Modeling of Composite Materials for Energy Absorption

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Objectives

- The objective of this project is to develop analytical and numerical tools that efficiently predict the behavior of carbon-fiber based composites in vehicular crashworthiness simulations. These predictive tools are intended to decrease the automotive design process time and cost by reducing component testing and to increase the simulation accuracy of carbon-fiber-reinforced structures. The developed tools are used in conjunction with existing crash simulation software.

Accomplishments

- Developed models that predict the pre-failure, elasto-plastic response of a triaxially braided large-tow, carbon-fiber composite.
- Developed composite constitutive models for random, carbon-fiber composites based on micro-mechanical formulation and a combination of micro- and macro-mechanical damage criteria.
- Implemented the models above into the finite element code DYNA3D to simulate crashworthiness of composite materials.
- Developed a unique test fixture for determining the energy absorbing mechanisms in automotive composite material systems.

Future Directions

- Conduct further assessment, development, and experimental validation of the composite material models to solve vehicle impact problems.
- Perform laboratory experiments for characterizing basic damage mechanisms and monitoring the damage variables during impact using nondestructive evaluation techniques to determine the model constants and damage parameters.

Introduction

Automotive structures manufactured from carbon-fiber based composites offer the potential for significant advantages in weight, durability, design flexibility, and investment cost. While substantial experience with graphite-fiber laminated composites exists in the aerospace community, little knowledge exists in how carbon-fiber composites respond in automotive type applications during impact-induced “crash” loading conditions (i.e., “crush”). Furthermore, predictive analytical and numerical tools required to accurately evaluate and design carbon-fiber automotive structures for crush do not currently exist. This project aims to understand and quantify the basic deformation and failure mechanisms active in carbon-fiber materials during vehicular crush conditions. The project entails modeling, numerical, and experimental components and deals exclusively with automotive type materials – braided, textile, and chopped random fiber architectures.

Damage Model for Braided Fiber Composites

A 3-D constitutive law for an impregnated fiber tow was developed from a micro-mechanical analysis of a single fiber embedded in a finite matrix region. The law uses the fiber’s elastic properties and the matrix’s elastic-plastic behavior to yield the tow’s elasto-plastic response. Results from the constitutive law were compared to detailed finite element (FE) simulations of uni-directional composites with fibers packed in regular arrays and showed good agreement. Finite deformation versions of the model were implemented in NIKE3D and DYNA3D (LLNL’s implicit and explicit 3-D FE codes, respectively).

In FY 98, a detailed FE model of a single, triaxially braided, composite unit cell was assembled [1] and used to predict the stretching and bending elastic response of a lamina. It was found that the effective lamina-level longitudinal and transverse flexural Young's moduli are substantially lower than their extensional counterparts. In laminates with few laminae (such as the ACC [Automotive Composite Consortium] intents to use) or with sublaminates created during delamination, properly accounting for the lower flexural moduli is important.

In FY 99, the Braid's Unit Cell Model was updated to reflect the present system's fiber, resin, and geometry, and used to predict the braid's elastic and inelastic stretching and bending behavior in conjunction with the new tow model. Although substantial plasticity developed within the braid's unit cell, the lamina response, in the absence of damage, remained linear up to their anticipated failure strength. The ratio of the flexural to extensional Young's moduli in the longitudinal and transverse directions was found to be 0.30 and 0.72, respectively. Experiments (described below) were conducted to verify these findings.

Material tests were initiated on both the bulk resin and the fabricated composite. Specimens were molded from the bulk resin system, and the cure cycle was adjusted to best match the resin's microstructure in the actual composite. Using these specimens, a series of quasi-static torsion, tension, and compression tests documented the resin's stress-strain response and its limited ductility. These tests provide basic material data and serve as a baseline for the high-rate resin-testing schedule in FY 00.

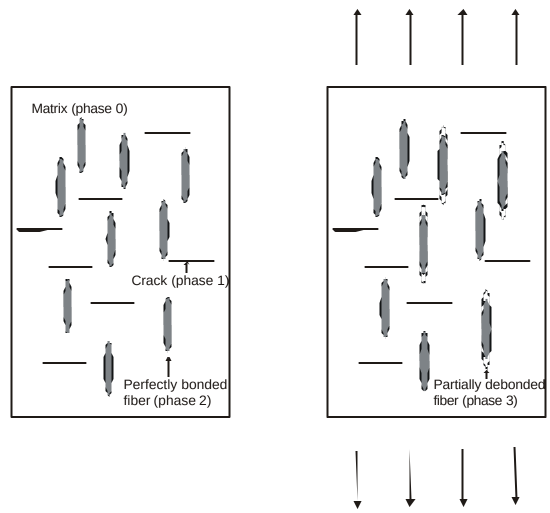
The composite's in-plane laminate elastic properties were selectively measured. Specimens were machined from 2-ply, thick, flat composite plaques and square composite tubes provided by the ACC. The in-plane longitudinal extensional Young's modulus (E_l^e) and longitudinal-transverse extensional Poisson's ratio (v) were obtained from uniaxial tension tests. The same specimens were then loaded by bending to measure the longitudinal flexural Young's modulus (E_l^f). Table 1 shows the measured and FE predicted laminate properties [2] and clearly supports the modeling conclusion that the flexural Young's moduli are a mere fraction of their extensional counterparts in braided systems.

Property	Experiment	FE Model
E_l^e (GPa)	53.7	52.8
v	1.17	1.01
E_l^e / E_l^f	0.782	0.826

Table 1. Experimental and FE predicted Young's moduli and Poisson's ratios.

Damage Model for Random Fiber Composites

Random, short carbon-fiber composite is modeled as a multiphase system where each of the phases corresponds to one of the modeled deformation mechanisms. Figure 1 shows a three-phase composite containing aligned, randomly dispersed, perfectly-bonded fibers and penny-shaped cracks. When this composite is subjected to remote tensile loading, some fibers may experience partial debonding on the top and bottom of the interfaces between the matrix and fibers as deformations proceed [see Figure 1(b)]. The composite becomes a four-phase material, consisting of a ductile matrix, penny-shaped cracks, perfectly bonded fibers, and partially debonded fibers. The partially debonded fibers will lose their load-carrying capacity, but they are still able to transmit internal stresses into the matrix through the bonded portion.



(a) the initial state (b) the damaged state

Figure 1. A Schematic of Aligned Fiber Composites Subjected to Uniaxial Tension.

Extending the work of Zhao and Weng [3] and Ju and Lee [4], a partially debonded elastic, isotropic fiber is replaced by an equivalent, perfectly bonded fiber that possesses a transversely isotropic elastic material property. The transversely isotropic fiber can be considered to be under condition of plane stress with the component in the 1-direction being zero. Partial debonding under uniaxial loading is controlled by the internal stresses of fibers and statistical behavior of the interfacial strength. The probability of partial debonding is modeled as a two-parameter statistical process. This approach has been systematically analyzed to investigate the effect of a weakened interface on partially debonded fibers [5].

The average process over all orientations upon governing constitutive field equations is then performed to obtain the constitutive relations and the overall yield function for randomly oriented composites. Accordingly, the constitutive relations and overall yield function of 2- and 3D-dimensional random, fiber-reinforced composites have been derived by performing the orientation averaging process over all orientations upon the governing field equations and overall yield function for aligned-fiber-reinforced composites [5,6].

Finite Element Implementation for Impact Simulation

The constitutive models are implemented into the nonlinear, finite element code using a user-defined material subroutine to simulate the dynamic inelastic behavior and the progressive damage of the composite materials. The methodology used in this work is based on the well-known, strain-driven algorithm in which the stress history is to be uniquely determined by the given strain history. The two-step operator splitting methodology is also adopted here to split the elastoplastic loading process into the elastic predictor and the plastic corrector.

Box 1 summarizes the iterative, computational algorithm for the damage behavior of four-phase, random-fiber composites accounting for interfacial damage evolution. It renders a step-by-step flow chart for the computational procedure to determine the current damaged fiber volume fraction in accordance with the evolutionary interfacial debonding model

(ix) 3D return mapping algorithm :

(a) Initialize : set $l = 0$; $(\bar{\epsilon}^{p}_{n+1})^{(0)} = \bar{\epsilon}^{p}_{n}$, $(\bar{e}^{p}_{n+1})^{(0)} = \bar{e}^{p}_{n}$ (for local Newton iteration)

(b) Compute : $\bar{\sigma}_n = \mathbf{C}_n : [\bar{\epsilon}_n - \bar{\epsilon}^{p}_{n}]$

(c) Compute the elastic predictor :

Trial elastic state : $\bar{\sigma}^{tr}_{n+1} = \bar{\sigma}_n + \mathbf{C}_n : \Delta\epsilon_{n+1}$

Compute : $\bar{\epsilon}_{n+1} = \bar{\epsilon}_n + \Delta\epsilon_{n+1}$;

$$\bar{F}^{tr}_{n+1}(\bar{\sigma}^{tr}_{n+1}, \bar{e}^{p}_{n}) = [1 - (\phi_1)_{n+1}]^2 \bar{\sigma}^{tr}_{n+1} : \bar{\mathbf{T}}_{n+1} : \bar{\sigma}^{tr}_{n+1} - K^2(\bar{e}^{p}_{n})$$

(d) Check whether plastic loading is active :

If $\bar{F}^{tr}_{n+1} \le TOL$ (elastic step; e.g., $TOL = 10^{-8}$) :

$\dot{\xi}_{n+1} = 0$; SET $\bar{\sigma}_{n+1} = \bar{\sigma}^{tr}_{n+1}$, $\bar{e}^{p}_{n+1} = \bar{e}^{p}_{n}$; GO TO (iv) in Box 1.

Otherwise (plastic step) : GO TO (e).

(e) Perform plastic correction; return mapping algorithm :

Solve nonlinear scalar equation for $\dot{\xi}_{n+1}$: use local Newton iteration

$$\bar{F}_{n+1}(\dot{\xi}^{(l)}_{n+1}) = [1 - (\phi_1)_{n+1}]^2 \bar{\sigma}^{(l)}_{n+1} : \bar{\mathbf{T}}_{n+1} : \bar{\sigma}^{(l)}_{n+1} - K^2[(\bar{e}^{p}_{n+1})^{(l)}] = 0$$

(f) Perform convergence check :

If $|\bar{F}_{n+1}[(\dot{\xi}_{n+1})^{(l)}]| \le TOL$ (e.g., 10^{-8}) : then update

$\dot{\xi}_{n+1} = \dot{\xi}^{(l)}_{n+1}$, $\bar{\sigma}_{n+1} = \bar{\sigma}^{(l)}_{n+1}$, $\bar{\epsilon}^{p}_{n+1} = (\bar{\epsilon}^{p}_{n+1})^{(l)}$, $\bar{e}^{p}_{n+1} = (\bar{e}^{p}_{n+1})^{(l)}$; EXIT.

Otherwise : SET $l = l + 1$

Compute derivative of $\bar{F}[(\dot{\xi}_{n+1})^{(l)}]$: $D\bar{F}[(\dot{\xi}_{n+1})^{(l)}]$

$$(\dot{\xi}_{n+1})^{(l+1)} = (\dot{\xi}_{n+1})^{(l)} - \frac{\bar{F}[(\dot{\xi}_{n+1})^{(l)}]}{D\bar{F}[(\dot{\xi}_{n+1})^{(l)}]}; \quad \text{GO TO (e).}$$

Box 1. Iterative algorithm for the Evolutionary Damage Model.

Figure 2 shows the effect of crack density and fiber debonding on the mechanical behavior of the composites. It clearly illustrates that the mechanical behavior of the composites is strongly dependent upon the crack density. Figure 3 compares present predictions based on the micro-mechanical constitutive model with experiments for predicting the progressive damage in composite materials.

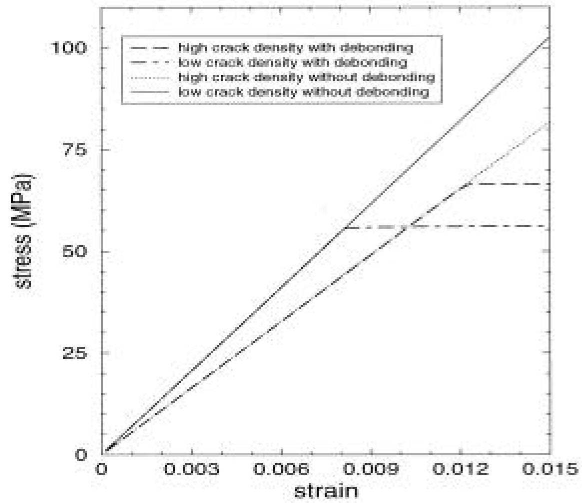


Figure 2. Effects of crack and fiber debonding on the stress-strain behavior of composite materials.

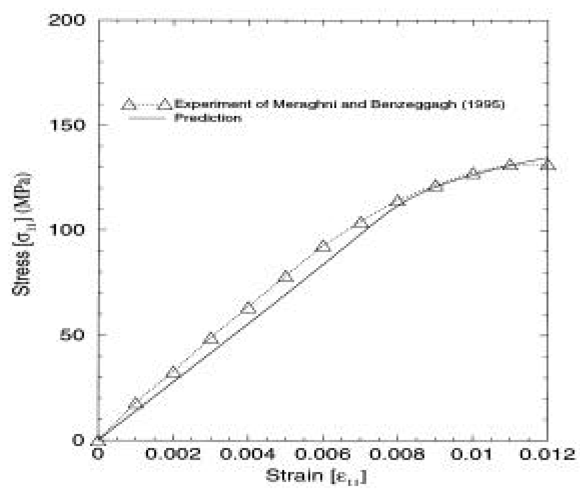


Figure 3. Comparison between model and experiments for random fiber composite

The mechanical response of the carbon-fiber composites fundamentally differs from that of the standard automotive materials. Therefore, it is necessary to develop new experimental techniques for investigating and quantifying their behavior. A new testing methodology for quantifying composite fracture mechanisms associated with the frond formation (splaying mode) in composite tubes was developed. Practical considerations related to the cost of production of the test specimens were of paramount importance in developing the test methodology. Composite plate specimens are very cheap to fabricate and it has been observed that plate specimens progressively crush in modes very similar to the damage modes that occur during progressive crushing of composite tubes.

The test fixture shown in Figures 4-5 was designed to study what effects the plate width, plate thickness, load rate, profile constraint, and profile shape had on the energy absorbing characteristics of composite plates. Features incorporated into the design include an observable crush zone, long crush length, interchangeable contact profile, frictionless roller for contact profile constraint, and out-of-plane roller supports to prevent buckling. The objective of the profile constraint was to determine if different damage mechanisms could be activated depending on the position of the roller.

To validate the fixture operation, a series of experiments were conducted on candidate, automotive composite material systems. The load-deflection response was recorded using a computerized data acquisition system. An idealized load-deflection response for progressive crushing is illustrated in Figure 6, where the area under this curve is the total energy absorption and the initial peak load and sustained crush load are identified.

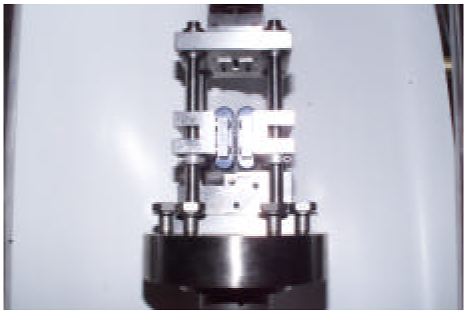


Figure 4. Test fixture assembly.

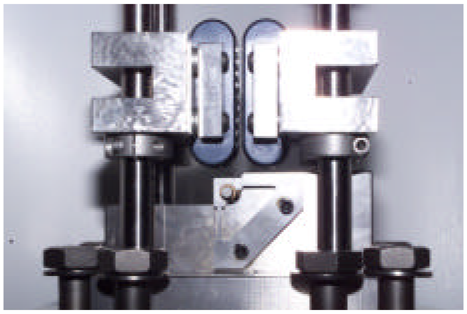


Figure 5. Roller ways and contact profile constraint.

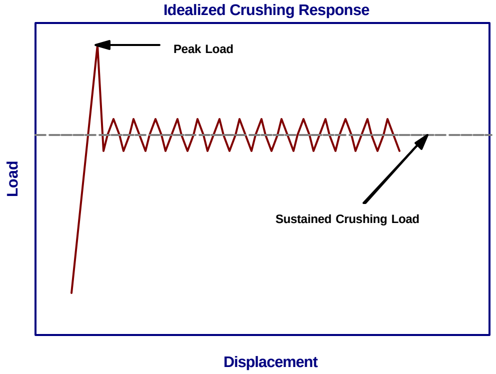


Figure 6. Idealized load-deflection response.

The material systems that were tested included a graphite/epoxy cross-ply laminate, a graphite/epoxy braided material, and a glass-reinforced continuous strand mat (CSM). For the braided material, the active damage mechanisms were localized crushing, fiber fracture on the tensile side of the specimen, and fiber buckling of the off-axis tows on the compressive side of the specimen. The fiber buckling was more extensive when the no constraint condition was used; whereas, the fiber fracture was more predominant in the loose constraint tests. From Figure 7, the loose constraint condition produced a nearly ideal response for progressive crushing. In the CSM specimens, finite length fractures across the entire width were observed. The load would monotonically increase until fracture occurred, and then the load would drop to almost zero (see Figure 8). Approximately the same magnitude of load was measured at each of the fracture points and the fracture lengths were approximately the same.

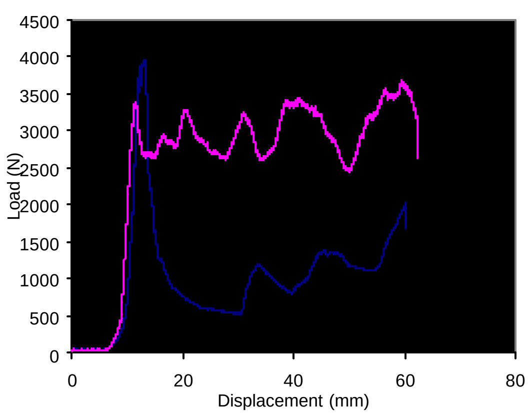


Figure 7. Load-displacement traces for graphite/epoxy braided laminate.

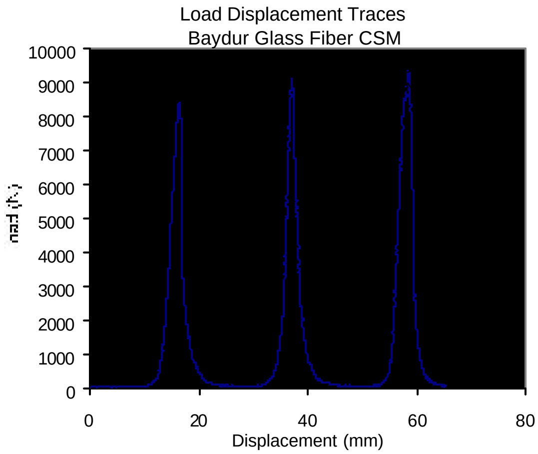


Figure 8. Load-displacement trace for CSM.

Conclusions

Three-dimensional micro-mechanical damage constitutive models have been developed to perform impact simulation of carbon-fiber-reinforced composites for automotive applications. The constitutive models are then implemented into the nonlinear, finite element code DYNA3D using a user-defined material subroutine to simulate the dynamic, inelastic behavior and the progressive damage of the composite materials. The damage model considering crack and progressive interfacial debonding is numerically simulated to illustrate the elastoplastic behavior of randomly oriented, crack-weakened, progressively debonded composites containing discontinuous fibers. Finally, composite impact simulations are carried out to predict the experimentally obtained target response during impact.

A unique test fixture was developed for determining the energy absorbing mechanisms in automotive composite material systems. The objective of the test method was to quantify the energy absorption and identify the failure mechanisms associated with the observed frond formation in progressive crush testing of composite tubes. This was accomplished by testing composite plates under progressive crush loading conditions. The activation of different damage mechanisms was demonstrated by a series of validation tests on representative composite material systems. A profile constraint was incorporated in the test fixture design for the purpose of activating the different damage mechanisms.

Based on the numerical simulations, we draw a conclusion that further laboratory experiment is needed to determine the model constants and damage parameters. In addition, further assessment and experimental model validation for the proposed framework are also needed to solve the practical crushing problems.

Future Work

In FY 2000, the basic material testing and microscopy will be completed and interpreted for the random fiber and braid composites. This includes performing the high strain-rate tests (10-1000 per second) on both the bulk constituents and composite materials as well as performing and modeling the fracture tests and the controlled ''strip'' tests completed in FY 99. Future testing will be conducted to quantify the effects of specimen width, profile radius, profile constraint and loading rate on the specific energy absorption and failure modes.

The experimental data in conjunction with the test observations will then be used to develop analytical models for predicting the crashworthiness of automotive composite structures. Concurrent with this, techniques to numerically simulate delamination or incorporate the effects of delamination in both composite systems will be explored.

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