Modeling of Composite Materials for Energy Absorption

Edward Zywicz and Steve DeTeresa
Lawrence Livermore National Laboratory, Livermore, CA 94550
(925) 423-5632, fax: (925) 424-2135

Srdan Simunovic, Haeng-Ki Lee, J. Michael Starbuck and Raymond G. Boeman,
Oak Ridge National Laboratory, Oak Ridge TN 37831-6359
(865) 241-3863, fax: (865) 574-7463

DOE Program Manager: Joseph Carpenter
(202) 586-1022, fax: (202) 586-7409

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

- A non-linear undulation model was developed and incorporated into the previously developed tri-axially braided constitutive model and validated against detailed finite element simulations of the braid's unit cell.
    1) a constitutive-level enhanced-strain element formulation was developed to simulate tensile failure
    2) compressive damage surfaces and evolution equations were formulated and implemented
- A three-dimensional constitutive model was developed for modeling of effective mechanical behavior and damage evolution of brittle random fiber composites. The constitutive model is based on a combination of a fracture mechanics and a micromechanical formulation.
- Completed mechanical characterization tests for a chopped carbon fiber, compression molded composite material system. Tests included uniaxial tension, compression, and flexure.
- Completed factorial analysis of energy absorption data from the progressive crush tests conducted using the strip test fixture that was developed in FY00 and the measured specific energy absorption (SEA).

Future Directions

- Validate material models by simulating previously conducted strip and tube crush experiments.
- Conduct additional testing on the chopped carbon fiber, compression molded composite material system to determine analytical model parameters.
- Evaluate the energy absorption of the composite material systems by conducting progressive crush strip tests.
- Conduct factorial analysis of energy absorption data for the peak load and sustained crush load.

INTRODUCTION

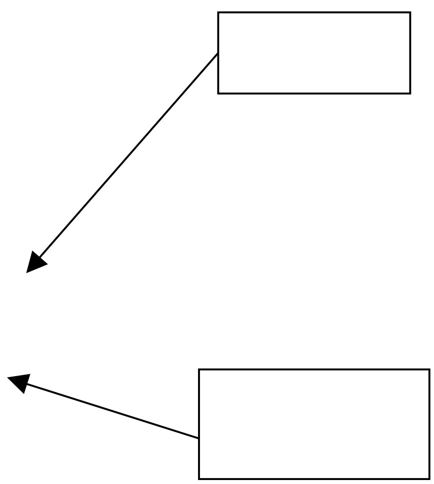
Automotive structures manufactured from carbon-fiber composites (CFC) offer the potential for significant advantages in weight, durability, design flexibility, and investment cost. While substantial experience with graphite-fiber laminated composites exists in the aerospace community, little knowledge exists in how CFCs 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 CARBON-FIBER COMPOSITES

Basic material tests were performed on the braided CFC at quasi-static and elevated rates to quantify and characterize the material behavior. While the resin demonstrated a marked dependence upon strain rate, little rate dependence was observed in the failure behavior of the $0^{o}/\pm30^{o}$ braided CFC tested. In addition to the physical experiments, detailed microscopic examinations were performed on the failed specimens tested at LLNL, strip specimens crushed by ORNL, and automotive tubes dynamically crushed by the ACC. The controlling failure mechanisms appear to be inter-tow rather than intra-tow ones. Results from all of LLNL's traditional and non-traditional material testing and post-mortem examinations of the present CFCs are summarized in [1].

DAMAGE MODEL FOR BRAIDED CARBON-FIBER COMPOSITES

A framework to numerically simulate the behavior of large-tow tri-axially braided CFC was developed in FY '00 [2]. 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 individually homogenized. The behavior within each layer is simulated using a tow-level constitutive model, which represents the basic elastic, plastic, and damage behavior of the straight fibers, and an undulation model, which replicates how the curved fiber regions respond.



In FY '01, the basic tow-level constitutive model was enhanced in several ways. First, a non-linear undulation model was formulated and integrated into the tow model. Second, the matrix behavior was expanded to include rate-dependent plastic deformation. Third, compressive and tensile damage mechanisms were derived and incorporated into the constitutive relationship.

A micro-mechanics based non-linear undulation model was formulated, implemented, and numerically validated. Detailed elasto-plastic finite element (FE) simulations of the curved tow region (shown in Figure 1) were used to distill the macro undulation response under uni-axial tensile and compressive loadings. The newly developed non-linear undulation model idealizes this complex behavior. It accounts for limited plastic deformation and stiffening in tension (due to tow straightening). Figure 2 shows the excellent agreement achieved between the macro stress-strain response of the undulation region obtained by the FE simulations and from the new undulation model for a $0^o/\pm30^o$ braid. The undulation model produced similar behavior and agreement for the other architectures examined.

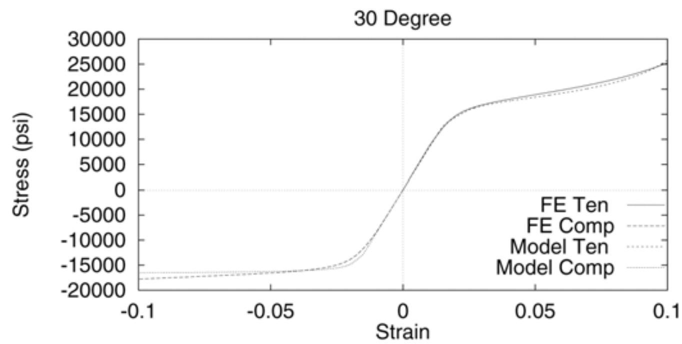


Figure 2 Simulated (FE) and predicted (Model) macro response of an undulation region in a $0^o/\pm30^o$ tri-axially braided CFC.

The non-linear undulation model is necessary to accurately represent braided CFC under shear and transverse loadings. Figure 3 shows the transverse extensional response obtained from detailed FE simulations of the braid's representative volume element (RVE) [3] and the newly enhanced 3-layer model. The agreement between the two results is greatly improved by the non-linear undulation model as is the, not shown, shear response.

Guided by experimental observations, two compressive and two tensile damage mechanisms were derived and incorporated into the elasto-plastic tow-level constitutive model. This allowed separate formulations to be developed for damage in the fiber and transverse directions as well as for different mechanisms in tension and compression.

While both tensile and compressive loadings generate inter- and intra-tow micro and macro cracking, commingling of the debris and the undamaged material causes the compressive stress-strain response to reach a non-zero saturation level after the peak load. In the fiber direction, this is simulated by abruptly lowering the maximum stress the fiber can carry to a prescribed level after the (in-plane) axial fiber strain reaches are critical level. Similarly, in the transverse direction, the matrix flow strength is reduced to a saturation value after the onset of damage. Motivated by recent triaxial experimental work on uni-directional CFC material, the matrix stresses are used in a J-2 plasticity-like criterion to determine when transverse damage commences.

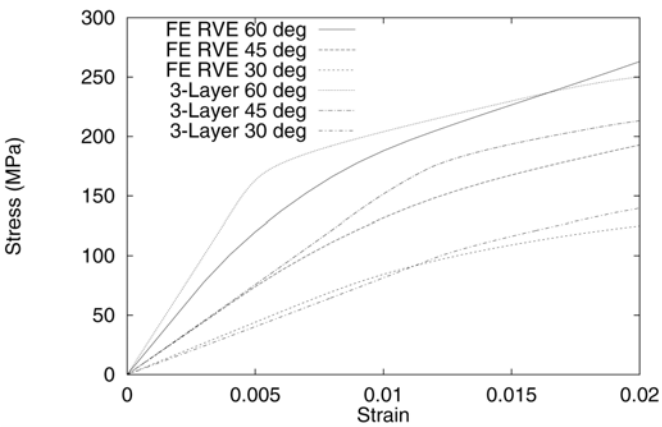


Figure 3. 3-layer model and detailed FE RVE predictions of the transverse extensional response of various tri-axially braided CFC.

The post-peak tensile response in each direction is replicated using a pseudo enhanced-strain element formulation [4]. In this approach, the total displacement field is additively decomposed into a material displacement field and a crack displacement field. The material strains, calculated from the material displacements, are used by the tow-level constitutive model to predict the bulk stresses, while the crack displacements and a rigid-softening traction-displacement law replicate how the "crack" evolves with deformation. Auxiliary constraints, which ensure that the bulk stresses and crack tractions are consistent, complete the formulation.

The present tensile damage formulation ensures that a fully damaged material supports no load across the postulated crack and is fully consistent with fracture mechanics concepts. Figure 4 shows the predicted in-plane stresses, as a function of the applied strain, for a uni-directional CFC lamina subjected to in-plane uni-axial straining. A square shell element, aligned with the x-y coordinate system is used, and the fibers are oriented at 40 degrees from the x-axis. Notice that the resultant stress-strain curves reach a peak and then decay to a zero stress level as desired. Similar behavior was demonstrated for fiber orientations between –180 and 180 degrees, i.e. any angle.

DAMAGE MODEL FOR CHOPPED, RANDOM CARBON-FIBER COMPOSITES

Micromechanical model developed in FY1999 and FY2000 [5,6] of random fiber composite has been extended to model microcracks and fiber-to-fiber interaction.

A new three-dimensional constitutive model was developed [7,8] for modeling of effective mechanical behavior and damage evolution of brittle random fiber composites. The model is capable of modeling strain softening in composites and overcomes small-strain restriction of the micro-mechanical damage model. We start the model formulation by assuming that the two damage processes, nucleation and crack growth, occur sequentially. The rationale for this assumption, besides the motivation for simplification of the problem, has roots in physical process occurring in a damage tolerant material. The process of microcrack nucleation is related to the distribution of the weak sites in the material. In the heterogeneous materials, the process is stochastic and the microcraks materialize uniformly across the material volume. This allows us to model the nucleation process using a scalar field that implies uncorrelated crack position and orientation. As the weak spots are depleted with the increasing load, the microcracks start to grow. A shift of dominance from nucleation to crack growth is most likely gradual, and therefore our approach can be portrayed as the first approximation to this transition. The developed model implemented in an explicit finite element (FE) code. The FE formulation contains several new numerical procedures for solving the system of equations constituting the material model. These procedures have shown to be very important for the numerical efficiency and stability of the model. Finally, numerical simulations for one finite element test are carried out to illustrate the key features of the developed model.

The material model has the following components:

1. Rate form of constitutive equations
2. Rate form of microcrack nucleation
3. Damage surface for microcrack stability
4. Rate of microcrack growth
5. Effective moduli for (a) randomly distributed, and (b) aligned microcracks

The damaged state of the material can be described by the number N, and the average size $\bar{c}$ of microcracks. The intent is not to relate these values to the exact crack distribution in particular material volume, but to use them to express the effects that the active microcracks have on the effective material properties. It is obvious that the microcracks in the real solids will not be straight nor penny-shaped, and their distributions will vary significantly from specimen to specimen. However, our premise is that their cumulative effect on effective material properties can be ualitatively and quantitatively described by using simple approximation of the evolving microstructural disorder.

The model can be described by a set of formulations:

(i) Damage surfaces that define regions of crack growth:

$$F(p,q,\bar{c}) = q^2 + \frac{45}{4(5-\nu_o)}\left[(2-\nu_o)p^2 - \frac{2K}{\bar{c}}\right] = 0, \qquad \text{if } p < 0$$

$$F(p,q,\bar{c}) = q^2 - \frac{45}{2(3-2\nu_o)}\left[(\mu p + \sigma_o)\left(\mu p + \sigma_o + \sqrt{\frac{\pi K}{\bar{c}}}\right) + \frac{K}{\bar{c}}\right] = 0, \quad \text{if } p > 0$$

where $\bar{c}$ is the mean crack radius; μ is the coefficient of friction; $p = -\frac{1}{3}\sigma_{ii}$ denotes the pressure; $q = \sqrt{\frac{3}{2}q_{ij}q_{ij}}$, in which $q_{ij} = \sigma_{ij} + p\delta_{ij}$, signifies the deviatoric stress; and $K \equiv \frac{\pi}{2}\frac{2-\nu_o}{1-\nu_o}K_{IC}G_o$, in which K_{IC} is the plane strain fracture toughness of composites.

(ii) Rate of crack growth:

$$\dot{\bar{c}} = \dot{c}_{\max}\tanh(d_s) = \beta\sqrt{\frac{E^*}{\rho^*}}\tanh(d_s)$$

where $\dot{\bar{c}}$ is the rate of crack growth, $\dot{c}_{\max}$ is the maximum crack-growth speed , β is the crack velocity scale factor, and d_s is the measure of the distance the state of stress exceeds the damage surface.

(iii) Rate of crack nucleation:

$$\dot{N} = \dot{N}_0 \cdot \exp\left[\frac{\sigma - \sigma_{n0}}{\sigma_1}\right], \quad \sigma > \sigma_{n0}$$
$$= 0, \qquad \sigma \le \sigma_{n0}$$

where σ is the total stress of the material, σ_{n0} is the threshold stress for the nucleation of cracks, and $\dot{N}_0$, and σ_1 are material constants.

Numerical tensile coupon tests were performed in order to investigate strain rate sensitivity to the crack growth and the corresponding response of composites. Prescribed velocity *v(t)* contains constant true strain rate and takes the form $v(t) = \dot{\varepsilon}L \cdot \exp(\dot{\varepsilon}t)$, where $\dot{\varepsilon}$ is the strain rate and *L* is the length of specimen. Figure 5 shows the evolution of crack size and the corresponding response of composites with several strain rate loading conditions. It is noted that high strain rate loading leads to slow crack growth and high stress-strain behavior.

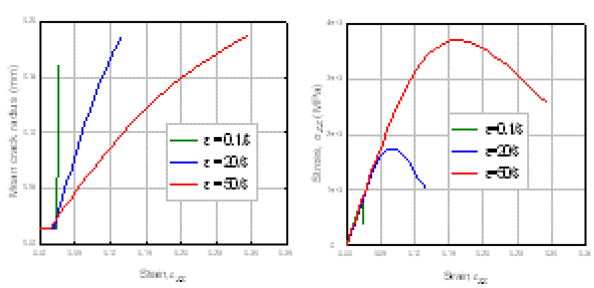


Figure 5. Strain rate sensitivity to crack growth and its effect on stress-strain behavior.

Drop tower test was simulated numerically to assess the potential of implemented damage model for impact simulation. In computational model, a single solid element was used for modeling of drop mass and the crush initiator was modeled as a rigid wall. In addition, composite tube was modeled using Belyschko-Tsay shell element. Contact conditions were applied between composite tube and initiator. An initial velocity of 8.75 m/sec was applied on nodes of composite tube and drop mass.

Figure 6 shows the sequence of deformed shaped of a square carbon/polyurethane composite tube. First, failure starts from the corner of composite tube. As the corner failure proceeds, the weakest segment of tube in the other direction is folded. The segment of folded section then fails.

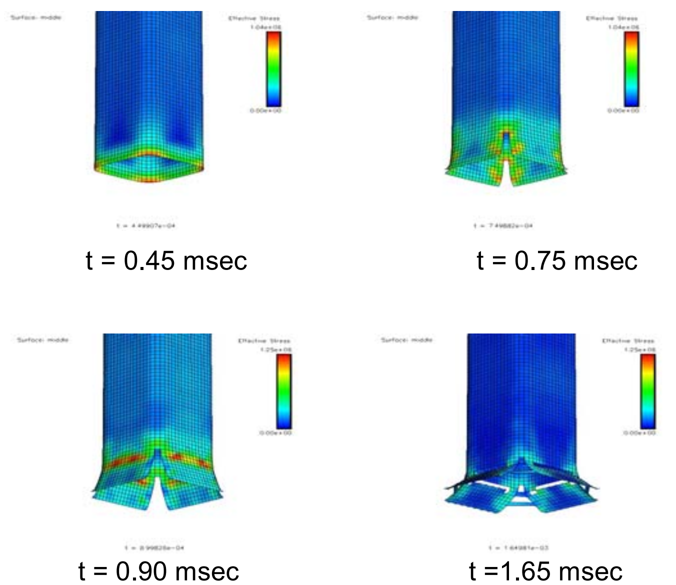


Figure 6. A sequence of deformed shape of a square tube during crushing

Figure 6 shows the predicted force-displacement (*p-u*) curves for composite tube. After *p-u* curves reach peak, they start to fluctuate because of progressive crushing of composite tube. Two failure criteria were employed in the drop tower test simulation: stress driven failure criterion and strain driven failure criterion. The details of the developed formulation are currently under review for publication in a peer-reviewed journal [7]. Technical details and current models are available from the ORNL Computational Materials Science Group web page:

http://www-cms.ornl.gov/composites

CHOPPED CARBON FIBER (CCF) COMPOSITE STRIP TESTS

Mechanical property tests were performed on composite plates manufactured from CCF with an epoxy resin using compression molding techniques. The carbon fiber was Toray T700 and the epoxy resin was YLA RS-35. To investigate the effect of various material parameters there were eight different panel types fabricated where the fiber length, fiber volume fraction, and fiber areal weight were varied. The different fiber lengths were 1-inch and 2-inch, the different fiber volume fractions were 40% and 50%, and the areal weight was either 150 gsm (grams per square meter) or 300 gsm. Different areal weights were evaluated as an attempt to study the effect of tow size. The Toray T700 fiber used for the prepreg was a 12K tow (12,000 filaments) but in manufacturing the molding compound the prepreg was slit in addition to cutting the length. The width of the slit was varied to provide the different areal weights.

The characterization tests were conducted to evaluate the tension, compression, and flexural mechanical properties of the eight different panel types. The tensile strength was evaluated using the ASTM D3039/D 3039M-95a with dog-bone specimen geometry and the strain was measured using an extensometer. Compression strength tests were run per ASTM D3410/D3410M-95 (IITRI Method) and strain gages were used for measuring strains. The flexural strength was determined based on ASTM D790-98 and 4-point loading with a span to depth ratio equal to 16. An LVDT was used for measuring the beam deflection. The test results, in terms of the different strength components, are summarized in Figure 1 based on a limited sample population (3 specimens per panel type for tension and compression, and 6 specimens for flexure).

The most consistent observation between the different panel types was the tension, compression, and flexure data indicated that testing smaller areal weight panels results in higher strengths and stiffnesses. It should be noted that all of the mechanical properties had tremendous scatter as indicated by the large standard deviations in the data. This variability in the property data may be indicative of a nonhomogeneous material system and the randomness of the chopped carbon fiber orientation. The results of the material characterization research are to appear in the Journal of Composite Material [9].

FACTORIAL ANALYSIS

To better qualify the effects that different testing and material parameters had on the SEA measured from strip tests a "Design of Experiments" approach was taken to analyze the data. A full factorial analysis was selected as the approach because all permutations of the test conditions had been conducted and the data was available for this study. Plus, this approach eliminates any ambiguous results associated with aliasing of the test data. In this study there were 6 parameters with 2 levels for each parameter (see Table 1). The total number of tests included in the analysis was 192 with 3 replicates per test condition yielding 64 distinct conditions. Interactions between parameters were considered to determine if they influenced the results. The software package selected for this work was Design-Ease-6 by Stat-Ease, Inc.

The three main parameters that were identified as to have affected the outcome of the SEA experimental measurements were profile radius, fixture constraint, and fiber areal weight (see Figures 7 and 8). The probability of these results being an artifact of statistical noise was determined by ANOVA (Analysis of Variation) to be less than 0.01%. Of the three parameters identified, two can be associated with inherent mechanical friction in the test (profile radius and constraint) while the third parameter, areal weight, is a material process variable.

From a one-factor plot of the data, the smaller areal weight resulted in a higher SEA. Recall, from the mechanical property tests the smaller areal weight panels consistently resulted in higher strengths and stiffnesses. From a one-factor plot of the data for profile radius and constraint, the effect of friction in the test is to increase the SEA. This is expected since friction is an energy absorbing mechanism in addition to the energy absorbed by the material being crushed.

During FY 2000 a comprehensive series of experiments were conducted to determine the specific energy absorption (SEA) of CCF composites. The objectives of these experiments were to quantify the energy absorbed and to identify the damage mechanisms. Quasi-static progressive crush tests were run using plate ("strip") specimen geometries. This test methodology was selected as an economical approach to quantify the energy absorption associated with the frond formation observed in tube testing and to study the effects of various testing and material parameters.

The material system was a Toray T700 carbon fiber with a YLA RS-35 epoxy resin. This combination of fiber and resin were processed into a chopped-fiber molding compound and then panels were fabricated using compression molding techniques. The panels were then machined into strip specimens for testing. The test matrix considered three test variables (specimen width, constraint type, and profile radius) and three material variables (fiber length, fiber volume fraction, and areal weight). The highest SEA was measured when the combination of short fiber length, low areal weight, and high fiber volume fraction was tested. For the CCF composites that were considered in this program, it was observed that the dominant damage mechanisms were matrix cracks initiating at the fiber ends and fiber-matrix debonding, and that the flexural deformations controlled the damage processes.

Mechanical property tests were conducted to better understand the differences between the different panel types in the progressive-crush strip tests. These tests included tension, compression, and four-point flexure on each of the eight different panel types. The tension tests were conducted per ASTM D3039/D 3039M-95a using dogbone specimen geometries and strains were measured using an extensometer. The flexure tests were conducted per ASTM D790-98 with a span to depth ratio of 16. A LVDT was used for measuring the beam deflection. The ASTM D3410/D3410M-95 IITRI test method was selected for the compression tests and the strains were measured using strain gages.

The overall conclusion from the mechanical property tests was that the smaller areal weight systems had consistently higher strengths and stiffnesses but there was tremendous variability in the data. Variability in the data or large scatter is indicative of a nonhomogeneous material system. The higher SEA's that were measured with the shorter fiber length corresponded to a CCF material system having a lower flexural strength but higher flexural stiffness. The flexural stiffness was also seen to be higher when the larger fiber volume fraction and lower areal weight material systems were tested.

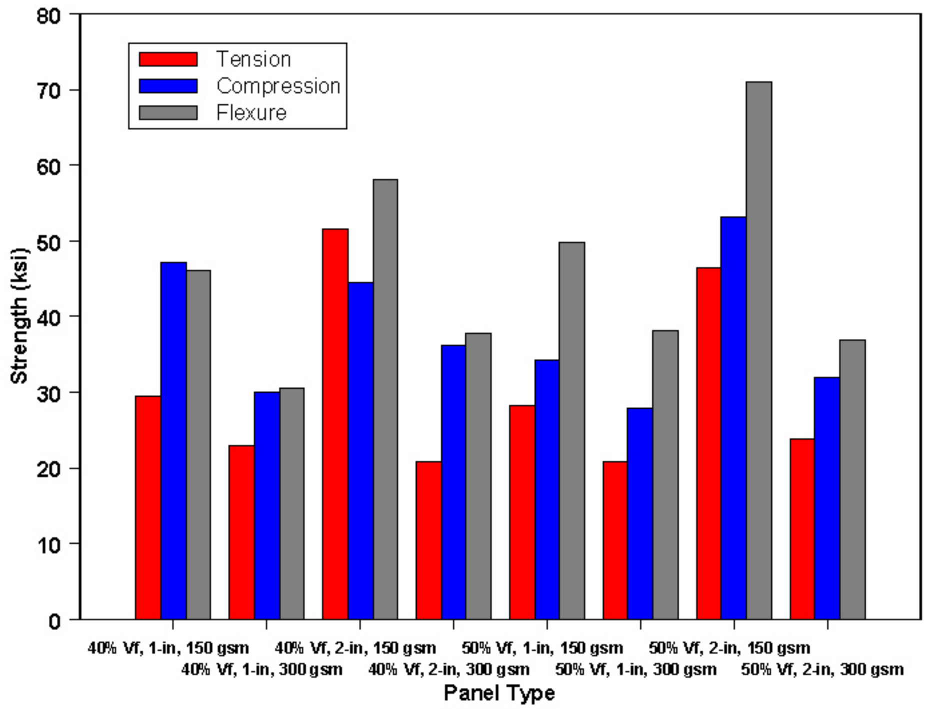


Figure 7. CCF mechanical property data.

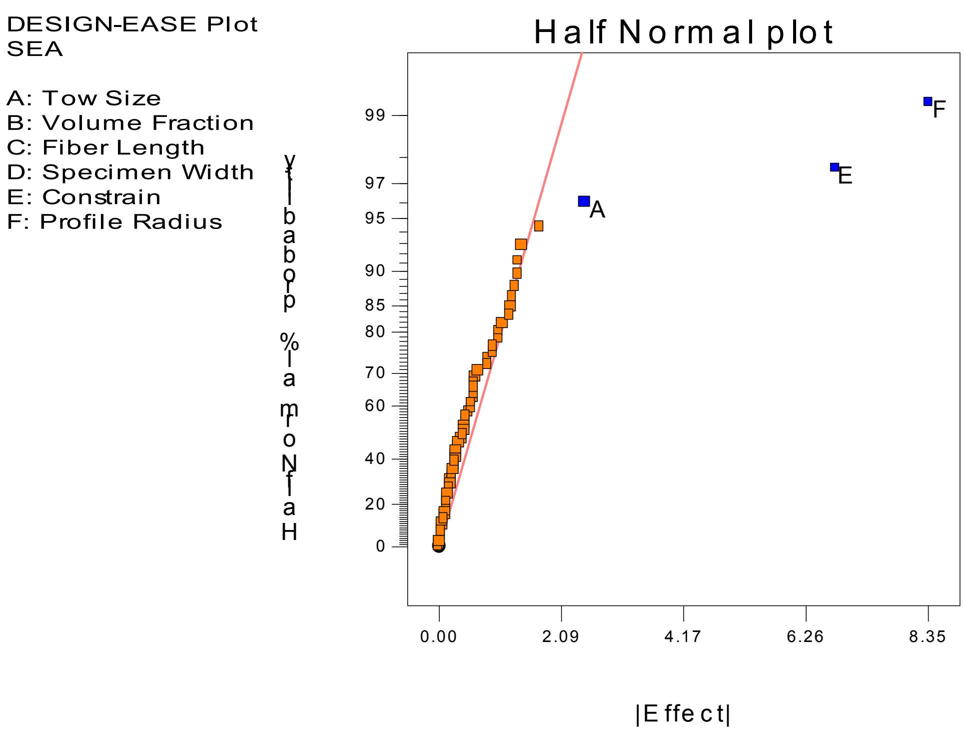


Figure 8. Half normal plot fromfactorial analysis results.

Table. 1. Parameters investigated in factorial analysis.

Parameter designation	Parameter	Levels
A	Fiber length	1”, 2”
B	Fiber volume fraction	40%, 50%
C	Fiber areal weight	150 gsm, 300 gsm
D	Specimen width	½”, 2”
E	Fixture constraint	None, Tight
F	Profile radius	0.25”, 0.50”

CONCLUSIONS

A three-dimensional micro-mechanical based finite-deformation constitutive models have been development and implemented into the nonlinear, finite element code DYNA3D. The model attempts to replicate progressive damage in CFCs and is intended for use in automotive crashworthiness applications. The new undulation component added in FY ’01 allows the model to accurately predict the elasto-plastic pre-damage response of braided CFC, while the tensile and compressive damage mechanisms added facilitate modeling the post-peak material response. A new three-dimensional constitutive model was developed for modeling of effective mechanical behavior and damage evolution of brittle random fiber composites. The model is capable of modeling strain softening and progressive crushing during impact.

FUTURE WORK

With the basic formulations of the models complete, the future emphasis will focus upon numerically “tuning” the model as necessary and validating it against experimental results as well as preparing documentation on its theoretical formulation. Using the existing and new experimental data, the necessary material properties will be determined and used to validate the model against previously conducted strip tests and drop-tower tube crush tests. The model will then be used to predict drop-tower tube crush tests of braided and random CFC architectures.

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