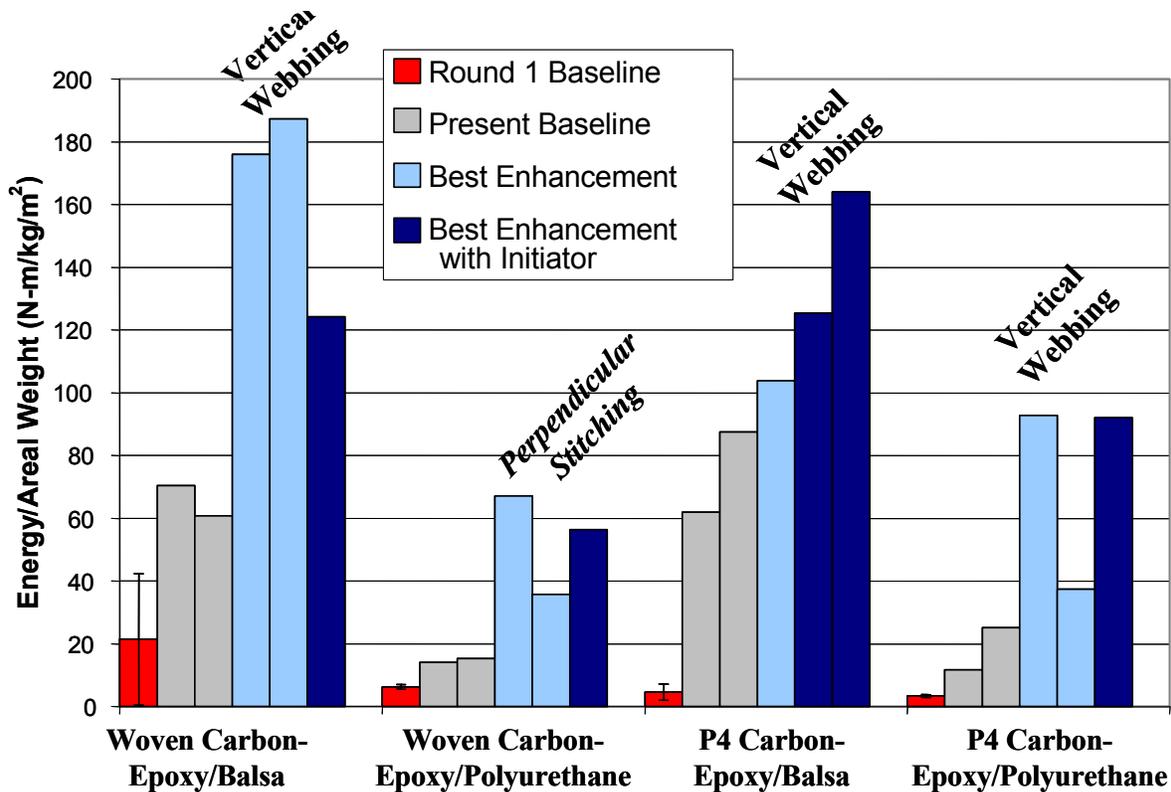


Figure 6. Improvements in Energy Absorption as a Function of the Structural Enhancement and Fixture Position.

to a numerical analysis using the virtual crack closure technique (VCCT) in the commercial software code ABAQUS®.

### Energy Absorption of Triaxially Braided Composite Tubes

The objective of the project is to develop a predictive tool for the crush analysis of triaxial braided composite structures under dynamic loads based on a smeared micro-mechanics model. The constitutive law developed for the analysis is based on an anisotropic viscoplastic model proposed earlier by Sun, et al. This viscoplastic law takes into account the effects of strain rate that are necessary to model dynamic behavior.

Fracture of the carbon-composite plies is also modeled in the current simulation. This fracture is not only based on the stresses obtained using the viscoplastic law but also on the critical damage zone that encompasses such fracture stresses. This damage zone takes into account stress

concentrations and fiber-tow scissoring. 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 entire modeling approach was demonstrated on dynamic crushing of both square and circular tubes with  $\pm 30$ , 45 and 60 degrees lay-up with very good correlation between experimental and numerical data over a wide range of crush speeds, Figure 7. The constitutive model with scissoring, stress-concentration and rate dependency has been implemented as a Vectorized User Material (VUMAT) subroutine in the explicit version of the commercial software ABAQUS®.

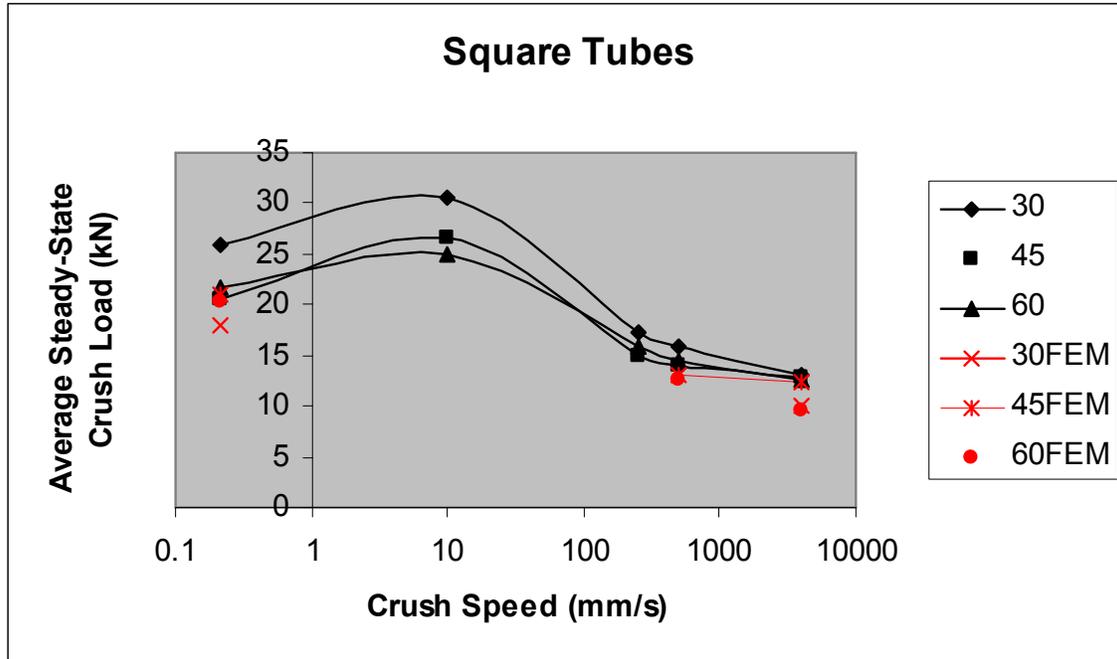


Figure 7. Correlation between Experimental Crush Data and Finite Element Predictions for Carbon-Fiber-Reinforced Square Tubes.

**Post-Peak Response Characterization of 2D Triaxially Braided Composites**

The objectives of this project are:

- 1) computationally demonstrate post-peak softening (PPS) observed with single unit-cell structural models on multi-cell structural models;
- 2) computationally investigate how the hierarchy of damage/fracture modes and the number/arrangement of unit cells affect PPS predictions;
- 3) computationally investigate how the variation in degree of imperfection in the micro-architecture affects the derived structural properties of the 2D Triaxially Braided Composite (2DTBC); and 4) experimentally test multi-unit-cell structural specimens in order to reflect, refute, or support the finding of the above objectives.

In 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 multi-cell unit structural models. The results of such analyses are directly applicable to the development of structural properties of 2DTBC for large-scale finite element (FE) simulations that are needed to assess energy

absorption in 2DTBC structural components. Using laser extensometers and speckle photography (for full-field strain measurements), experimental tests to measure PPS on single- and multi-cell 2DTBC will be performed. Further, computational models that incorporate cohesive zones (CZ) 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 in order to study and characterize the effects of measured architecture imperfections on the single-unit-cell and multi-cell structural stress-strain properties of 2DTBC, including the effects of different types and distribution of imperfection on PPS.

The primary resin matrix 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 *in-situ* material properties. Compression tests on coupons were also performed in the transverse (matrix-dominated) direction. It was found that *in-situ* matrix properties differ from pure matrix properties, and hence, the *in-situ* properties should be used for subsequent FE

analyses. Since axial fiber tows are the dominant load-carrying component, 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 need to be accounted for in finite element 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 micro-fracture. Note that Hetron typically exhibits an approximately 10% shrinkage during curing. However, detailed SEM images of Epon-based composite show that the tows are fully wetted and micro-cracks are minimal (typically, Epon exhibits little or no shrinkage while curing). Such a difference might explain (at this stage in the study) the higher energy absorption capacity of the Hetron-based system as compared with the Epon-based system.

Detailed FE models have been developed for a representative unit cell (RUC) for both material systems (Hetron and Epon). A RUC model (which is based on the real geometry) was analyzed using a new method in order to obtain the *in-situ* stress state of the matrix within a braided textile composite. It was found that when performing RUC-based analysis, it is important to recognize volume consolidation processes occurring during manufacturing. For example, when an enlarged cross-sectional image of a multi-layered braided composite is analyzed and the “theoretical” boundaries of adjacent RUCs within this image are marked, one notices that some RUCs are overlapping. To account for this fact in subsequent analyses, a computer program was developed to analyze the image and calculate the “actual” axial fiber-tow area. Based on the latter, the actual fiber volume fraction is recalculated, and the axial fiber-tow modulus within a RUC was adjusted.

An imperfection analysis study on a RUC was performed using FEA. The geometric imperfection was derived from the eigen modes of the RUC with the imperfection amplitude used as a parameter. Nonlinear geometry and nonlinear material properties were included. The analyses demonstrated

the imperfection-sensitivity character of this material/ structural system.

It was found that when a plasticity model is used, the Mises stress within the matrix element (in the RUC) has already reached the maximum value specified by the plasticity curve. This results in an artificial stiffening of the matrix. Because inelastic behavior is associated with work-loss, the team has suggested the development and employment of a Schapery-like, thermodynamically-based theory (ST) to characterize the progressive (inelastic) damage. Such an approach requires the definition of internal state variables. Further, the Schapery-like methodology will encompass mechanism-based damage/fracture modeling in order to model degradation at both the micro and macro (structural) levels. The principal investigator (PI) and team have formulated the mathematical basis for this work and have presented it to the sub-group. This formulation shows several relations between internal state variables and the energy of the system, as well the relation between instantaneous moduli in damaged state and virgin state. The PI and team have received 1-ply plaques of the same material systems (Epon- and Hetron-based) and performed coupon-level experiments. Extensive testing was performed on the 1-ply specimens, followed by experimental data processing including the extraction of the ST internal state variables (ISV) for RUC damage modeling.

A computer program was developed to calculate the ISV from the stress/strain test data. This program is incorporated directly into a FEA code so that ISV (implicit to the constitutive law) are automatically calculated during a FEA.

### **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 micro-mechanics material model previously developed in the Energy Management Program, available as a user sub-routine with ABAQUS®. Following a correlation study based on a simple test coupon, a

specimen representative of an automotive component subjected to bending impact loads will be evaluated.

The overall study involves three distinct phases: 1) smeared micro-mechanics material model of composite strips under lateral bending, 2) validation of the model using experimental data, 3) extension of the model for designing automotive components. Phase I of the project has been completed with the modeling and analysis of a  $[0^\circ 80k / \pm 45^\circ 12k]$  triaxial carbon-fiber braided composite strip subjected to off-axis compressive loading.

Phase II experimental testing of composite strips to validate the model effectiveness was completed by a university contractor in January 2005. Ninety specimens were tested to characterize the properties of triaxially braided composites in tensile, compression, pure bending and lateral bending.

Continuing software development during the course of this project has produced improvements in the basic ABAQUS® routines. Correlation studies with the updated version of the UMAT subroutine and Phase II test data were reported in May 2005. Problems noted with the test data were identified for further study.

### **Multi-scale Modeling for Crash Prediction of Composite Structures**

The objective of this research project is to develop a material model that considers microstructural aspects of damage and an efficient multi-scale modeling tool that is able to predict dynamic crush response of automotive composite structures at an affordable computational cost.

Four tasks of the research were proposed to accomplish the goal: (1) development of damage models for polymeric composites under the multi-scale computational framework; (2) calibration of the models to the experimental data provided by the ACC; (3) implementation of the developed capabilities into ABAQUS® Explicit, and finally (4) validation of the developed simulation capabilities against the experimental data on tubes in a drop test.

Research efforts so far have focused on Task 1 and Task 3. For Task 1, rate-independent damage material model for polymeric composites has been developed under the multi-scale framework based on the mathematical homogenization theory. At each representative volume element, the fracture of the composite materials was modeled as a progressive debonding and delamination at the material interfaces, as well as the degradation of the phase material properties. Two damage variables were introduced correspondingly to reflect the phase damage and the interface damage between phases using continuous damage mechanics. The constitutive relationship resulting from this microscale damage model is to be used in the numerical simulation of its corresponding macroscale model.

To significantly reduce the computational cost devoted to obtaining the constitutive relationship at each representative volume element for the simulation of the macroscale model, a novel model reduction technique was formulated by representing the damage-induced fields by influence functions. The influence function can be numerically evaluated at preprocessing stage ahead of the macroscale simulation. The model reduction approach was incorporated into the classical nonlinear homogenization theory. The accuracy and the computational cost of the homogenized model with model reduction is a function of the number of degrees-of-freedom used to interpolate the interface damage variables and the number degrees-of-freedom used to interpolate the microscale phase damage variables.

The developed multi-scale model has been implemented for two- and three-dimensional problems and incorporated into ABAQUS® Explicit using the user material utility (Task 3). A number of numerical verifications were conducted by comparing the newly developed multiscale model to the most sophisticated mathematical model involving no model reduction. As shown in Figure 8, a three-dimensional unit-cell problem with interface damage was considered. The unit-cell was under tensions along the 1 and 2 directions. Figure 9 illustrates the damaged unit-cell due to the tensions obtained from the classical unit-cell calculation without the model reduction. Figure 10 shows history curves of the response force along 1

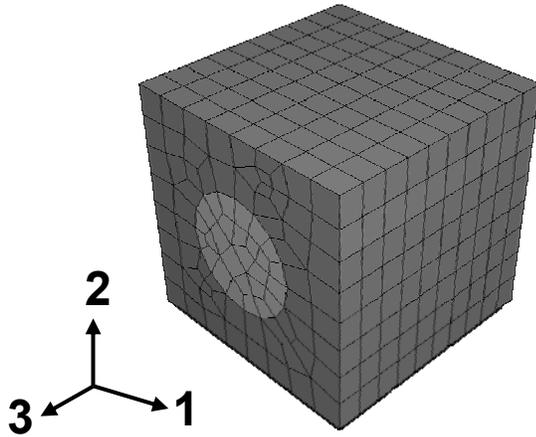


Figure 8. The Unit-Cell Problem.

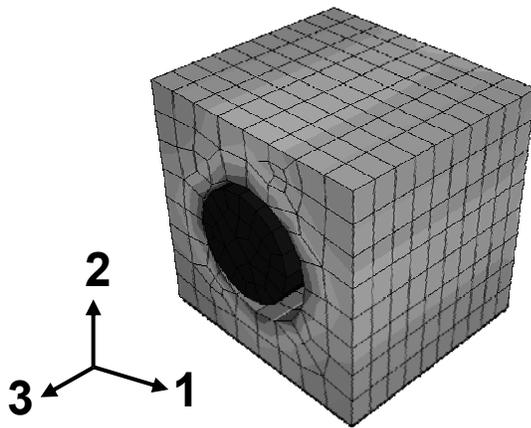


Figure 9. The Deformed Unit-Cell Under Tensions.

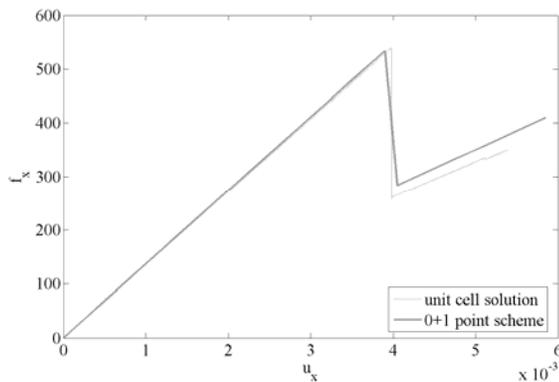


Figure 10. The History Curves of The Response Force Verses The Displacement.

direction with respect to the displacement along 1 direction for the classical unit-cell calculation and the developed unit-cell calculation with the model reduction. In this case, the developed approach only

used one degree-of-freedom to approximate the interface damage variable and achieved quite agreeable response to the expensive classical unit-cell calculation, which used more than 1000 degrees-of-freedom.

The next phase of this project will concentrate on the development of the rate-sensitive damage model for interface debonding and phase degradation (completing Task 1), calibration of the developed material models to the experimental data provided by the Automotive Composites Consortium (Task 2) and validation of the simulation capabilities developed against the experimental data on tubes in a drop test (Task 4).

**Summary**

The Crash Energy Management Program develops and demonstrates technologies that are used 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. During FY2005, in the experimental projects,

The effects of friction on the energy absorption of composites, including the differences between quasi-static and dynamic behavior, have been characterized and reported

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In the analytical studies,

- A computational model employing a discrete cohesive-zone representation of the fracture plane was used to evaluate the performance of composites with two different polymer matrices.

The analyses showed that fracture toughness is more critical than material strength when energy absorption is to be maximized.

- A rate-dependent plasticity model, incorporated into the ABAQUS® code, was used to predict the dynamic crush behavior of square and circular tubes with good correlation to experimental results.
- A Schapery-like, thermodynamically-based theory was developed to characterize post-peak progressive (inelastic) damage. The methodology encompasses a mechanism-based damage/fracture model in order to represent degradation at both the micro and macro (structural) levels.
- The modeling and analysis of a  $[0^\circ 80k / \pm 45^\circ 12k]$  triaxial carbon-fiber braided composite strip subjected to off-axis compressive loading has been completed.
- A rate-independent damage material model was developed under a multi-scale framework based on the mathematical homogenization theory and a novel model reduction technique that represented the damage-induced fields by influence functions. The multi-scale model was implemented for two and three-dimensional problems and incorporated into ABAQUS® Explicit using the user material utility.

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