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 a micro-mechanics based framework and numerical model to predict the elasto-plastic and tensile damage response of a tri-axially 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 and characterized the energy absorption of a randomly oriented chopped carbon fiber composite material system and quantified process and test parameter effects.

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.

EXPERIMENTAL INVESTIGATION OF BRAIDED FIBER COMPOSITES

Material tests were performed at elevated rates to better understand how braided composites actually behave under “crush” conditions. While compression tests on the bulk resin showed that the effective yield strength increases about 10% per decade increase in strain rate (for rates between 10^{-4} and 10 $1/\sec$), elevated rate tests on the carbon-fiber composite in tension and compression are relative insensitive to the imposed strain rate at rates above 10^{-4} $1/\sec$.

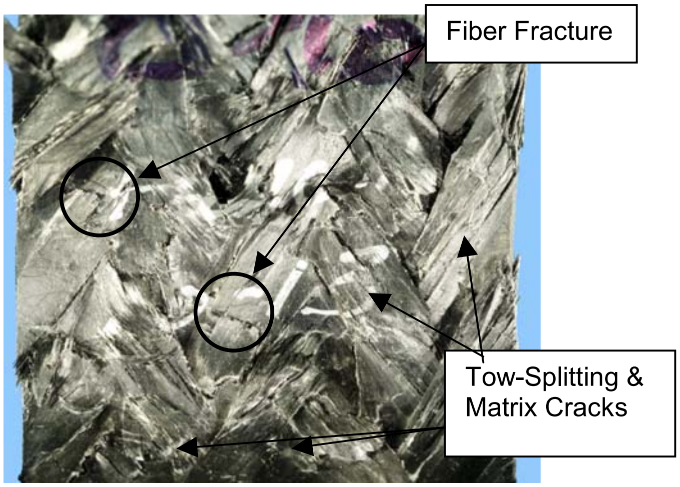


Figure 1 Crushed strip specimen showing defuse intra- and inter-tow cracking.

Stripes of braided carbon-fiber composite were crushed in ORNL's strip fixture during FY 99. Post mortem examinations were conducted in FY 00 to identify the active failure mechanisms and quantify the amount of cracking produced. The damage was highly aligned with the primordial tow boundaries and was dominated by intra-tow cracking, although inter-tow cracks were prevalent. The mode of loading strongly affected whether the damage was diffuse or localized and how much cracking developed. Figure 1 shows a specimen with defuse damage obtained by forcing the strip around a moderate radius of curvature. BET surface area measurements performed with krypton gas determined that this specimen had 134% more cracks than a specimen crushed without any constraint. Based upon the observations made, tensile cracking appears to occur either perpendicular or parallel to the fibers within the primordial tows.

DAMAGE MODEL FOR BRAIDED FIBER COMPOSITES

A framework to numerically simulate the behavior of large-tow tri-axially braided Carbon-Fiber Composites (CFC) was developed [1]. It represents the layered composite material on a layer-by-layer basis and depicts the complex fiber geometry using a simplified unit cell approach. The material within the braid's unit cell is partitioned into three distant layers and then each layer is homogenized individually. The behavior within each layer is simulated using a tow-level constitutive model, which represents the basic elastic, plastic, and tensile damage behavior of the straight fibers, and an undulation model, which replicates how the curved fiber regions respond. The framework also addresses a variety of other issues including appropriate finite-deformation measures, integration of the unit cell, and mesh dependency. In FY 99, a 3-D constitutive law was developed from a micro-mechanical analysis of a single fiber embedded in a finite matrix region [2]. Based upon the experimental observations, the relationship was expanded in FY 00 to include two tensile damage mechanisms that simulate the smeared influence of cracks forming parallel and perpendicular to the fiber. The model was implemented in DYNA3D, LLNL's explicit finite element (FE) code, as a plane-stress shell element material model along with an elastic undulation model. The elasto-plastic response of three different tri-axially braided composites, 0^o /± 30^o, 0^o /± 45^o, and 0^o /± 60^o, were numerically simulating using the newly developed 3-Layer model and compared to results from very detailed 3-D continuum FE simulations of the braid's representative volume element (RVE), *i.e.* the composite unit cell [3]. A single ply of the material was numerically subjected to uni-axial tension and uni-axial flexure in the two primary directions as well as to in-plane shear loading. (Damage was suppressed to facilitate comparisons.) The effective elastic extensional and flexural braid properties from the 3-layer model are in good agreement with the results from the detailed FE simulations [1]. A slight deterioration is noted at higher braid angles for properties dominated by the undulation response. Figures 2 and 3 show the 3-Layer and detailed FE RVE non-linear effective stress-strain responses for longitudinal extension and flexure, respectively. Similar trends in overall agreement are observed in the non-linear behavior of the other loadings examined as well.

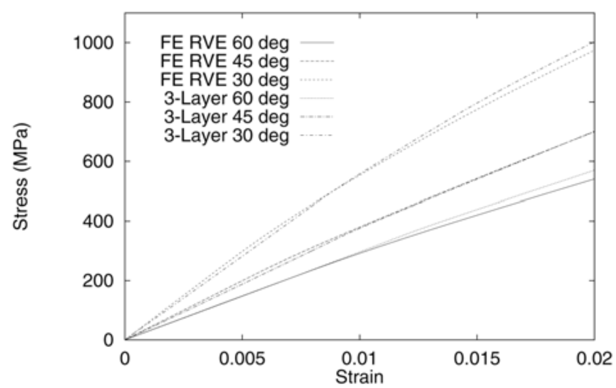


Figure 2. 3-layer model and detailed FE RVE prediction of longitudinal extensional response of braided CFC

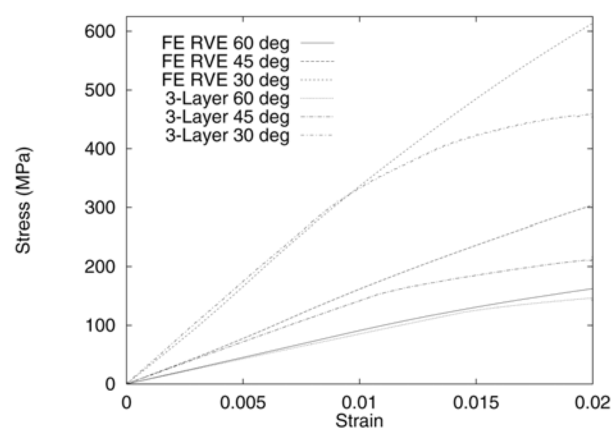


Figure 3. 3-layer model and detailed FE RVE prediction of effective "upper surface" longitudinal flexural response.

DAMAGE MODEL FOR RANDOM FIBER COMPOSITES

The constitutive model for Random Fiber Composites (RFC) developed in FY 99 is further extended to accommodate the effect of microcracks in the matrix. Based on governing micromechanical ensemble-volume averaged field equations for composites containing arbitrarily non-aligned and/or dissimilar ellipsoidal inclusions [4, 5], effective elastic moduli of crack-weakened, random fiber composites are derived [6]. In our derivations, penny-shaped microcracks are regarded as oblate ($a_1<a_2=a_3$, see Figure 4) spheroids and remain the same volume fraction during the deformations. That is, one can collapse one axis of a spheroidal microvoid to recover a penny-shaped microcracks.

From approximate solutions for the interaction problem of two identical yet randomly located elastic inclusions embedded in a matrix material, a micromechanics-based inter-fiber interaction formulation is developed to model composites with high fiber volume fraction as well.

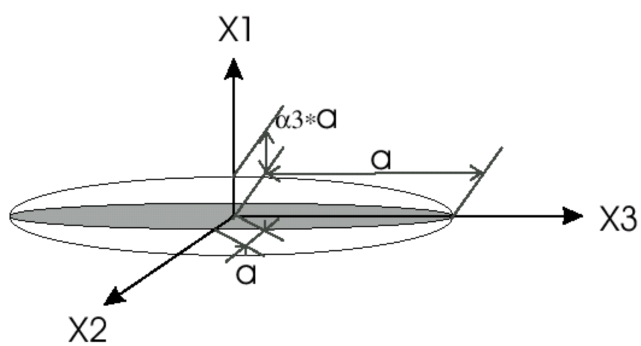


Figure 4. Schematic description of spheroidal inclusion.

We display the normalized effective Young's modulus E_*/E_o versus the contract ratios E_1/E_o in Figure 5 to illustrate the effect of inter-fiber interaction. The volume fraction of fibers is taken as 0.5 and the Poisson's ratio is assumed to be 0.23 for both the matrix and fibers. It is evident from this figure that inter-fiber interaction significantly affects the overall elastic moduli when the contract ratios are high.

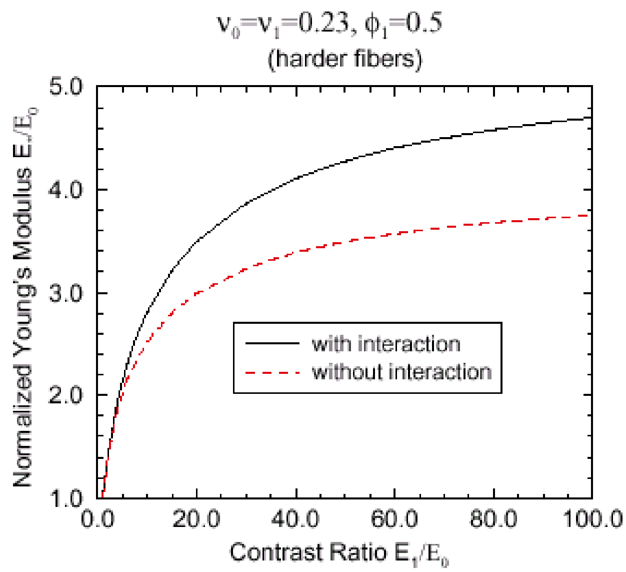


Figure 5. Comparison of E_*/E_0 versus E_1/E_0 predicted by with and without inter-fiber interaction formulations.

A new constitutive model for RFC composites based on Fracture Mechanics has been developed for random carbon fiber composites in order to address the strain softening and fragmentation of the composite under impact loading. Model based on micro-cracks distributed statistically uniformly was developed by employing Cauchy stress rate based on self-consistent and differential scheme estimates of the secant material moduli, damage surface defining the ultimate strength of the composite material based on Griffith energy balance principle for growth of the micro-cracks and evolution of micro-crack radii based on physical laws governing growth of cracks. •The 3D constitutive model was specialized for 2D plane stress state condition for use with shell finite elements. The 3D and 2D plane stress models have been implemented in the open source version of DYNA3D explicit finite element code and preliminary numerical studies for debugging and verification of the code implementation were conducted.**IMPACT SIMULATIONS OF RANDOM FIBER COMPOSITE MATERIALS**

1. Parametric study of Weibull parameter

In order to illustrate the influence of Weibull parameter S_o on the damage evolution in composite materials and evaluate constitutive model sensitivity to Weibull parameter S_o, parametric analysis is carried out. As a debonding property of the fiber-matrix interface, four sets of the Weibull parameters are used: S_o=0.109*150MPa and M=4; S_o=0.80*150MPa and M=4; S_o=1.09*150MPa and M=4; and S_o=10.9*150MPa and M=4. For comparison, four-point bend impact simulations are conducted. We plot time history for the volume fraction of perfectly bonded fibers ϕ_1 for various values of Weibull parameter S_o at the contact surface of the composite plate around loading noses during four-point bend impact in Figure 6. As shown in Figure 6, if the interfacial strength between fibers and the matrix is low (lower S_o), most fibers are debonded in early stage and the material will show the nonlinear behavior. It is concluded from the parametric study that the influence of Weibull parameter S_o on the constitutive behavior and damage evolution of the composite is significant.

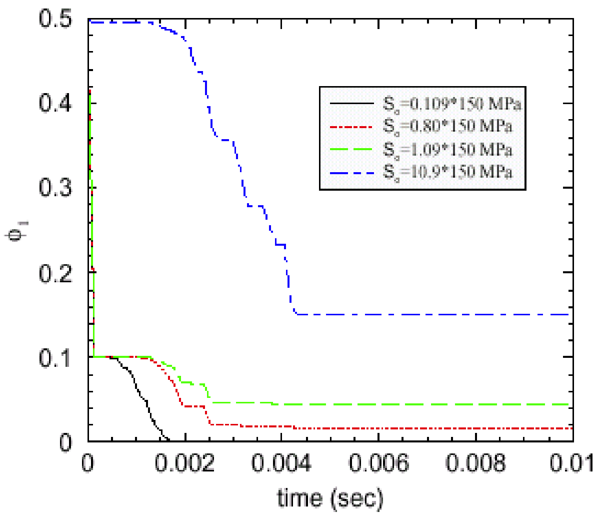


Figure 6. Time history plots for ϕ_1 for various values of Weibull parameter S_o during four-point bend impact

2. Biaxial test simulations of composite specimen

Numerical simulations for the biaxial test are carried out to examine whether the implemented computational model is able to predict the experimentally obtained response. The geometry and loading conditions in this problem are symmetric along the x- and y-axes. The composite specimen is loaded proportionally with the rate of 30 lb/sec (130 N/sec) in biaxial compression and tension in the ratio of 1:1. A computational model of the cruciform shaped composite specimen and loading conditions are shown in Figure 7. Figure 8 shows the sequence of damage contours during biaxial loading, representing the growth of damage zone due to the advancing damage one emanating from the edges of the cutout, which corresponds with Waas and Quek [7]'s observations.

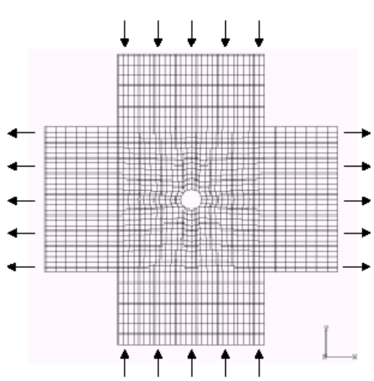


Fig. 4. Finite element discretization of cruciform shaped specimen during biaxial loading

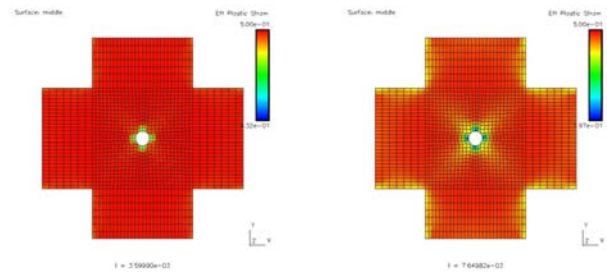


Figure 8. Contours of damage index, indicating the volume fraction of damaged fibers, during biaxial loading.

3. Composite contact test simulations

Preliminary numerical simulations for the composite contact test are carried out to quantify the energy absorption and predict the damage evolution in the composites during the progressive crushing. In DYNA3D program, we specify roller ways, contact profile plate, and roller as the master rigid surface and the set of nodes on the composite specimen as the slave contact node set (see Figure 9). The nodes at the top of the composite specimen are given at an initial velocity of 10m/sec in the negative direction.

From a sequence of numerical results for von-Mises effective stress and deformation displayed in Figure 10, one can observe apparently specimen buckling between the contact plate profile and the roller. Figure 11 shows a load-displacement trace at a node with prescribed velocity. The area under the load-displacement curve in Figure 11 is the total energy absorption of the composite specimen. Further numerical simulations for the composite contact test with different profile radius, material property variables, and constraint condition will be performed to meet the test conditions and compare with the test results.

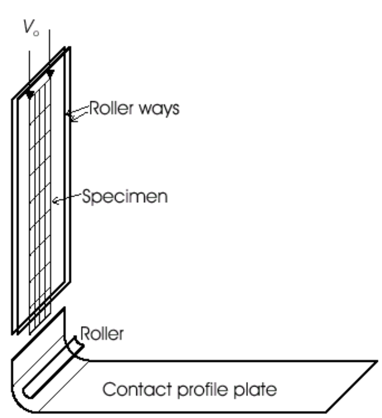
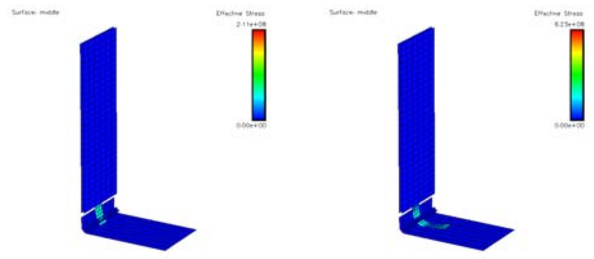


Figure 9. The composite strip test



(a) t=3.0 x 10^{-3} *sec* (b) t=9.0 x 10^{-3} *sec*

Figure 10. von-Mises effective stress and deformation sequence of the composite plate

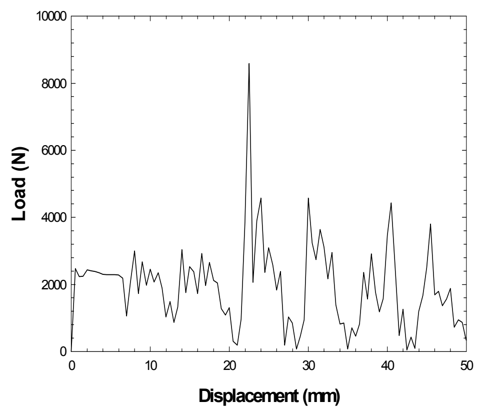


Figure 11. A load-displacement trace at a node with prescribed velocity

DEVELOPMENT OF EXPERIMENTAL METHOD FOR COMPOSITE CRASHWORTHINESS EVALUATION

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. In FY 99 a new testing methodology for quantifying composite fracture mechanisms associated with the frond formation (splaying mode) in composite tubes was developed [8]. This test methodology was used to study the energy absorbing characteristics of chopped carbon fiber (CCF) composites and to study the effects of various testing and material parameters. The technical approach was an economical one in the sense that quasi-static progressive crush tests using plate ("strip") specimens were conducted.

The plates for machining the test specimens were fabricated using the compression molding technique. YLA supplied the CCF molding compound using a Toray T700 carbon fiber with a YLA RS-35 epoxy resin and CCS compression molded the plates. There were eight different types of plates fabricated to study the effect of three different material variables; tow-size or areal weight, fiber volume fraction, and fiber length. The test parameters that were considered included the profile radius, profile constraint, and specimen width. In total 80 plates were fabricated and tested, using three replicates per test condition, and the parameters are summarized in Table 1.

Table 1. Test Matrix

Test Variables		Material Variables	
Profile radius	6.5 mm	Areal weight	300 gsm
	13 mm		150 gsm
Constraint	None	Fiber fraction	50%
	Loose		40%
	Tight		
Specimen width	13 mm	Fiber length	25 mm
	25 mm		50 mm
	50 mm		

The tests were conducted on a MTS servo-hydraulic machine using a load rate of 5.0-mm/min and the load-deflection response was recorded using a computerized DAQ with customized Labview software. The area under the load-deflection was numerically calculated for the total energy absorbed, and the initial peak load and sustained crush load identified. The specific energy absorption (SEA) was then calculated by dividing the total energy absorbed by the mass of the crushed material. In all tests, a 45° chamfer was used as the crush initiator.

The identified damage mechanisms included local crushing of the chamfer, matrix cracking at the ends of the fibers, and fiber-matrix debonding. When testing under the none constraint condition, fiber pull-out, fiber breakage, and fiber buckling was observed. The loose and tight constraint conditions resulted in more predictable damage mechanisms, whereas the none constraint was less predictable and more catastrophic. For the loose and tight constraint conditions the roller directed the crushing process and the load-deflection response was similar to that of progressive tube crushing. The response consisted of four distinct stages: the first stage being an initial rapid load increase, the second stage was a rapid load decrease, followed by the third stage that was a gradual load saturation, and then finally the fourth stage where stable crushing occurred at a constant mean load (see Figure 12).

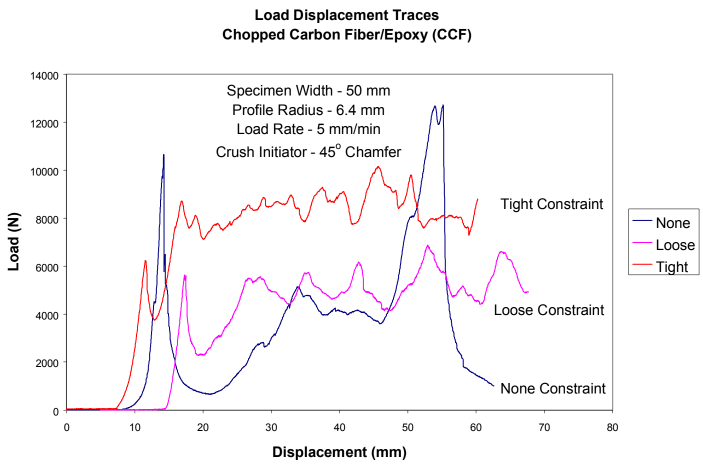


Figure 12. CCF Load-Displacement Traces

In comparing the SEA's between the different test and material parameters the following observations were made. For the shorter fiber length, an increase in areal weight decreased the SEA and an increase in fiber volume fraction increased the SEA. For the longer fiber lengths the areal weight had no effect and an increase in fiber volume fraction decreased the SEA. For both areal weights the SEA decreased when the fiber length was increased. Overall, the highest SEA was measured when testing the shorter fiber length with the smaller areal weight and larger fiber volume fraction. Less energy was absorbed when the specimen was crushed through a larger bend radius and when the narrower specimens were tested. The effect of the constraint condition was a higher initial peak load when the none constraint condition was used while the SEA was highest when testing under the loose and tight constraints.

CONCLUSIONS

A test method has been demonstrated that provides insight into the damage mechanisms and energy absorbing capability of CCF composites. The dominant damage mechanisms are matrix cracks initiating at the fiber ends and fiber-matrix debonding, and the damage process is controlled by the flexural deformations. For absorbing energy the fiber length appears to be the most critical material parameter, with shorter being better.

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 2001, braid-modeling emphasis will focus upon completing the braid model and validating it against experimental results. The braid model presently lacks a non-linear undulation model and compressive failure mechanisms; both are required to accurately predict the response of braided composite. Previously conducted strip tests and drop-tower tube crush tests will be simulated with the new tools, and their results will be compared with experimental findings.

Future efforts on modeling random fiber composites will concentrate on improvement of computational performance of the models, incorporation of effects of secondary tensile cracks in compression, localization and failure in compression, simulation of strip tests, develop better approximations to micro-crack growth, and consideration of non-uniform crack distribution. Explicit modeling of delamination may also be needed for modeling damage evolution under complex loads.

Mechanical testing will be conducted on the eight different types of CCF plates to quantify their strengths and stiffnesses, as well as provide further insight to the energy absorption data. The possible fabrication of tubes using compression molding techniques with CCF will be explored and testing of such tubes will be conducted for comparison with the plate experiments.

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