# Fracture Toughness of Through-Thickness Reinforced Composites

Project: F04-MD12

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## I. ABSTRACT

Organic Polymer Engineering Composite (OPEC) materials based on layered fabrics have many advantageous property and processing features. While OPEC materials are used in a wide variety of applications, one of their structural drawbacks is their generally poor interlaminar shear strength. Layered OPECs have little or no fiber reinforcement in thickness direction. Therefore, their inter-ply strength is always less than their longitudinal strength. This leads to poor impact and interlaminar flexural fatigue strength. Our research will lead to dramatic improvement of the interlaminar shear strength of fabric layered OPEC materials and increase the Mode I and Mode II fracture toughness of these composites. This will be accomplished by electro-orienting flock fibers, micro-fibers and/or high aspect ratio nanoparticles in the Z-direction at these inter-ply interfaces.

## II. GOALS

The goals of this project are:

1. Investigate the fundamental materials and structural parameters that lead to the Z-direction fiber reinforcement of fabric based laminar composites.
2. Develop effective fiber electro-orientation techniques (like flocking) for the Z-direction placement of fibers, micro-fibers or high aspect ratio nanoparticles in laminar structures.
3. Evaluate and determine the material and structural properties that lead to an optimization of the impact and interlaminar shear strength of composites using the through-thickness electro-oriented fiber reinforcement.

## III. INTRODUCTION

Through-thickness, micro-fiber reinforced/layered textile structures such as woven fabrics, directionally oriented warp knitted fabrics and braided structures offer the potential to produce net shape “pre-forms” continuously, as well as provide a product form with improved damage tolerance and impact resistance at lower cost. This proposed z-directional micro-fiber reinforcement technology also offers a cost reduction potential for OPEC materials for automotive, aerospace, sports, safety and other industrial applications. Our study will enhance competitiveness of high-tech textile pre-form manufacturing sectors by providing the industry with an effective means of introducing quality and cost-effective z-directional fiber reinforcement to these relevant composite materials. Furthermore, the uses and markets for advanced fibers, i.e., polyaramid, emerging new advanced fiber M5, glass and carbon fibers, would be greatly increased if techniques could be developed for fabricating OPEC materials having less anisotropic behavior. The knowledge base and trained personnel will enhance competitiveness of the U.S. Textile Industry.

Various techniques have been introduced to enhance the interlaminar strength of layered composite materials.[1, 2] A common technique is to use rubber-toughened matrix material resin [3]. However these resins are generally not thermally durable. An alternative approach is to manufacture special pre-forms using advanced textile technologies such as knitting, 3-D weaving/braiding or through-the-fabric stitching processes.[4] However, these methods are slow and expensive. While fabricated performs will have yarns in a z-directional orientation, these reinforcements are usually not conducive to an optimized stress distribution in the mechanically functioning structural component. Such 3-D structures are prone to stress concentrations under mechanical service leading to poor fatigue resistance. All these approaches work in their primary goal, but they degrade the composite's in-plane properties.[5]

In recent work by Hoskote, Kim and Lewis [6] studies were conducted on developing a method of fabricating layered fabric composites with improved delamination resistance by electro-orienting (by a flocking technique) short micro-fibers between the fabric plies. In this study it was shown that:

1. The addition of through-thickness reinforcement in the form of (nylon) flock fibers (aspect ratio of 1000 or higher) produced a significant improvement in both Mode I and Mode II fracture toughness. An improvement of as high as 10 and 3 times in mode I and mode II fracture toughness respectively was observed as compared to conventional (not flocked in the z-direction) glass fabric/epoxy composites. (See Figure 1 and 2)
2. The in-plane properties, especially the tensile strength, were found to be gradually degraded by high concentrations of z-direction reinforcing fiber. However, there was no significant reduction in tensile strength for the low concentration z-direction reinforced composites. So, for optimal performance low-density z-flock reinforcement is suggested.
3. Using the falling weight method, the impact resistance of flock-reinforced composites was found to be greatly improved as compared to conventional glass fabric laminar composites. The higher density flock reinforcement showed the highest improvement of up to 2.6 times the standard non-flocked composites.

4. Overall, glass fabric/epoxy resin laminates that are z-directionally reinforced with thermoplastic nylon flock fibers show a significant improvement in delamination fracture toughness.

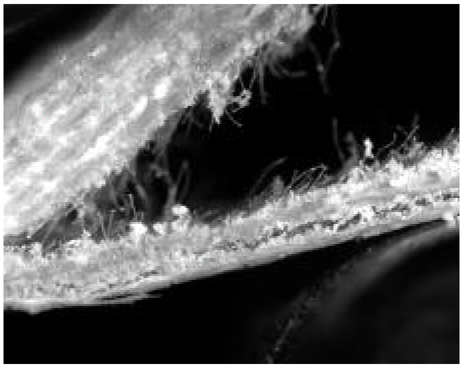


**Figure 1.** Mode I Fracture of Z-direction Reinforcements on Mode I Fracture Toughness.

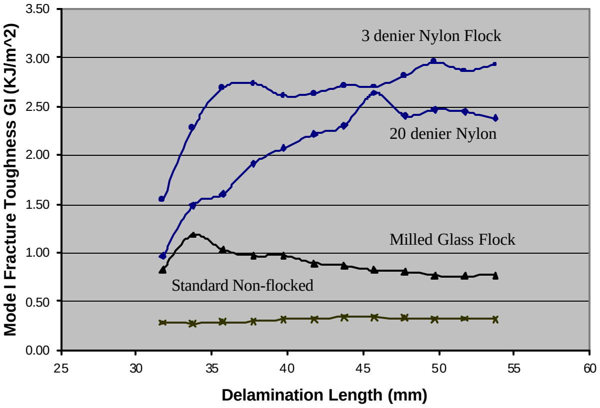


**Figure 2.** Effect of Various Z-Reinforced Laminar Composite Structures.

In other work, Kim, Nam and Lewis observed the electro-orientation of carbon nanofiber (CNF) particles as well as graphitic carbon powders that were suspended in organic media. Electrophoretic migration of CNFs was observed.[7] Also, the orientation of the particles into strings of connected "trees" occurred suggesting that 3-D (fiber) reinforced composites could be prepared employing these electro-orientation techniques. In the 1980's, McCollough and Sturman explored a technique of preparing discontinuous short fiber reinforced resin composites by orienting Nickel coated carbon fibers in a magnetic field for orientation control.[8] They met with some success in this endeavor.

## IV. ACCOMPLISHMENTS TO DATE

In recent work z-reinforced laminar composite plates were fabricated by vacuum electro-orientation/deposition of flock fibers. The plates were then used in two sets of tests, as described below, fiber pull-out tests and mode I double cantilever beam tests (DCB). Mathematical models of the plates were developed in parallel to plate testing, using the finite element method. The models were used to investigate important toughness and strength parameters of the composite.

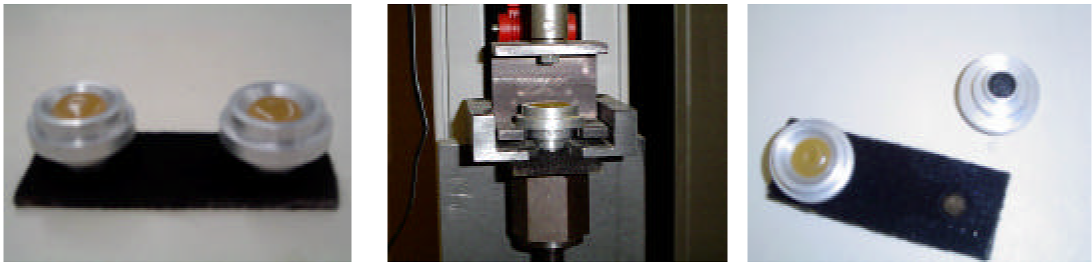
## A. THEORY

### Fracture criterion for fiber-flocked composite

If $G_I - \Phi_{ir} \geq G_{IC}$, then the crack will grow, where $G_I$ is the strain energy release rate due to the applied loads, $\Phi_{ir}$ is the energy dissipation rate during fiber pullout, $\left(G_I - \Phi_{ir}\right)$ is the net energy release rate at the crack tip including the effect of the z-direction fibers, and $G_{IC}$ is the delamination toughness of the composite. Our objective is to obtain a high value of $\Phi_{ir}$, thus increasing the through-thickness toughness of the composite. To understand the micro-mechanics of fiber pull-out, fiber pull-out tests were conducted. The resulting data was used to provide a basis for the modeling of fiber pull-out in the finite element macro-model of the composite, and to understand the important parameters that effect the energy dissipated during fiber pull-out.

## B. EXPERIMENTAL DATA

Fiber pull-out tests were performed on flocked plates, as shown in Figure 3a. The fibers were flocked to a plate with a thin epoxy resin layer of $37\mu$m thickness, and the free ends were bonded to small disks using a hot melt adhesive. After the adhesive set, the specimens were pulled by a test apparatus, as shown in Fig. 3b. Fig. 3c shows the specimen after fiber pull-out.



**(a)** **(b)** **(c)**

**Figure 3.** Pull-out test samples (a) before pull-out test (b) during pull-out test (c) after pull-out.

From these tests, typical force vs. displacement curves were obtained for nylon and polyester (PET) fiber samples at different densities, as shown in Figure 4. The dissipation energy during fiber pull-out is proportional the area under the curve.

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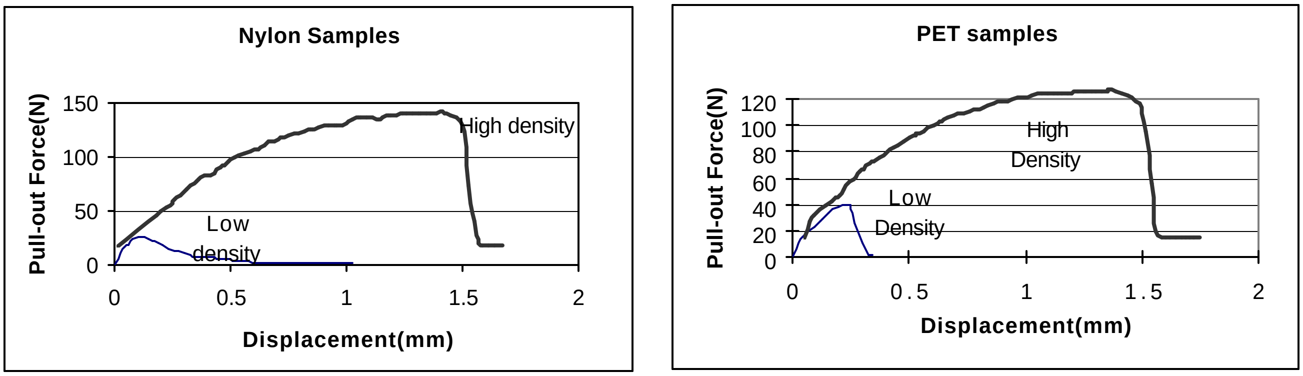


**(a)** **(b)**

**Figure 4.** High and low density pull-out force vs. displacement curves for (a) nylon samples, and (b) polyester samples.

In Fig. 4 the high and low densities $\left(\frac{\text{fibers}}{\text{mm}^2}\right)$ for the nylon are 123, 27, respectively, and for the polyester are 68 and 12, respectively.

Using the data from the pull-out tests, the relationship between flock density and max pull-out force was obtained, and the results are shown in Figure 5.

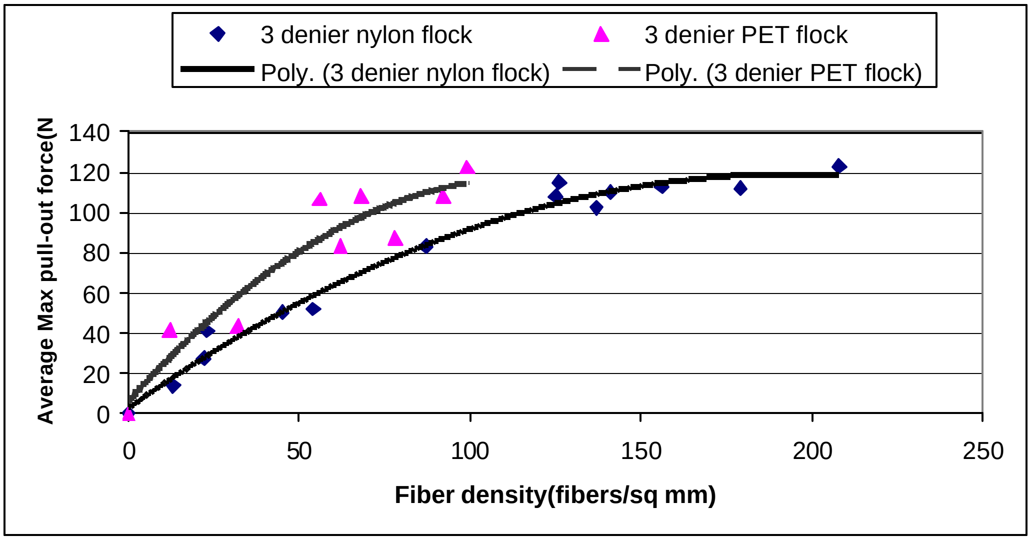
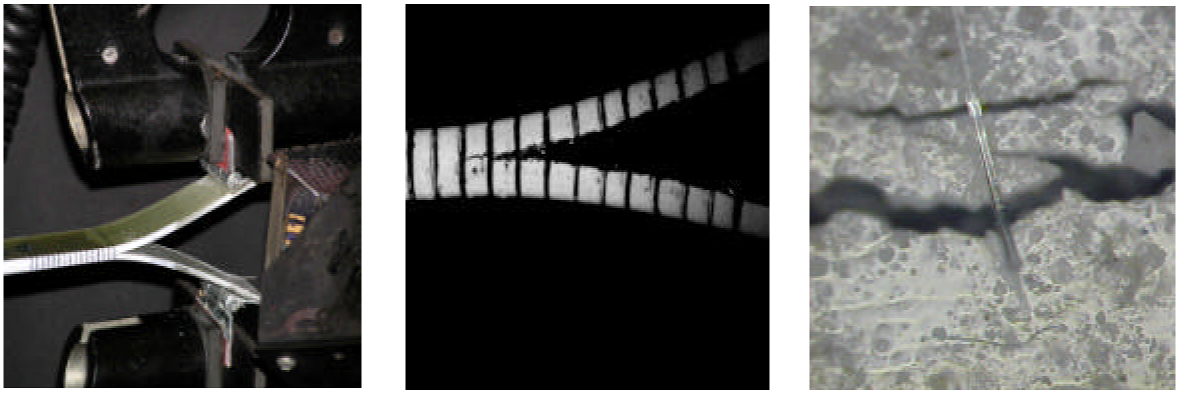


**Figure 5**. Relationship between fiber density and maximum pull-out force.

## Double Cantilever Beam (DCB) tests

The double cantilever beam specimen as shown in Fig. 6 is used in a mode I fracture toughness tests.



(a) (b) (c)

**Figure 6**. Double Cantilever Beam test (a) sample during test ; (b) fracture behavior of the sample; and (c) a typical bridging fiber at the crack tip.

The composites samples were made of the following components: woven glass fabric, epoxy resin 2000 system matrix, and 3 denier nylon flock. Table 1 contains more technical data for the DCB samples.

**Table 1** Composite properties.

| | |
|---|---|
| Layer number | 24 layers |
| Flock density | 17 fibers/sq mm |
| Fiber volume Friction | 51.58% |
| Average Fracture Toughness | 2.12 KJ/ $m^2$ |

A fracture toughness vs. delamination length curve was plotted from the data of the DCB tests, as shown in Fig. 7.

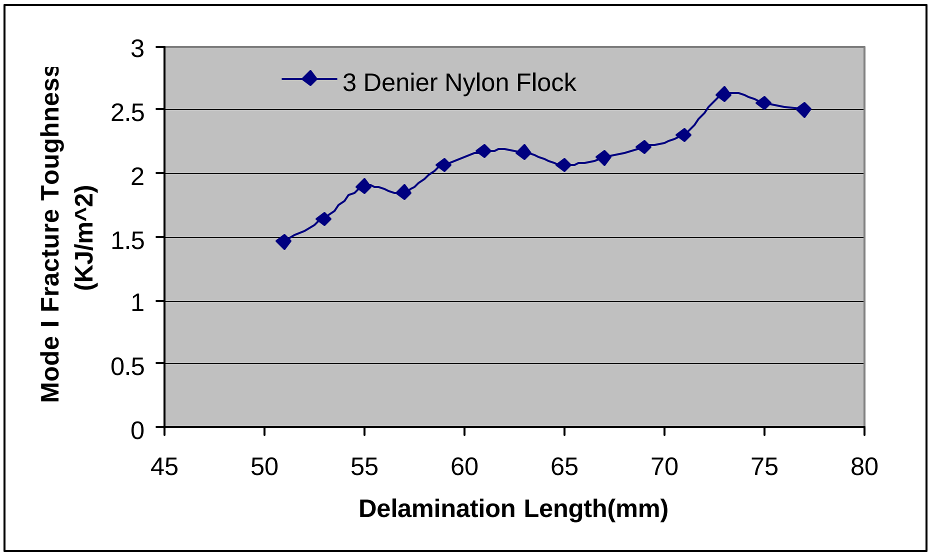


**Figure 7** Fracture toughness vs. Delamination length curve.

## C. FINITE ELEMENT MODELING

A finite element model of fiber pull-out was developed for the finite element macro-model of the composite.

### Finite element modeling of fiber pull-out

Fig. 8 demonstrates how we modeled the pullout test using the finite element method.

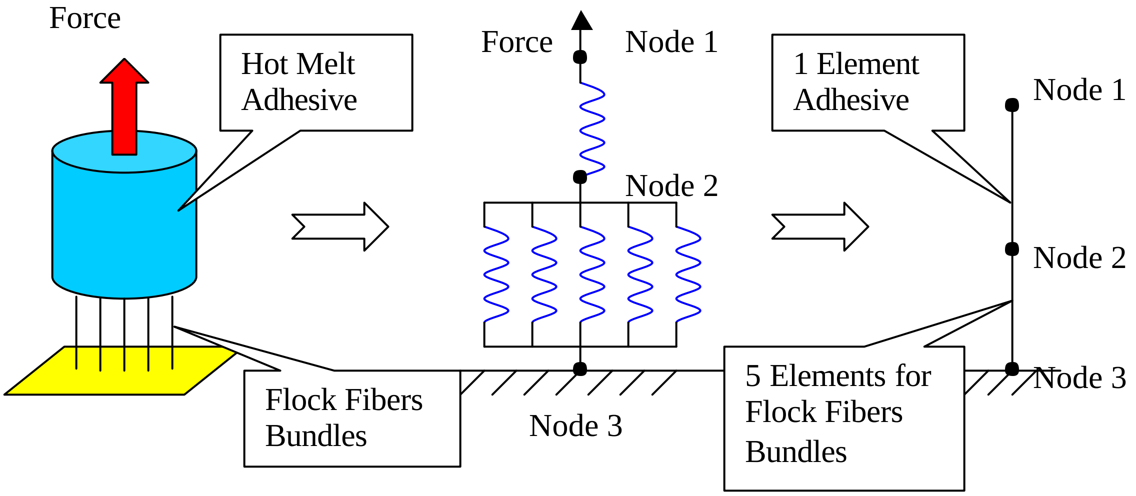


**Figure 8.** Steps to transfer the Fiber Pull-out Test experiment to FE model

The fibers were modeled using spring-slider elements. A “breakaway” feature is available to allow the element stiffness to drop to zero once a limiting force has been reached, which simulates the fiber bundles being pulled out.

The FE model fits the experimental data for the pull-out test very well, as shown in Fig. 9 by a typical comparison of the FE model and the pull-out curve for the high density nylon sample from Fig. 4.

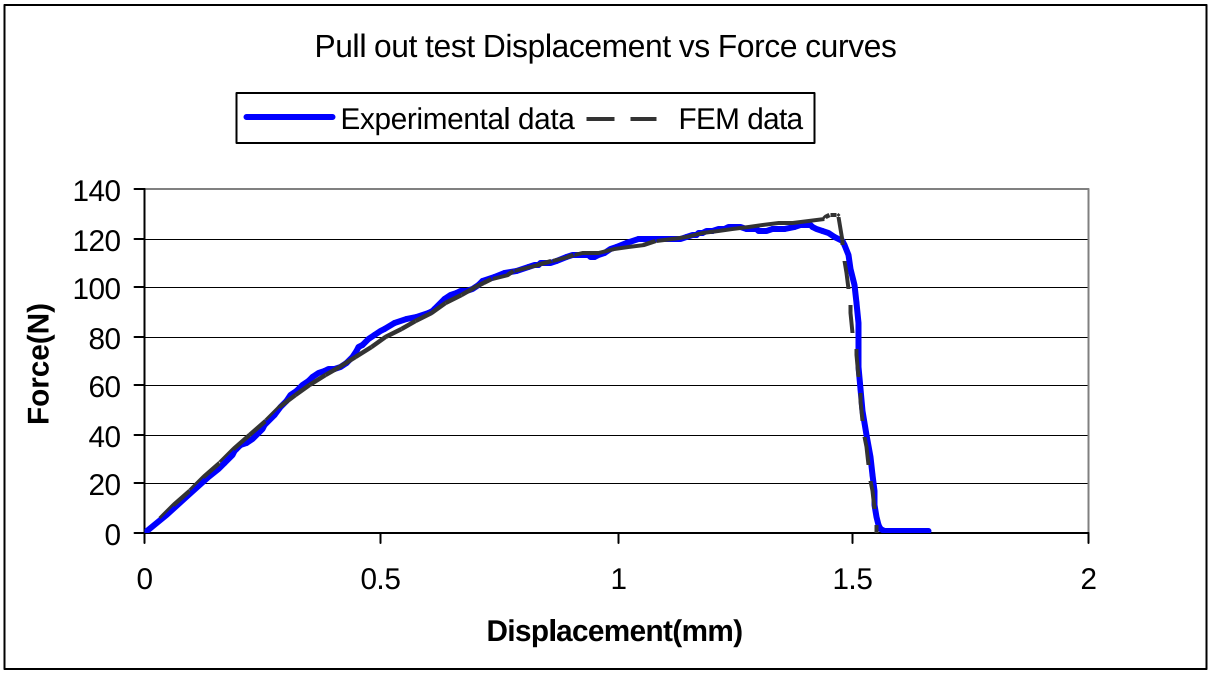
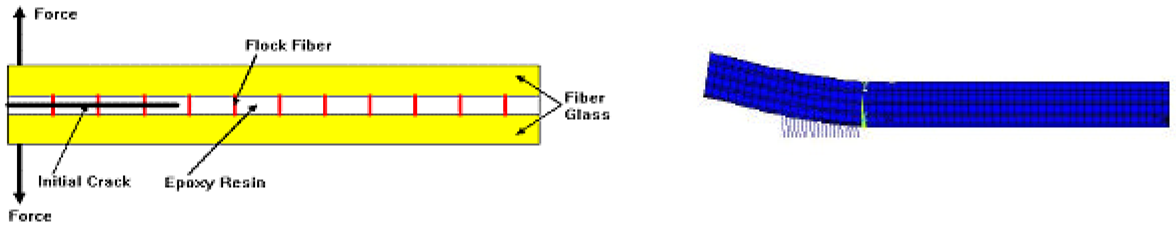


**Figure 9** Comparison of the pull-out experiment for the high density nylon sample in Fig. 4 and FE model.

## Finite element modeling of DCB tests

A finite element analysis was performed to model the Mode I failure mechanism and fracture toughness in a Double Cantilever Beam (DCB) test. We developed a 3-D symmetric finite element model using composite and spring-slider elements, as shown in Fig. 10.



(a) (b)

**Figure 10** (a) Sketch of flocked DCB sample and (b) FE Model of flocked composite

For this study we want to determine the energy release rate, which is the change of strain energy required to open new crack areas, and can be calculated from the equation

$$G = \frac{1}{t}\frac{dU}{da} = \frac{1}{t}\frac{U_{a+\Delta a} - U_a}{\Delta a} \qquad (1)$$

where $t$ is the width of the composite model. In this finite element model we use the so called "virtual crack extension method", which calculates G as the crack opens, starting at a crack length of $a$ and increasing a small increment $\Delta a$. In this method the strain energy is calculated at both crack states, $U_a$ and $U_{a+\Delta a}$. We then use the discretized form of Eq. (1) to calculate the energy release rate.

## D. DISCUSSION AND CONCLUSIONS

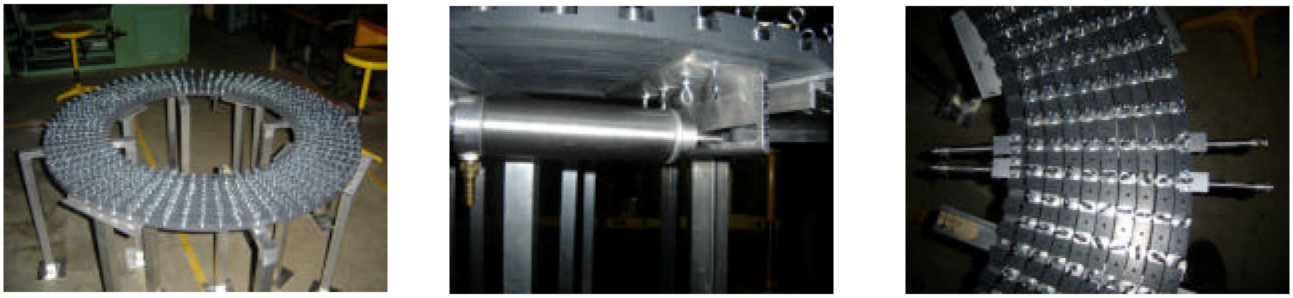
1) We can gain some insight into the mechanics and important parameters of fiber pullout from Fig. 4. As you can see from the nonlinear pull-out force vs. deflection curve, the slope of the curve is constantly changing. Effectively, the stiffness of the fibers are decreasing as the deflection increases. This is due to the fibers breaking the bonds and sliding in the epoxy a few at a time until all the bonds are broken. After the maximum force is reached the pull-out force either is nearly constant or decreases due to the sliding of the fibers in the epoxy.

2) From the Fig. 5, we can draw the conclusion that the higher flock density we have, the higher maximum pull-out force and therefore the higher dissipation energy; in general the PET will have a higher dissipation energy than the same denier nylon during fiber pull-out.

3) Using the non-flocked composite fracture toughness obtained from [6], $G_I = 0.34 KJ/m^2$, as a reference, you can see that the nylon flocked-composite in Fig. 7 is 6.23 times tougher than the non-flocked composite.

## E. OTHER ACCOMPLISHMENTS

4) To verify the efficacy of the z-reinforced laminar composite plates compared to the other 3-D composites, we will produce 3-D braided pre-form based composites. A 3-D braiding machine is under construction in our lab, as shown in Fig 11.



(a) (b) (c)

**Figure 11** (a) overall view of the 3-D braiding machine; (b) front view of the underside of the braiding rings; and (c) top view of the rings and yarn carriers.

Fig. 11a shows an overall view of the machine with 10 PVC rings and 72 radial sets of yarn carriers. Each radial set consists of 9 yarn carriers for a total of 648 yarn carriers. Each individual carrier rotates in a circle due to motion of the 8 inner PVC rings. The circular motion is achieved by 4 pneumatic cylinders. A typical cylinder is shown in the side view under the PVC rings in Fig. 11b. The carriers also move in a radial direction. This is achieved by 72 pairs of pneumatic cylinders, one pair for each radial set of yarn carriers. Two typical pairs of pneumatic cylinders are shown in the top view in Fig. 11c.

## V. REMAINING TASKS

Several tasks will be undertaken:

1. Fabricate other types of z-reinforced laminar composite plates by vacuum electro-orientation/deposition of flock fibers, e.g., carbon, glass, as well as micro-fibers including functionalized multiwall carbon nanotubes, and test them for toughness and impact strength.

2. Understand the mechanism of the Mode I and II fracture energy, and impact strength improvements of the electro-oriented layered fiber reinforced resin composite materials. A finite element macro-model will be developed for the composite to model the Mode II fracture energy and impact strength.

3. Complete the assembly of the 3-D braiding machine and fabricated specimens equivalent to z-reinforced laminar composite plates. These specimens will undergo the same tests conducted for the z-reinforced laminar composite plates to compare their fracture energy and impact strength.

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