

G. Composite Crash-Energy Management (ACC100ⁱ)

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

Accomplishments

- A study of the static and dynamic behavior of composite crash was completed to experimentally determine the microstructural factors that lead to decreased dynamic tube-crush energy absorption.
- The average strain energy release rate, G_{IC} , was obtained in Mode I testing of adhesive joints under static and dynamic loading. Tests showed the effects of mixed loading modes on fracture-energy values.
- A study of structural concepts to improve the energy absorption of sandwich panels showed that the effectiveness of the improvements is highly dependent on the type of core material and somewhat less dependent on the type of fiber facesheet reinforcement.
- Experimental adhesive lap-joint data were used to develop theoretical and numerical tools that describe non-self-similar progression of cracks without specifying an initial crack. A cohesive-decohesive zone model was adopted to represent the degradation of the material ahead of the crack tip. This model unifies strength-based crack initiation and fracture-mechanics-based crack progression.
- A rate-dependent plasticity model for triaxially-braided composites was incorporated into the current predictive tool, along with an implementation of the Tsai-Hahn fiber-bundle theory as applicable to braided composites, to account for the effect of a critical damage area (CDA).
- Tests of 30°, 45°, and 60° triaxially-braided square and circular tubes were completed. The experimental data were obtained for test speeds of 1 m/s and 4 m/s. A predictive algorithm has been developed as a vectorized user material (VUMAT) subroutine for use with the commercial software ABAQUS® and is being validated.
- Kink banding in axial tows was investigated as another phenomenon that contributes to post-peak softening in braided composites. All models investigated included several degrees of tow misalignment. Stress-strain plots for such models show snap-back behavior which is dependent on misalignment degree.
- The study of multiscale modeling methods included the verification of the proposed framework against benchmark computational models. The verification of the multiscale simulation toolkit was completed. The proposed multiscale fracture model was verified against the direct homogenization method and significant improvements in computational performance were demonstrated.

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 Composite Crash-Energy Management project is to develop and demonstrate the technologies required to apply production-feasible structural composites in automotive crash and energy-management applications. Efforts within the project 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 effort'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.

The effort has been completed and a final report drafted. The study conclusions include:

1. Static 3-pt bending fracture tests (Mode I) showed that the average fracture energy is the best variable for characterizing the "fracture behavior" of carbon-fiber braided materials. It was found that the fracture energy is influenced by the local microstructure.
2. Low-velocity impact tests showed that two "crack systems" were present during crack propagation, i.e., a primary crack in the matrix and a retarded secondary crack within the fiber-bridging zone.
3. The low-velocity impact fracture energies were found to be lower than the static fracture energy for both the Hetron and Epon matrix composites. It was found that under static loading conditions, the extent of the bridging zone was larger and contained a great deal of fiber pullout. In addition, the primary crack was found to be wavy in its trajectory during static loading. Macro- and micro-scopic examination showed that the biased tows pull out of the matrix during crack propagation under static loading. Under impact conditions, the biased tows break cleanly and show less fiber pullout.
4. A comparison of the *in-situ* properties of the Hetron and Epon composites was made. This included a procedure to extract *in-situ* properties from basic specimen-level tests. The results showed that even though the virgin material properties between these resins are similar, the *in-situ* behavior that is observed from composites made from these materials is different. For example, the fracture toughness of the Hetron was about eight times larger than the Epon.
5. Off-axis compression tests used to characterize the shear stress-strain response showed that the shear response in Epon was lower than the Hetron composite. This is an indicator of why there is a difference in the fracture toughness.
6. In addition, the Hetron composite contained 3.6 times more voids than the Epon, especially at the center of the tows. There were also residual tensile stresses in the Hetron composite that led to more cracking in the biased tows. These two factors also led the Hetron composite specimens to absorb more fracture energy.
7. Mode II fracture tests were also carried out under static and dynamic conditions. The Mode II fracture toughness values were found to be insignificant when compared to the Mode I data. The conclusion is that during crushing, the energy dissipation due to interlaminar cracking within the tube walls is insignificant when compared to the corner cracking energy (Mode I).

8. A discrete cohesive zone model (DCZM) was developed and used through ABAQUS® as a subroutine. Simulations using DCZM were used to study Mode I fracture in the braided composites. Using the material's orthotropic properties along with a one-parameter plastic material model, fracture toughness, and the specimen geometry, the DCZM simulations were found to be in close agreement with experimental values.
9. The DCZM model is a simple tool for characterizing the corner cracking of tubes that explicitly takes into account the fracture energy of the materials in question. As such, it is recommended that codes that are intended to be used for tube crushing utilize the material fracture energy, especially if gross cracking is present, as in the case of tubes.

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.

The scope is a combined computational and experimental study of the dynamic response and fracture of an adhesively-bonded, automotive sub-structural component under impact loading. The approach consists of characterizing the dynamic fracture of the adhesive material from falling- wedge drop-tower tests of bonded beam-type specimens under various mode mixities. Numerical constitutive models of the adhesive are developed and validated from the drop-tower tests. The structural sub-component selected is a 4 in. by 4 in. square, composite material tube fabricated by adhesively bonding the overlap of two U-sections. Axial impact tests of the composite tubes are being conducted at ORNL. The numerical constitutive model of the adhesive has been implemented in the LS-DYNA software package to simulate the tube crush tests. Comparison between test results and those from numerical simulation are being used to assess the computational modeling methodology.

Experimental work:

Mode I fracture testing has been successfully completed using the standard double-cantilever beam (DCB) specimen geometry. Results from both quasi-static and various dynamic rates are presented. Driven-wedge test results have been analyzed and compared with Mode I DCB test results in order to establish a correlation among testing procedures. Additionally, a finite-element (FE) analysis has been conducted in order to establish correction factors for shear and root rotation at the crack front associated with the short crack lengths observed in the driven-wedge test. Mixed-Mode I/II tests were completed for both quasi-static and dynamic loading conditions utilizing the asymmetric double-cantilever beam (ADCB) and single-leg bend (SLB) specimen geometries. A Mode III test fixture has been designed in order to aid in the full characterization of the PL-731SIA adhesive and to develop a full three-dimensional fracture envelope for the adhesive.

Mode I Testing Results

Results show that the average strain-energy release rate (SERR), G_{Ic} , for 11-ply and 36-ply DCB specimens range from an average of 2800 J/m² and 2460 J/m², respectively, under quasi-static loading conditions to an average of 1060 J/m² and 700 J/m², respectively, at an applied loading rate of 1 m/s. These average values take into account cohesive fractures within the adhesive layer only, as delamination within the composite adherends has been observed in some specimens. Stick-slip behavior is still present and is thus resulting in very few data points per specimen. On average, two to three fracture events are observed along the length of each 300 mm test specimen under quasi-static loading conditions, while as many as five fracture events have been recorded at higher loading rates. It should also be noted that 20-ply specimens have been tested at various loading rates; however, only about 10% of the fracture events have been observed within the adhesive layer, while the remainder have been observed to propagate into the composite adherends resulting in interlaminar fractures. Figure 1 illustrates the relationship established between the Mode I fracture energy, G_{Ic} , and the applied loading rate.

Mixed-Mode I / II Testing Results:

Initial Mode I DCB dynamic fracture testing was conducted using a servo-hydraulic test machine capable of achieving test velocities up to 1 m/s. This particular machine was outfitted with a 2.5 kip strain gage-based load cell. All data acquisition software for this machine was developed in-house by

engineers at ORNL using National Instruments LabVIEW software. A lightweight slack adaptor was developed in-house from standard off-the-shelf components (#2 Morse Taper) to allow the test machine to reach maximum velocity prior to applying any load to the test specimens.

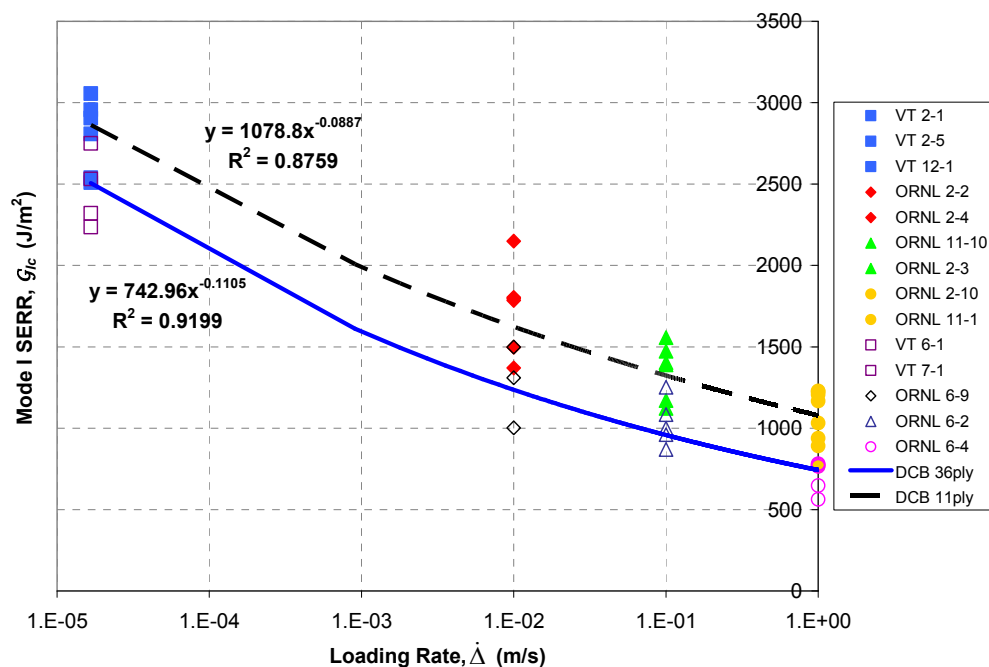


Figure 1. Mode I SERR, G_{Ic} , vs. applied loading rate for 11 and 36-ply bonded composite specimens. Note: filled symbols = 11-ply specimens and unfilled symbols = 36-ply specimens.

The remaining dynamic tests (mixed-Mode I/II and Mode II) were conducted using a custom designed MTS servo-hydraulic test machine at ORNL outfitted with a 500-lb. piezoelectric load cell and improved slack-adaptor design. This machine is capable of achieving test velocities up to 18 meter/second. A high-speed imaging system was used for monitoring crack propagation during all dynamic test events.

From the ADCB tests it was observed that, with the addition of even a small Mode II component, the total mixed-Mode I/II fracture energy values, $G_{I/IIc}$, are an average of about 50% lower than those observed under pure Mode I loading conditions. This was believed to be the case due to the fact that the fracture surfaces of the asymmetric specimens showed that the crack was driven to the interface,

thus resulting in lower total fracture energies. Another important aspect of these tests was that many more data points per test specimen were obtained because of the interfacial failure, thus allowing for a more complete mode-mixity characterization. When compared with a maximum of three to four data points per specimen for the Mode I tests, as many as twelve to fifteen data points were recorded for several of the ADCB tests. In conjunction with the ADCB tests, SLB specimens were utilized to help further characterize the mixed-mode fracture behavior of this particular material system. Symmetrically-bonded composite specimens were utilized for this aspect of the study, resulting in a fixed level of mode-mixity. Although the fracture surfaces were similar to those observed from the ADCB tests, only a limited number of data points could be gathered from the SLB tests, with roughly

five data points per specimen being recorded. Figure 2 provides a complete summary of the ADCB and SLB test results.

Computational Work:

The computational work continued on providing support to the experimental work done on lap joints at ORNL. Using experimental data obtained from standard fracture-test configurations, theoretical and

numerical tools are developed to mathematically describe non-self-similar progression of cracks without specifying an initial crack. A cohesive-decohesive zone model, similar to the cohesive zone model known in the fracture mechanics literature as the Dugdale-Barenblatt model, is adopted to represent the degradation of the material ahead of the crack tip. This model unifies strength-based crack initiation and fracture-mechanics-based crack progression.

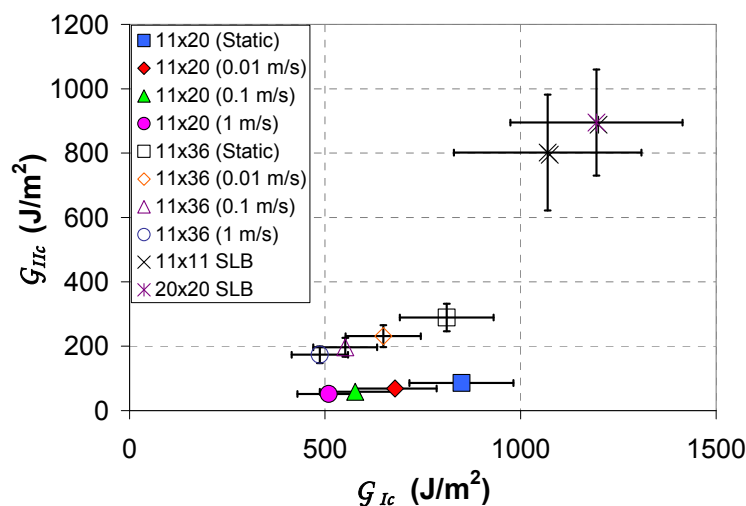


Figure 2. Summary of ADCB and SLB mixed-mode fracture tests.

The cohesive-decohesive zone model is implemented with an interfacial surface material that consists of an upper and a lower surface that are connected by a continuous distribution of normal and tangential nonlinear elastic springs that act to resist either Mode I opening, Mode II sliding, Mode III sliding, or a mixed mode. The initiation of fracture is determined by the interfacial strength and the progression of the crack is determined by the critical energy release rate. The adhesive is idealized with an interfacial surface material to predict interfacial fracture. The interfacial surface material is positioned within the bulk material to predict discrete cohesive cracks. The interfacial surface material is implemented through an interface element, which is incorporated in ABAQUS using the user-defined element (UEL) option.

A procedure is established to formulate a rate-dependent model based on experiments carried out on compact tension test specimens. The rate-

dependent model is incorporated into the interface element approach to capture the unstable crack growth observed in experiments under quasi-static loading conditions. The compact tension test gives the variation of the fracture toughness with the rate of loading; this information is processed and a relationship between the fracture toughness and the rate of the opening displacement is established. The cohesive-decohesive zone model is implemented through a material model to be used in an explicit code (LS-DYNA). Dynamic simulations of the standard test configurations for Mode I (DCB) and Mode II (End Load Split) are carried out using the explicit code. Verification of these coupon tests leads to the crash analysis of realistic structures such as the square composite tube. Analyses of bonded and unbonded square tubes were completed. These tubes show a unique fracture mode that has been captured in the analysis. Disadvantages of the interface element approach are well documented in the literature. An alternative method, known as the

Extended Finite- Element Method (XFEM), is implemented here through an eight-noded quadrilateral plane-strain element. The method, based on the partition-of-unity, is used to study simple test configurations like the three-point bend problem and a double-cantilever beam. Functionally-graded materials are also simulated and the results are compared to the experimental results available in the literature.

Performance of Novel Sandwich Composites

The objective of this effort is to investigate the viability and crashworthiness of novel sandwich composite concepts for automotive applications. It addresses 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, to mention a few. The research work being performed at the University of

Utah is split into three phase-specific objectives as has been noted in earlier reports.

Phase II work that was completed during the dates outlined involved testing of the four sandwich configurations shown in Table 1. The focus of the current phase during this timeframe was on the following:

Structural testing

- Development and understanding of structural-level concepts for energy absorption.
- Structural impact testing.
- Necessary improvements to test fixture to help progressive crushing of sandwich panels.

Damage evolution testing

- Mixed mode testing of the sandwich panels to determine critical strain-energy release rates.

Table 1. Sandwich Configurations Used in Phase II Study.

	Facesheet	Core
1	Woven Carbon Epoxy	Balsa Wood
2	Woven Carbon Epoxy	Polyurethane Foam
3	P4 Carbon-Epoxy	Balsa Wood
4	P4 Carbon-Epoxy	Polyurethane Foam

The development of structural-level concepts was completed and involved a study of beveled ends, embedded notches, stitches and improvements to the test fixture to obtain progressive, high energy-absorbing fracture mechanisms. The findings show that the effectiveness of the structural-level concepts is highly dependent on the type of core material (balsa vs. foam) and somewhat less dependent on the type of facesheet (woven vs. P4). The structural impact testing involved the edgewise impact tests of 280 x 280-mm sandwich panels. These structural impact tests were completed using the Test Machine for Automotive Crashworthiness (TMAC) facility at ORNL (see 8.B). Figure 3 shows a summary of the improvements made in energy absorption due to progressive crushing as a result of adding features in the core as well as improvements made to the test fixture.

The damage evolution testing was completed and involved the Mixed Mode tests of the sandwich

configurations shown in Table 1. As reported earlier, the Mode-I (DCB), Mode-II (ENF) had already been completed on these panels. The mixed-mode test is illustrated in Figure 4. Stable crack growth was achieved in this test, as in the other two fracture tests, thus enabling the measurement of an initiation and propagated values of the critical strain-energy release rate.

Phase III involves development of finite-element modeling methodologies for damage progression, effects of geometric/material alterations on damage progression and energy absorption with a view toward the implementation of closed-form analytical models to address specific deformation modes. This phase is currently underway.

Energy Absorption of Triaxially-Braided Composite Tubes

The objective is to develop a predictive tool for crush analysis of triaxially-braided composite

structures based on a smeared micromechanics model utilizing shell elements. A smeared micromechanics model developed under an earlier contract was extended to dynamic analysis. The project answers questions pertaining to the basis of the mathematical representation of the energy absorbing mechanisms, unit-cell size relative to the FE size, rate effects, stress-concentration effects on load-sustaining ability, objectiveness of damage-evolution assumptions, and micro-mechanics application to shell FEs.

The smeared micro-mechanics unit-cell model code has been rewritten to improve its computational efficiency. A rate-dependent plasticity model was incorporated into the code, along with an implementation of the Tsai-Hahn fiber-bundle theory as applicable to braided composites, to account for the effect of a critical damage area

(CDA). The numerical results after accounting for CDAs are shown in Figure 5 for the case of a static crush of a 45° braided coupon with a hole and in Figure 6 for the case of dynamic crush of a 45° square tube. These simulations are accomplished on one-eighth of the tube model assuming symmetric boundary conditions. Tests were conducted both at the TMAC facility at ORNL and at Stanford University to generate crush data for both circular and square tubes. This was done in order to collect experimental data to help establish a better correlation between the numerical code and tests. Tests included 30°, 45°, and 60° tubes with the crush being initiated by 1/4th- and 5/16th-inch fillet radius steel plugs in the square and circular tubes, respectively. The tubes used for the experiments are shown in Figure 7. The experimental data were obtained for test speeds of 1 m/s and 4 m/s.

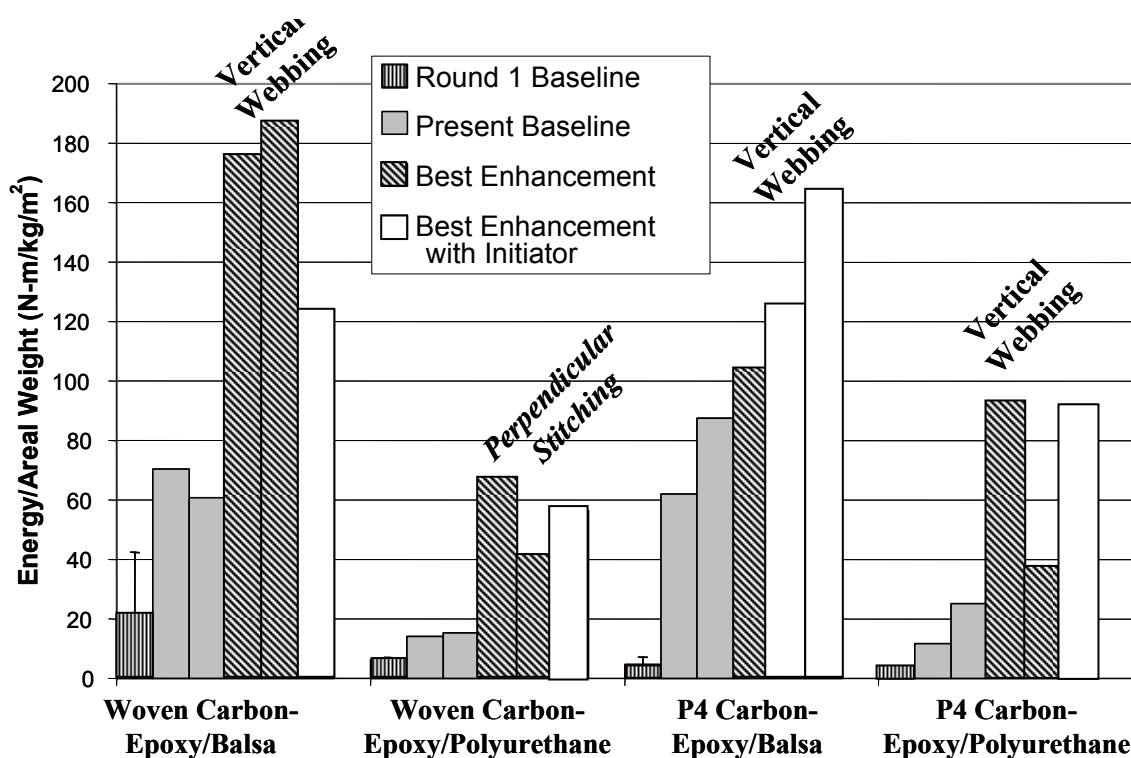


Figure 3. Energy absorption improvements from design modifications.

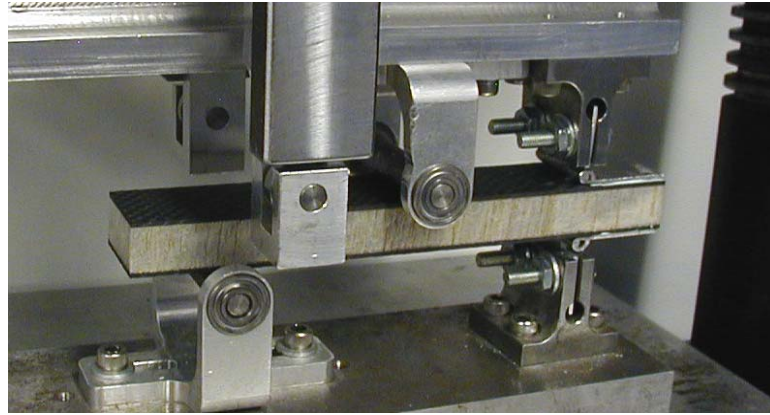


Figure 4. Mixed-mode bending (MMB) test.

The code has been developed as a VUMAT subroutine for use with the commercial software ABAQUS®. The code is currently being tested for validity against the crush of a full tube as opposed to a symmetry model used by the developer.

Post-Peak Response Characterization of Two-Dimensional Triaxially-Braided Composites

The objectives of this effort 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); 4) experimentally test multi-unit cell structural specimens in order to reflect, refute, or support the finding of the above objectives.

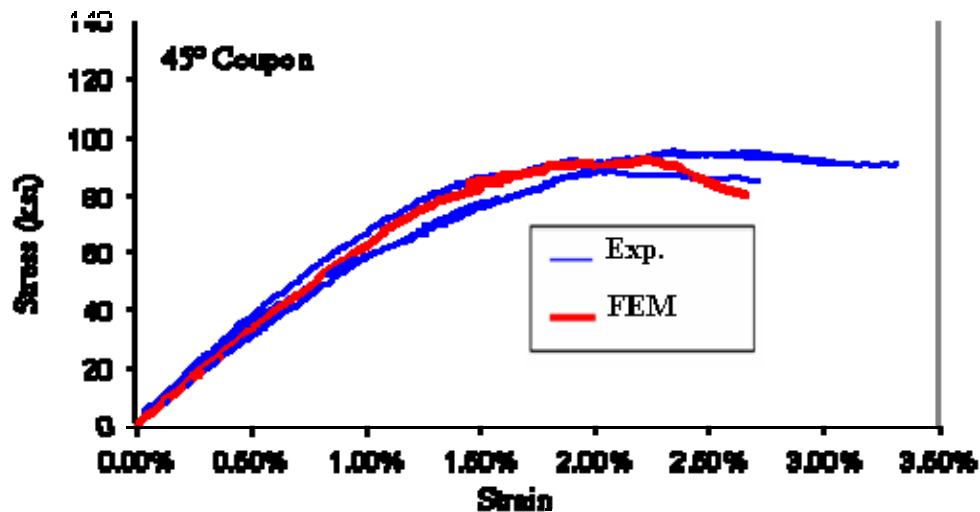


Figure 5. Comparison between test and numerical analysis showing the effect of implementing a critical damage area (CDA).

In this effort, 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 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 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 materials (Hetron and Epon) were experimentally characterized by measuring their

pure (virgin) properties, performing coupon tension tests (with different tow orientations), and then using data-reduction techniques to back-calculate *in-situ* material properties. Compression tests on coupons were also performed in the transverse direction (which are matrix-dominated).

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, Figures 8 and 9. 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 (e.g., in FE analysis) by a reduction in tow cross-sectional area and/or material constants. Such regions which reduce the fiber volume fraction exist in the Hetron-based composite and are usually associated with micro-cracking. 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,

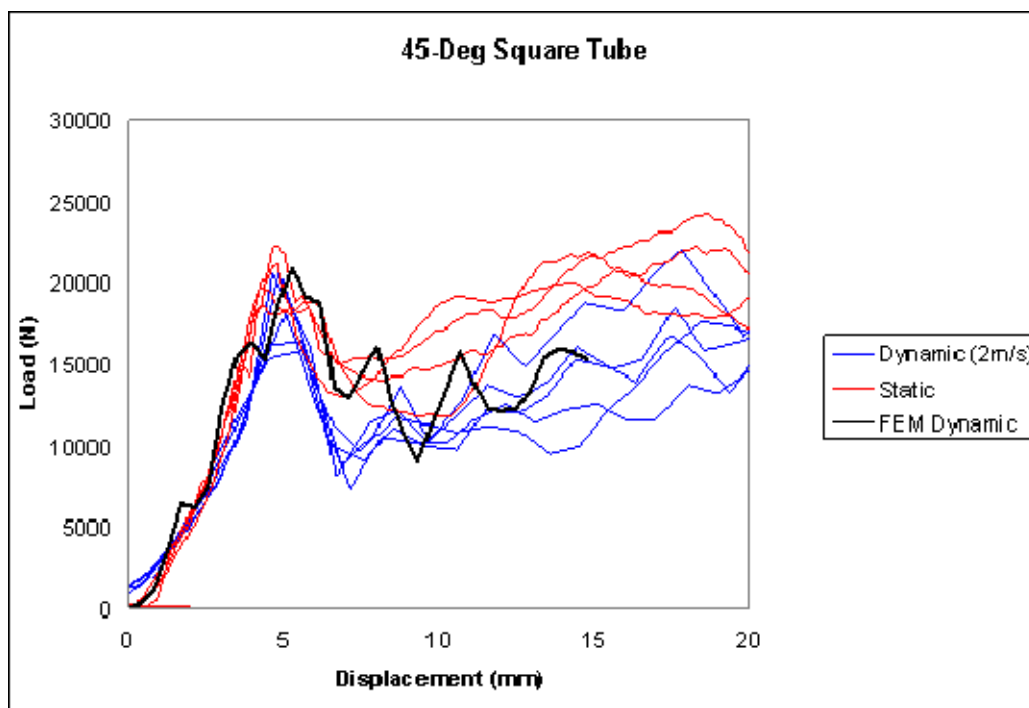


Figure 6. Comparison between test and numerical analysis for the dynamic crush of a 45° square tube.

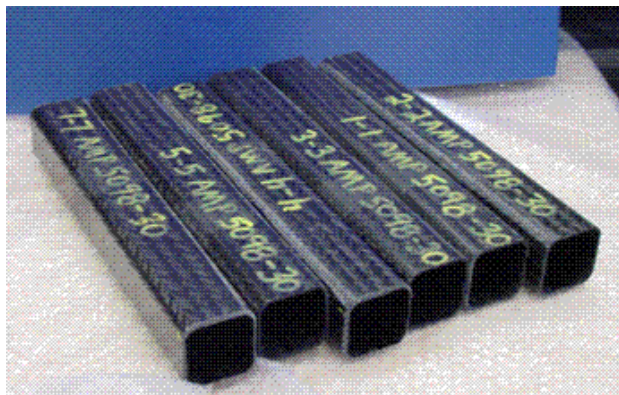


Figure 7. Square and circular tubes used for the dynamic tests at ORNL.

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 one as reported in the literature. To investigate this voids effect, two detailed FE models of a fiber tow were developed; one does not include any voids, while the other has the core cut out resulting in a tow resembling an undulated thick cylinder. Eigen analyses were performed and subsequent response

analyses (with 6% imperfections—scaled with respect to eigenmodes) showed that an appreciable reduction in the maximum Plateau stress can be caused by including such tow voids. However, FE analyses showed that as the number of RUCs increase, the effect of voids on peak-stress reduction decreases.

Detailed FE models have been developed for one RUC for both material systems (Hetron and Epon).

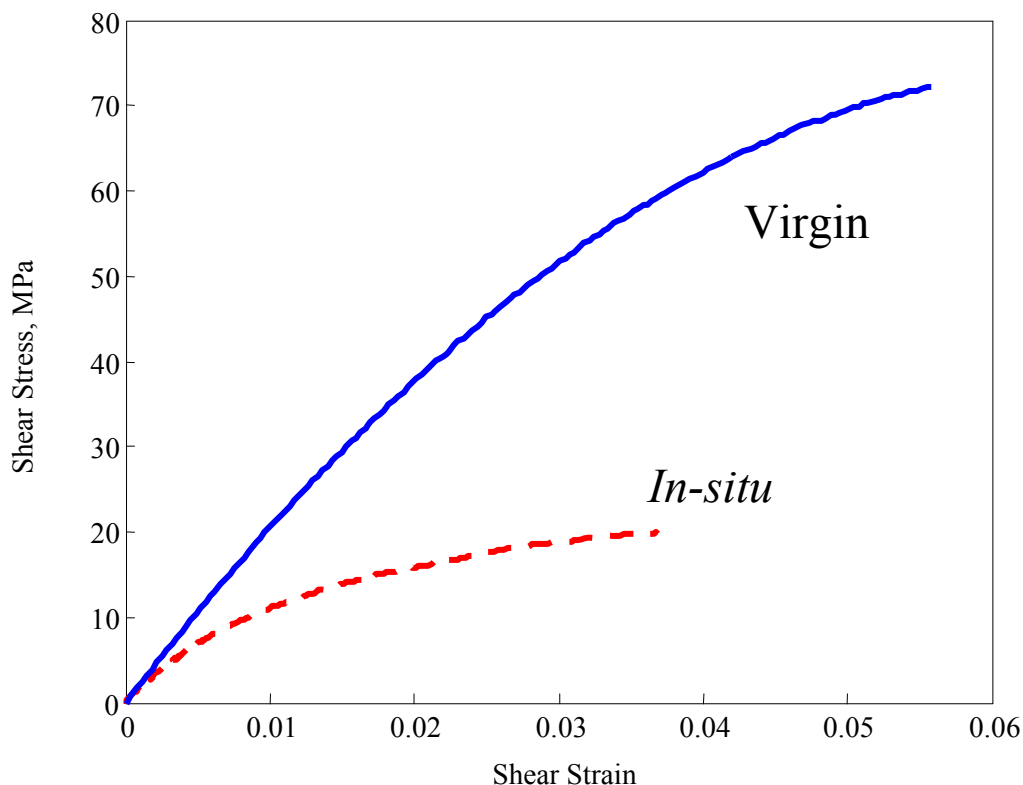


Figure 8. Shear stress vs. shear strain for pure (virgin) matrix (solid line) and the corresponding *in-situ* matrix (dashed line).

The 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 images) 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 one RUC is adjusted.

An imperfection analysis study on one RUC was performed using finite-element analysis (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

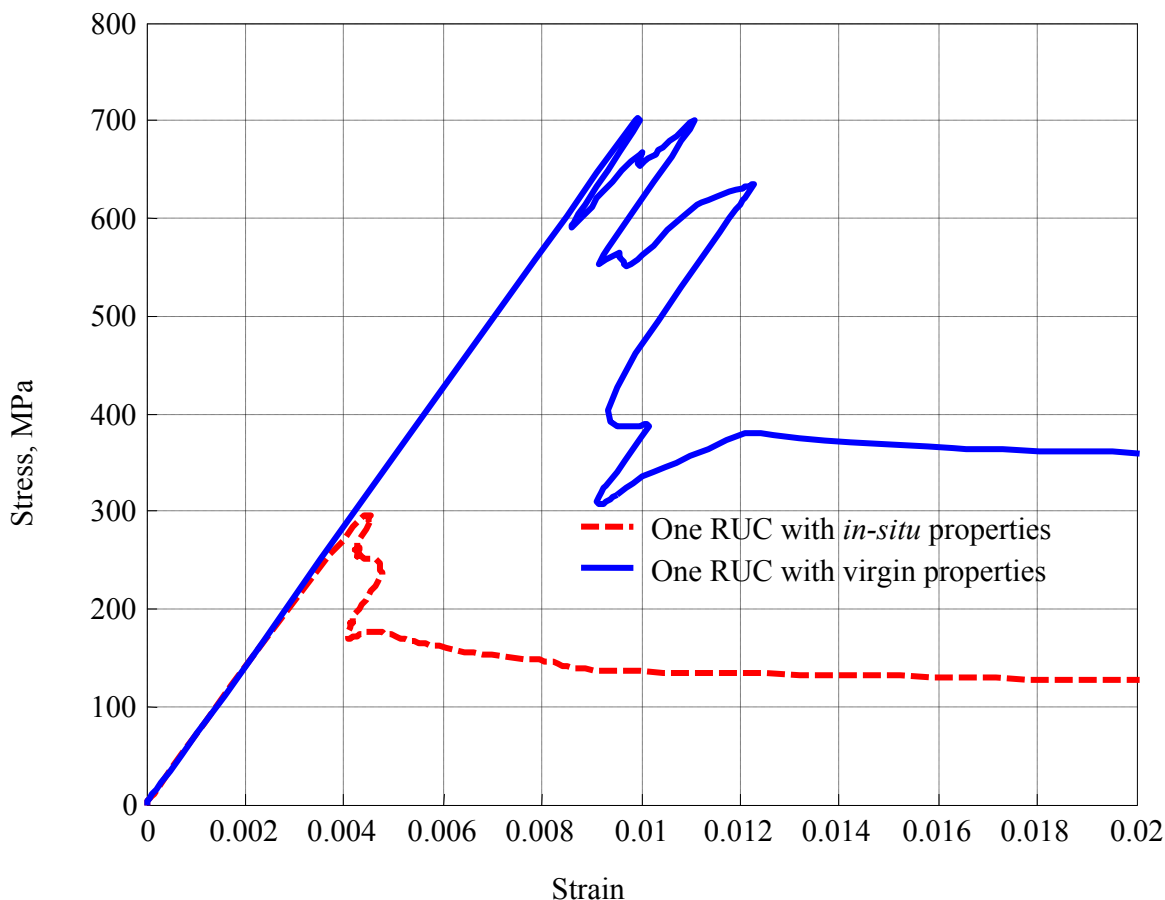


Figure 9. Finite-element analysis results for compressive stress vs. strain for one representative unit cell (RUC) using pure (virgin) matrix properties (solid line), and the corresponding *in-situ* matrix properties (dashed line).

(ST) to characterize the progressive (inelastic) damage. Such an approach requires the definition of internal state variables (ISV). Further, the above methodology (based on Schapery) will encompass mechanism-based damage/fracture modeling in order to model degradation at both the micro- and macro-(structural) levels. A mathematical model was developed, and several laboratory tests were carried out on coupon specimens. Using the stress-strain test data, the ISV were extracted for RUC damage modeling. Such information was then incorporated directly into a FEA code so that ISVs (implicit to the constitutive law) are automatically calculated during analysis execution.

In previous studies, fiber tows were treated as elastic, which is an approximation since the matrix influences the transverse tow properties. To improve the model, an orthotropic deformation theory featuring an elastic-plastic formulation was derived and implemented. Several models for one RUC (with different imperfection amplitudes—as previously described) were analyzed in which the effects of tow plasticity were investigated. It was found that such effects on such simplified models are not significant and are significantly less dominant than tow-void inclusion.

More detailed FE models were developed which included multiple RUCs (4, 9 and 16 RUCs). Such models introduced various new modeling challenges including how to preserve edge/boundary conditions, imperfections and periodicity. In addition to uniform global imperfection, a local imperfection was added so that the “center column” of the fiber tows would bulge out more than the neighborhood cells. Convergence computational studies were carried out and trends of convergence started to appear between the 1, 4, 9 and 16 RUCs. Figure 10 shows the preliminary results for the 1, 4, 9 and 16 RUCs with 6% imperfections. For models including 9 RUCs or more, the computational resources become significant and model execution time becomes large.

Kink banding in axial tows was also investigated as another phenomenon that contributes to post-peak softening in braided composites.

Since tows can include tens of thousands of fibers, simplified (but detailed) 3D FE models were developed which included fibers within a matrix (modeled using matrix *in-situ* properties). Two tow models were developed, one with isotropic fiber properties and another with orthotropic fiber properties. All models included several degrees of tow misalignment. Stress-strain plots for such models show snap-back behavior which is dependent on misalignment degree. For larger misalignment (approx. 1 deg.) the stress-strain relation resembled an almost elastic-perfectly plastic behavior (with some decreasing plateau stress). Figure 11 shows the preliminary results for an orthotropic fiber-tow kinking model with different misalignments.

Investigations into fiber-kinking modes were carried out. The FEA predictions showed qualitative agreement with tests when damaged zones, predicted by model, are compared with images taken of the damaged test specimens. Such agreement provided additional confidence in the modeling methodologies and predictive capabilities.

Lateral Impact Study

The objective of this effort 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 this project, 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, and 3) extension of the model for designing automotive components. Phase I of the project has been completed with the modeling and analysis of a $[0^\circ 80k / \pm 45^\circ 12k]$ triaxially-braided carbon-fiber composite strip subjected to off-axis compressive loading and Phase II was previously reported. Further work on Phase III has not occurred due to personnel changes.

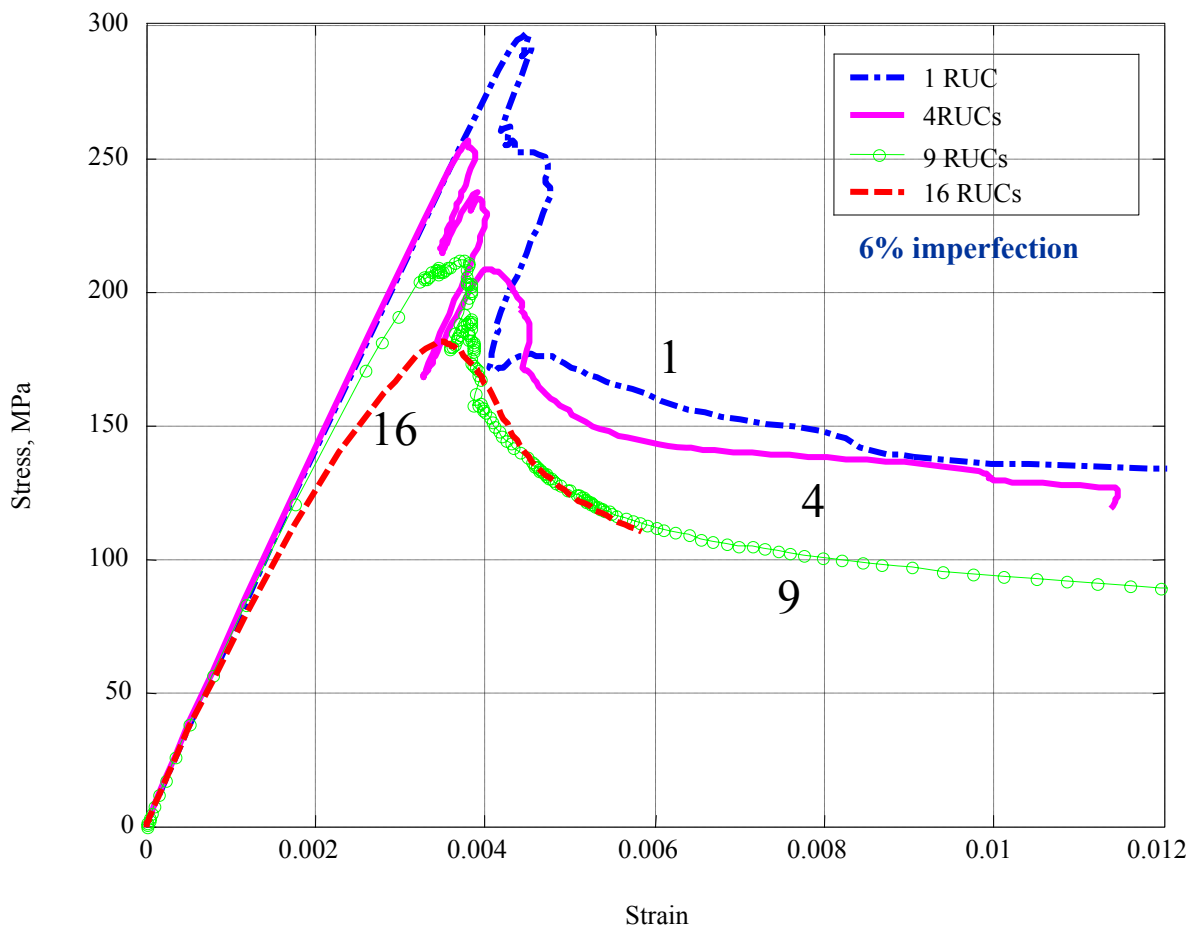


Figure 10. Preliminary FEA results for the 1, 4, 9 and 16 representative unit cells (RUCs) with 6% imperfections.

Multiscale Modeling for Crash Prediction of Composite Structures

The objective of this work is to develop a material model that considers microstructural aspects of damage and an efficient multiscale modeling tool that is able to predict dynamic crush response of automotive composite structures at an affordable computational cost. Five tasks of the research were proposed to accomplish the goal: (1) development of a multiscale computational framework for the crash analysis of polymeric composites, (2) implementation of the framework into ABAQUS Explicit, (3) verification of the proposed framework against benchmark computational models, (4) calibration using experimental data, and (5) validation of the proposed simulation capabilities against composite tube specimens' behavior under crushing loads.

Tasks (1) and (2) were completed and presented in previous reports. The current research efforts have been focused on completing tasks (3) and (4). Task (3), verification of the multiscale simulation toolkit, was completed. A direct homogenization method based on the classical nonlinear homogenization theory was implemented and compared to the fixed- and variable-reduced-order models. The fixed-point reduced-order-model was developed and verified earlier. A variable-point reduced-order model was developed and verified against direct homogenization. The computational performance of the variable-point reduced-order model is documented in Table 2 and clearly shows the computational advantages of the multiscale methodology developed over the classical nonlinear homogenization approach.

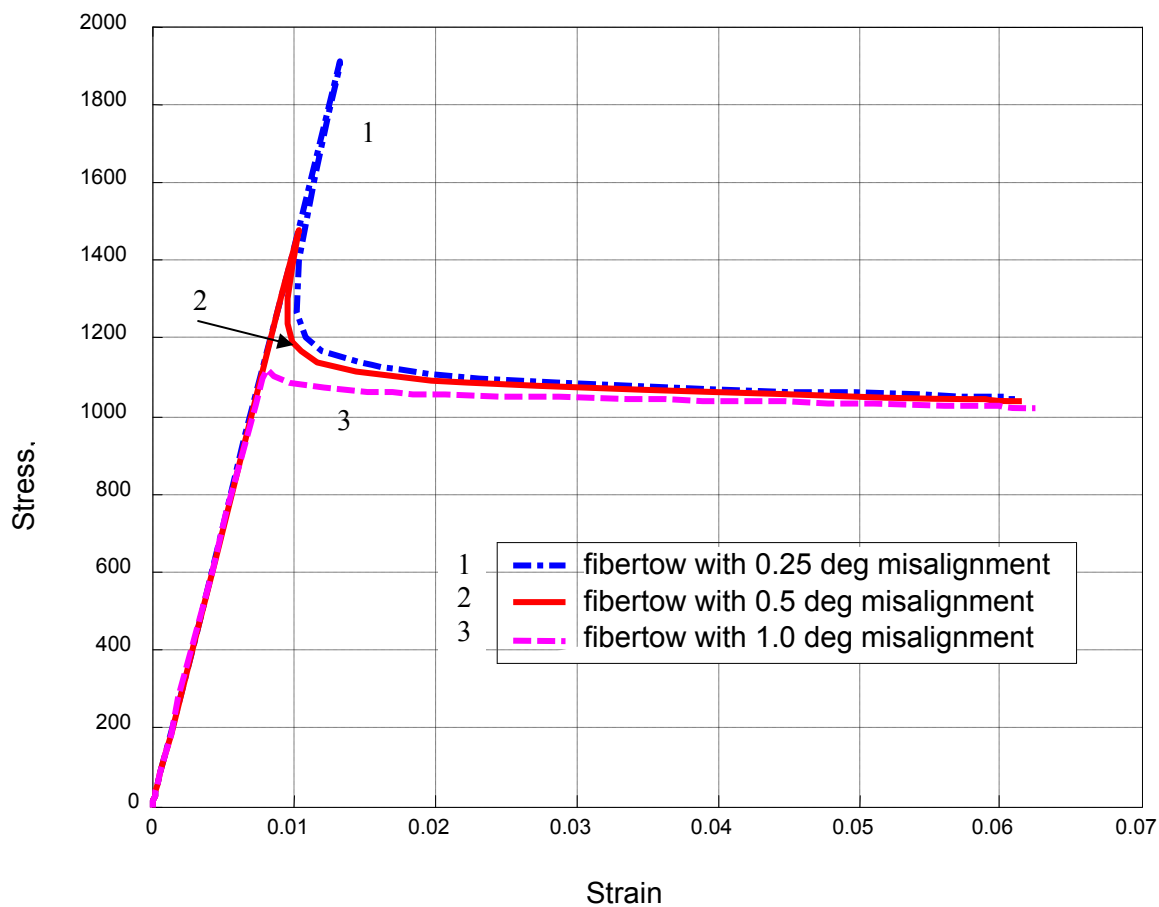


Figure 11. Preliminary results for an orthotropic fiber-tow kinking model with different misalignments.

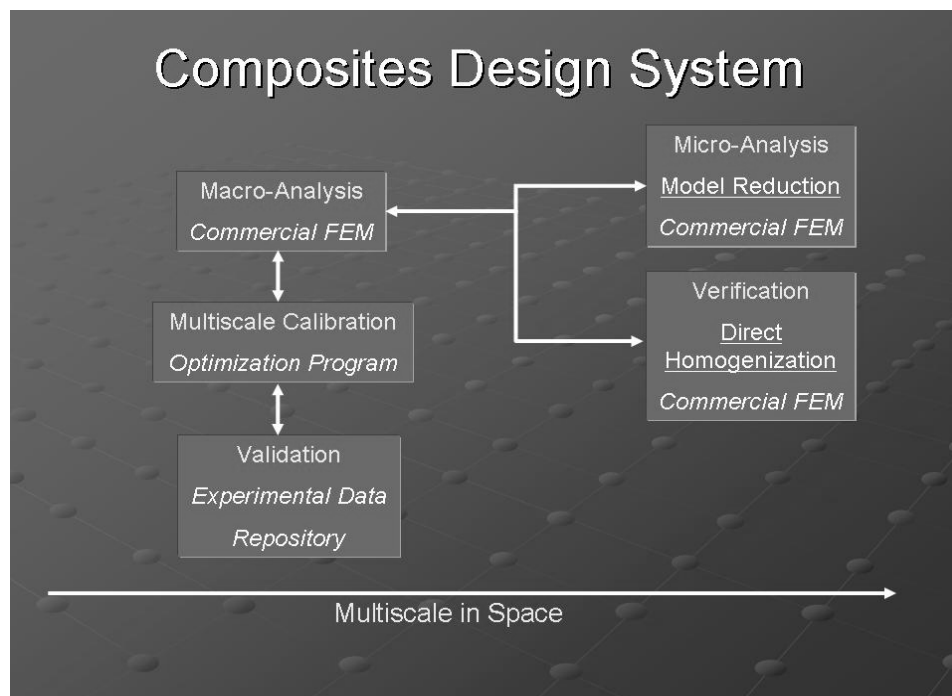


Figure 12. Components of the Crash Prediction Design System.

For Task (4), a calibration strategy was developed for the evaluation of the material properties associated with the elastic and failure behavior of the composite microconstituents and interfaces. The calibration toolkit, Figure 12, developed permits incorporation of various experiments into the experiment simulator repository. In the multiscale

simulation toolkit developed, an objective function is automatically created based on the available experiments, and model failure parameters are identified using optimization techniques with minimal user interference.

Table 2. Simulation performances of the variable point reduced order multiscale model and comparison to fixed point reduced order model and direct homogenization.

Model	# of incr.	# of iter.	total CPU time
Fixed 0+1 point	32	57	~1 min.
Fixed 0+5 point	32	122	~3 min.
Variable pt.	32	109	~5 min
Fixed 0+10 point	32	112	~25 min.
Direct homogenization	9	81	~ 6 days

The calibration strategy was integrated with ABAQUS and used for the calibration of the braided composite architecture provided by the ACC. The braided composite unit-cell shown in Figure 13 consists of three phases: axial tows, bias tow and matrix. It was constructed using ABAQUS/CAE. The general guidelines for preparing arbitrary unit cells with ABAQUS/CAE were developed. The elastic properties for microconstituents were calibrated based on the chord moduli from the

tensile and compressive tests provided by ACC and Reference 1. The calibrated values are summarized in Table 3. The failure parameters of the 1+4-point reduced-order model were calibrated based on three types of tests: tensile test to failure, compression test to failure and short-beam three-point bending to failure. The resulting predictions of the moduli and strengths compared with experiments are summarized in Tables 4 and 5.

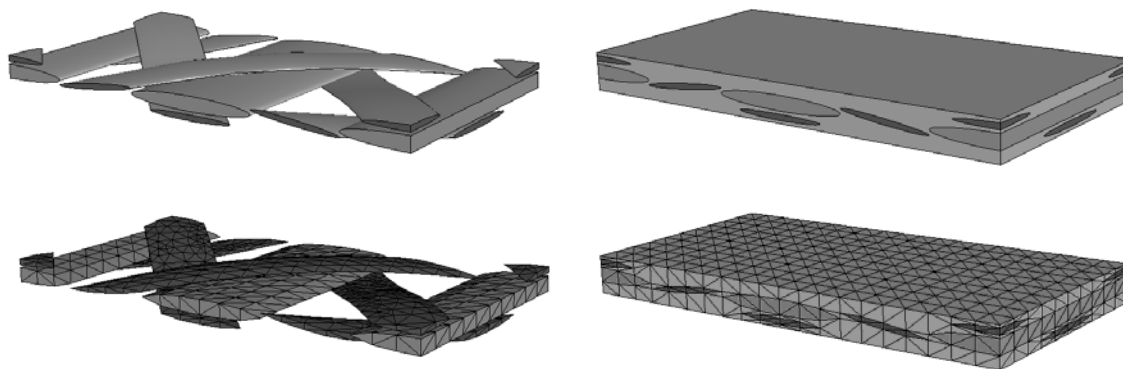


Figure 13. The unit-cell model for braided composite.

Table 3. Calibrated elastic properties of micro-constituents for the braided composite.

	Axial Tow					Braider Tow					Matrix	
X1=XA	E11	E22	G12	ν_{12}	ν_{23}	E11	E22	G12	ν_{12}	ν_{23}	E	ν
(GPa) for E & G	218	15.3	9.9	0.36	0.3	218	15.3	9.9	0.37	0.3	3.57	0.35

Table 4. The comparison of the overall moduli between experiments and simulations.

(GPa)	Experiment*	Simulation(relative error)
$\bar{E}_A$	60.3 ± 2.95	60.29 (0.009%)
$\bar{E}_T$	8.7 ± 0.24	8.70 (0.13%)

Table 5. The comparison of the strengths between experiments and simulations.

(MPa)	Experiment	Simulation
Tensile Strength	654 ± 66.7	663
Compressive Strength	376 ± 29.4	370.5
Short-beam Strength	43.1 ± 2.33	41.3

The next phase will focus on incorporation of rate effects into the multiscale reduced-order model, calibration of additional parameters corresponding to rate effects (completing Task 4) and validation of the simulation capabilities developed against the experimental data on braided composite tubes in a drop test (completing Task 5).

Summary

The Composites Crash-Energy Management project develops and demonstrates technologies that are used to apply production-feasible structural composites in automotive crash and energy-management applications. Efforts within the project 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 FY 2006, in the experimental projects,

- The contract to study the static and dynamic behavior of composite crash was completed and a final report drafted. This study's objectives were to experimentally determine the microstructural factors and behaviors that lead to decreased energy absorption when crushing tubes dynamically.

- Results of Mode I testing of adhesive joints show that the average strain energy release rate, G_{Ic} , for 11-ply and 36-ply DCB specimens range from an average of 2800 J/m^2 and 2460 J/m^2 , respectively, under quasi-static loading conditions to an average of 1060 J/m^2 and 700 J/m^2 , respectively, at an applied loading rate of 1 m/s. These average values take into account cohesive fractures within the adhesive layer only, as delamination within the composite adherends has been observed in some specimens.
- Adhesive sample tests showed that, with the addition of even a small mode II component, the total mixed-Mode I/II fracture energy values, $G_{I/IIc}$, are an average of about 50% lower than those observed under pure Mode I loading conditions.
- A study of structural concepts to improve the energy absorption of sandwich panels was completed and included the use of beveled ends, embedded notches, stitches and improvements to the test fixture to obtain progressive, high energy-absorbing fracture mechanisms. The findings show that the effectiveness of the structural improvements is highly dependent on the type of core material (balsa vs. foam) and somewhat less dependent on the type of fiber facesheet reinforcement (woven vs. random P4).

In the analytical studies,

- Analyses of adhesive lap joints were conducted to support the experimental studies at ORNL. Using experimental data obtained from standard fracture test configurations, theoretical and numerical tools were developed to mathematically describe non-self-similar progression of cracks without specifying an initial crack. A rate-dependent model was incorporated into the interface element approach to capture the unstable crack growth observed in adhesive-joint experiments under quasi-static loading conditions.
- A rate-dependent plasticity model for triaxially-braided composites was incorporated into the current predictive tool, along with the implementation of the Tsai-Hahn fiber-bundle theory, to account for the effect of a critical damage area (CDA).
- Tests of 30°, 45°, and 60° triaxially-braided square and circular tubes were completed at test speeds of 1 m/s and 4 m/s. A predictive algorithm was developed as a vectorized user material (VUMAT) subroutine for use with the commercial software ABAQUS® and is being validated.
- The development and employment of a Schapery-like thermodynamically-based theory (ST) to characterize the progressive, inelastic damage is continuing. The proposed formulation shows several relationships between internal state variables and the energy of the system, as well the relation between instantaneous moduli in damaged state and virgin state.

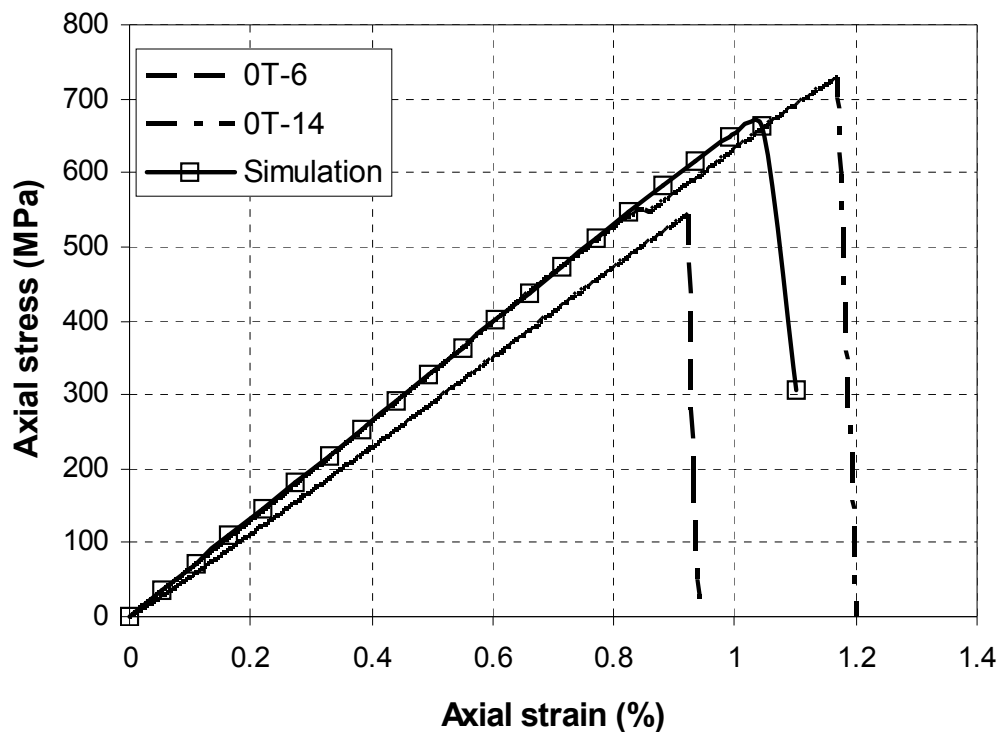


Figure 14. The stress-strain curve for tensile test.

- As part of the study of post-peak behavior, a computer program is being developed to calculate internal state variables from stress-strain test data. This program is incorporated directly into a FE analysis code so that ISVs implicit to the constitutive law are automatically calculated during a finite-element analysis.
- Kink banding in axial tows was also investigated as another phenomenon that contributes to post-peak softening in braided composites. All models included several degrees of tow misalignment. Stress-strain plots for such models show snap-back behavior which is dependent on misalignment degree.

- The study of multiscale modeling methods included the verification of the proposed framework against benchmark computational models. The verification of the multiscale simulation toolkit was completed. The proposed

multiscale fracture model was verified against the direct homogenization method and significant improvements in computational performance were demonstrated.

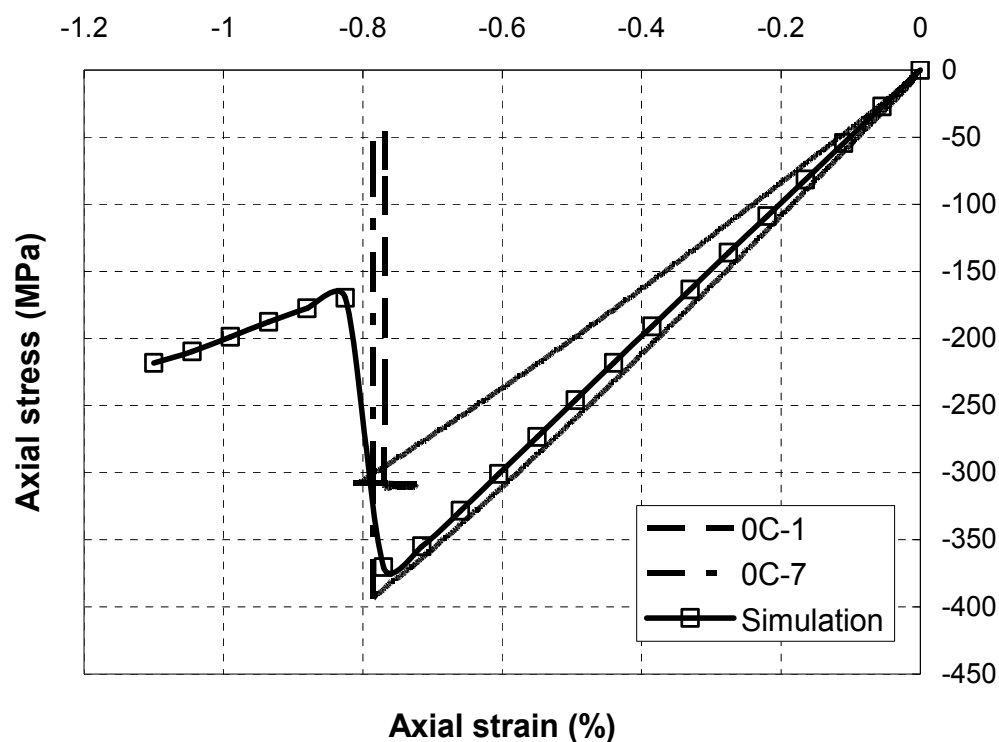


Figure 15. The stress-strain curve for compressive test.

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ⁱ Denotes project 100 of the Automotive Composites Consortium (ACC), one of the formal consortia of the United States Council for Automotive Research (USCAR), set up by the "Big Three" traditionally USA-based automakers to conduct joint pre-competitive research and development.