

VIRGIN CARPET-POLYMER STRUCTURAL LAMINATES

By

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May, 2011

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Problem Statement

Post-consumer carpet waste recycling is in its infancy in the United States. Currently, a number of initiatives have been taken to recycle carpet waste with an effort to divert away from landfill and incineration. Some of the current and previous methods [2–14] suggest that waste carpets can be chopped or shredded and reused, or melt blended to form into a desired product shape. However, none of these methods was simple enough to reduce the energy and the total cost involved. A recent technique proposed by Singh *et al.* [15] (Patent pending), suggests the use of simple resin infusion technique to convert the post-consumer carpet waste into useful structural laminates. Initial studies [15, 16] that were conducted on post-consumer waste carpet based structural laminates, using vacuum infusion technique, showed promising results on mechanical and physical properties. In an attempt to understand the deterioration of carpet fibers upon its long usage, this study has been primarily aimed at establishing reference properties using virgin carpet–polymer based composites that can further be utilized to create a comprehensive database.

Most of the manufactured carpets today consist of one of these six pile fibers: nylon, olefin (polypropylene), polyester, acrylic, cotton, and wool. These fibers make up to 98% of the fibers used by the various carpet industries across the United States [1]. Each fibers have their own advantages and disadvantages that must be identified from the viewpoint of their usage and construction. Of the three most commonly used fibers (nylon, olefin, and polyester), nylon is by far the most expensive fiber and the best all-around material [1]. Nylon has attained a greater popularity and is utilized in approximately 65% of the carpet

sold in the U.S. market [1, 17]. It provides excellent performance and durability in heavy foot traffic conditions. Furthermore, there are two basic types of nylon currently available in the market, type 6 and type 6,6. Of these two types, type 6,6 is considered to be the premium nylon fiber.

The olefin fiber carpets are rapidly growing in the commercial market segment [1, 39]. It is cheaper than the nylon fiber, and can be easily extruded by most of the carpet manufacturers. 30% of fibers used in carpets manufactured in the U.S. today are the olefin fibers [1]. In the year 2009, according to Carpet America Recovery Effort (CARE), the Nylon 6,6 fiber had the highest post-consumer carpet fiber inventory level, followed by polypropylene [17, 40]. Concurrently, these fibers had a less recycling percentage compared to Nylon 6 in the same year 2009 [17, 40]. Table 1.1 is a comparison of merits of all carpet fibers that provided a platform to choose the best carpet that fits into our needs. It is the listed superior properties of nylon and olefin fibers that led us to choose them to fabricate structural laminates that give better mechanical and physical properties than any other available carpet fiber materials.

<b>Property</b>	<b>Nylon 6,6</b>	<b>Olefin</b>	<b>Polyester</b>
Resilience	Excellent	Excellent	Good to excellent
Abrasion resistance	Excellent	Excellent	Good to excellent
Resistance to UV	Good	Loses strength and deteriorates unless chemically modified	Good. But weaken with prolonged exposure
Stain resistance	Good to excellent	Good if oily soils and stains are treated promptly	Good to excellent

Table 1.1: Fibers properties [1]

Nonetheless, carpets fail to perform their intended service after some point of duration, and consequently, they are either incinerated or sent to landfills. To classify carpet waste, it can be conveniently divided into two broad categories: pre-consumer carpet waste and post-consumer carpet waste. Pre-consumer carpet waste is the considerable amount of scrap generated due to trimming and fitting processes, while the post-consumer carpet waste includes the waste generated after their long term period of use.

## **1.2 Carpet Structure and Its Types**

Generally, any carpet comprises of four component structures: face fibers, primary backing, secondary backing, and binder. The predominantly used fibers may range from nylon, olefin, and wool. As the individual fiber properties vary by their chemical nature, the fiber properties are well utilized to suit the specific needs warranted by specific applications. For example, heavy duty stain-resistant carpets with main fibers as nylon or olefin can be used for industrial applications without any deterioration of carpet fibers upon exposure to different chemicals.

Figure 1.1 shows the three broad types of carpets that are currently available in the market [1]. As these carpet fibers are tufted in different forms, they are mainly divided into three designs such as, cut pile, level loop pile, and multi-level loop pile. In cut pile versions, face fibers are cut at the top to give a smooth or plush feeling. Because they give the feeling of softness, they are predominantly used in houses. Level loop pile carpets have their fibers wound in a loop fashion. They are typically meant for heavy foot traffic conditions for commercial applications. The multi-level loop carpets have different fiber loop sizes that are arranged in alternate rows. Unlike the cut-pile carpets, these carpets have less fiber density and thus they are easy to clean.

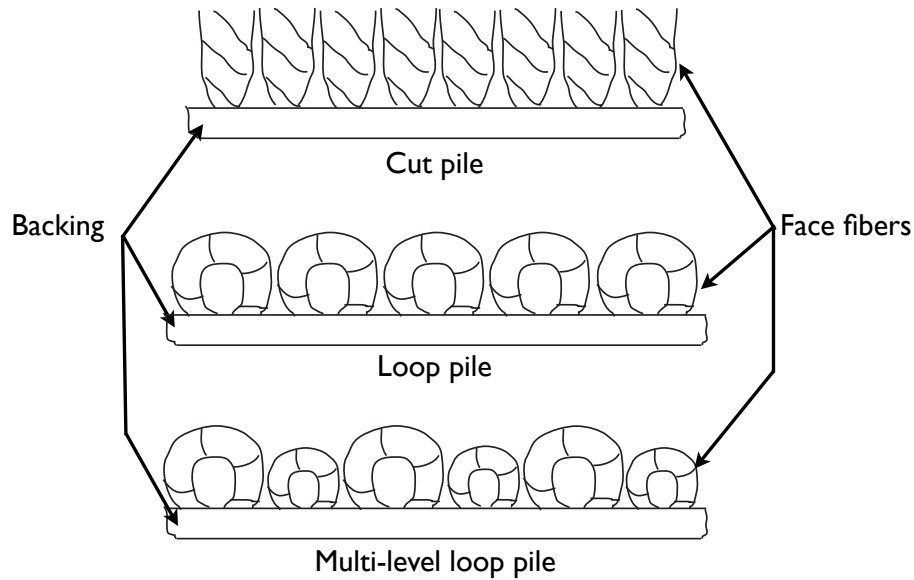


Figure 1.1: Carpet construction

### 1.3 Conventional Carpet Recycling Techniques

Several researchers have tried to recycle carpet with different recycling techniques. However, none of them is cost effective and simple. This is because of the fact that the carpet is made of multi-component materials that are chemically diverse in nature, and require more energy intensive processes to recycle. The conventional techniques can be broadly categorized into following methods [12]:

#### 1.3.1 Primary recycling or depolymerization

Depolymerization is the process of converting material constituents of a carpet into their monomers [7, 11, 18, 19]. This chemical process involves breakdown of polymers into their monomers such that they can be polymerized again when needed. Here, face fibers are mechanically separated from backing and chemically converted into their monomer forms.

### **1.3.2 Secondary recycling or polyamide extraction**

This is a physical approach that involves extraction of carpet components without breaking them into their monomers. Conventionally, face fibers are separated from backing using mechanical choppers/shredders and taken to injection molding to form into required product shapes [6, 20–25].

### **1.3.3 Tertiary recycling or melt-blending**

Tertiary recycling has two stages: Initial mechanical shredding [5] of carpet components followed by melt blending of the components to get an overall mixture. Melt-blended carpet mixtures are further extruded in molds to get secondary or low-grade plastic materials [2, 26–28]. This technique does not require the separation of face fibers from backing.

### **1.3.4 Quaternary recycling or incineration**

In the incineration process, carpets are burnt in kilns to produce energy out of carpet derived fuels (CDF). The disadvantages of these CDF are the  $\text{NO}_x$  emissions and higher ash content than coals.

## **1.4 Proposed Technique and Its Advantages**

This study utilizes simple vacuum assisted resin infusion to make carpet structural laminates followed by curing at recommended temperatures. The advantages of using this technique [15, 16] are: it eliminates chopping/shredding and pre-processing steps that are mechanically energy intensive – enables to use all types of carpets – exploits the three dimensional architecture of carpet face fibers and backing fibers – ensures adaptability to parts of various shapes and sizes – provides flexibility to scale laminates to various sizes and produce laminates with superior properties.

In the following chapter, fabrication of structural laminates with different matrices and

laminated configurations is discussed in detail. The idea of making different laminated configurations was to understand the failure mechanisms of various carpet-polymer design styles in different applications. Mechanical properties such as flexural and screw pullout strengths were evaluated on different structural laminated configurations with two different resins (SC 79 and vinyl ester) as the matrix.

Physical properties: density and thermal conductivity, were measured to examine their characteristic dependence on flexural and screw pullout strength properties. Fiber volume fraction experiments were done on the two carpets to find the percentage share of fiber and matrix on the total composite.

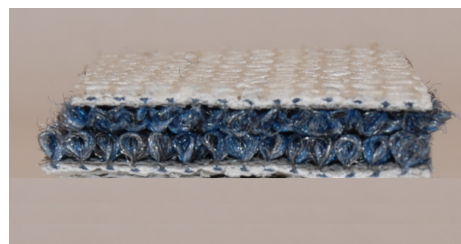


## CHAPTER 2

### FABRICATION

#### 2.1 Material Preparation

Careful attention has been endued to prepare samples with various stacking sequences with different types of epoxy-resins in order to portray the dependency of structural layer sequence and epoxy combination on the mechanical and physical properties. Sample preparation processes include: selection of carpets and resins, method of laminate fabrication, and machining processes based on the type of tests to be conducted.



(a) Cut-pile carpet, nylon based, BFFB

(b) Loop-pile carpet, olefin based, BFFB

Figure 2.1: Sample stacking configuration of nylon and olefin based carpets

##### 2.1.1 Constituent materials

In this study, the following two types of commercial carpets (fig. 2.1) were chosen to make structural laminates:

1. Nylon, cut loop ( Commercial name: Romper room/ Orange cool-aid, Make: Shaw)
2. Olefin, level loop (Commercial name: Pay dirt / Sapphire, Make: Monticello)

These carpets of size 60 cm × 144 cm were bought from M/s Georgia Carpet Industries Inc., Atlanta, Georgia, and then cut into pieces of size 28 cm × 28 cm for further sample preparation processes. Two types of epoxies—SC 79 (Diglycidyl ether of bisphenol A – DGEBA) and vinyl ester—were used to make composite structural laminates in this study. SC 79 Part A (with hardener SC 79 Part B) and vinyl ester (with hardener methyl-ethyl-ketone-peroxide – MEKP), were procured from Applied Polymeric Inc. and Fiberglast Corporation, respectively.

The epoxy SC 79 is prepared by mixing the hardener Pt B with the resin SC 79 Pt A with a percentage ratio of 40/100. For example, for every 1000 grams of SC 79 resin, 400 grams of hardener is added and then stirred for 5–10 minutes to ensure better cross linking. As the pot life of this resin is 45 minutes, it can be held sufficient time before going to the actual infusion process. These resins are typically subjected to 350°C to complete the curing process. On the other hand, vinyl ester epoxies are prepared by mixing the hardener MEKP with the vinyl ester resin with a percentage ratio of 1.25/100. Thus for every 1000 grams of vinyl ester, 12.5 grams of MEKP is added and mixed well for five minutes. Since the curing temperature of this resin takes place at room temperature itself, it has a pot life of 30 minutes.

### **2.1.2 Fabrication process**

Samples were fabricated using a simple vacuum assisted resin-infusion based fabrication technique. SC 79 and vinyl ester were employed to make structural laminates with two different combination of layers such as face fiber-backing-backing-face fiber (FBBF) and Backing-face fiber-face fiber-backing (BFFB) configurations.

Vacuum assisted resin transfer molding, VARTM, is a simple and very useful technique to infuse resins into different materials where the primary interest is to get a product which is essentially made of more than one material. The resulting product has the combined essence of both the material properties which would be multifunctional and useful in many

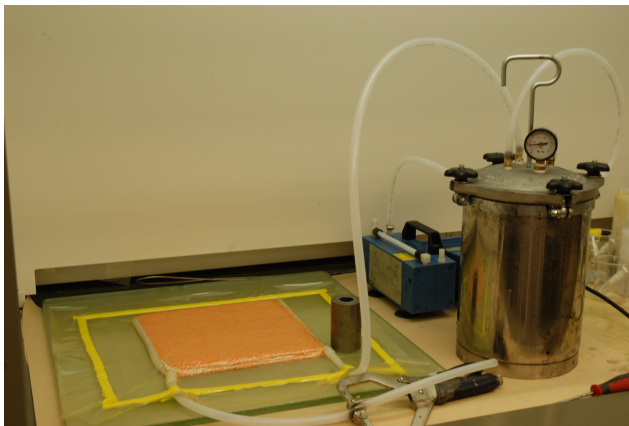
engineering applications. Among the available techniques to infuse resins, the most simple and cost effective method is the use of vacuum bag technique, which wastes only a small amount of resin during the whole infusion process. This technique requires a vacuum pump, polyethylene sheet for vacuum bagging, tacky tape, large glass plate, mold release agent, spring clamp, connecting tubes from pump to vacuum bag, and vacuum bag to resin container. Initially the glass plate is cleaned properly and a mold release agent is applied over the surface to ensure easy removal of the resin at the end of the process. The required size of polyethylene sheet for vacuum bagging, tacky tape, and connecting tubes are cut initially.

The conventional method is to lay the tacky tape to a size just greater than the effective material/infusion area over the glass plate first, and the sample (through which resin is to be infused) is placed between the tapes. Then the polyethylene sheet is stuck. During this lay up a careful attention is being given to ensure that there is no shrinkage or air pockets trapped between the sheet, tape, and the connecting tubes on the inlet and outlet side of the bagging. After ensuring no air pockets, the resin inlet tube end is closed and the pump is switched on to suck all the air out inside the bag. The resin is now ready to be infused.

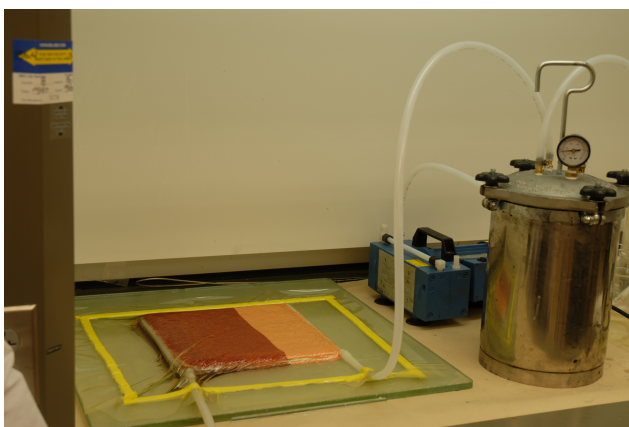
In the above conventional procedure, we had come up with an improvisation that made the bagging/layup process much easier and more reliable for multiple times of VARTM processing. In this method, instead of sticking the tacky tape initially on the glass plate, it was first stuck over the polyethylene sheet to a size just greater than effective infusion area. And, after placing the sample over the glass plate, this sheet with already stuck tacky tape was stuck directly over the glass plate. Here there was no problem of shrinkage during the layup, since the tape can be stuck easily with the sheet initially under our control without any shrinkages. Thus the total time of VARTM process by this method was almost reduced by 50% of the total time taken by the conventional layup process.

Figure 2.2 depicts the VARTM process of nylon-vinyl ester carpet sample. Two tubes are placed inside the vacuum bag and the same bag is sealed on all the sides to ensure

a tight sealing across the sample. After the VARTM process, samples with SC 79 resin



(a) Before resin infusion



(b) During resin infusion



(c) Sample under compression in hot press

Figure 2.2: VARTM process of Nylon–Vinylester sample

were placed into the hot press at 350°C, while laminates with vinyl ester resins were cured in the hot press under room temperature. The samples thickness was maintained with a compression under certain pressures in order to get 50% of initial total laminate thickness. Table 2.1 shows the samples that were used in this study.

<b>Carpet fiber</b>	<b>Resin used</b>	<b>Laminate configuration</b>
Nylon	SC 79	FBBF – Backing facing eachother
Nylon	SC 79	BFFB – Face fibers facing eachother
Nylon	Vinyl ester	FBBF – Backing facing eachother
Nylon	Vinyl ester	BFFB – Face fibers facing eachother
Olefin	SC 79	FBBF – Backing facing eachother
Olefin	SC 79	BFFB – Face fibers facing eachother
Olefin	Vinyl ester	FBBF – Backing facing eachother
Olefin	Vinyl ester	BFFB – Face fibers facing eachother

Table 2.1: Specimen fabrication

For the subsequent machining processes, samples were initially cut using band saw and then sanded down to final dimensions. Mechanical tests such as flexural test and screw pull-out test were performed using ASTM D 790 and ASTM D 7332, respectively. In addition, density, thermal conductivity, and fiber volume fraction were also measured.

## **CHAPTER 3**

### **EXPERIMENTATION**

The two selected carpets—orange-nylon and sapphire-olefin—were cut from rolls to a size of 1feet x 1feet for two numbers, each. Two orange-nylon and sapphire-olefin carpet cut layers were taken to stack with FBBF and BFFB configurations. These stacked carpets were then taken separately to the VARTM setup and kept over the glass plate. Upon completing the vacuum bag layup process, SC 79 or vinylester epoxy was prepared.

After infusion of the resin, the infused sample was taken to the hot press and pressed until the total thickness was reduced by 50% of initial total height of the laminates [33,34]. Carpet layers with SC 79 were heated up to 350°C for 1 hr and subsequently kept under the same compression for 24 hrs at room temperature before releasing it from the hot press.

Carpet layers with vinylester as resin were cured for 2 hours at the following recommended cycle: 80 °F–100°F–120 °F. These structural laminates were further taken to subsequent machining process where they were cut according to ASTM standards for different type of mechanical and physical property tests. In this study, two types of mechanical properties: Flexural and Screw pullout, and two types of physical properties: Density and Thermal conductivity were studied. For conducting mechanical tests, Instron (model-5567) was used. In each of the experiments a minimum of four to five samples were tested.

#### **3.1 Mechanical Property Tests**

In nylon carpets, nylon face fibers are tufted with olefin (polypropylene) backing in cut-pile version to give a smooth plush, while in olefin carpets, olefin fibers are tufted with olefin backing in a level loop fashion. As the olefin backing layers are crafted in criss-cross

direction with the face fibers, it allows us to harness respective fiber strength dominance to get better mechanical properties in multi-directions.

### 3.1.1 Flexural testing

Three point bend test, shown in fig. 3.1, as per ASTM D 790 [29] was conducted to determine flexural properties of structural laminates such as maximum flexural strength and flexural modulus. Samples were cut to a support span-to-depth ratio 16:1 using band saw and sanded down further considering the overhang length of 10 percent of the support span. A minimum of one-fourth inch of overhang distance was maintained. The finished samples were then placed in the 3 point bend test setup and the upper nose was set to touch exactly at the top of the specimen surface. Finally the loading was applied with a particular rate of cross head motion which was obtained from the equation 3.1.

$$R = \frac{ZL^2}{6d} \quad (3.1)$$

where:

$R$  = rate of crosshead motion, mm (in.)/min,

$L$  = support span, mm (in.)

$d$  = depth of beam, mm (in.)

$Z$  = rate of straining of the outer fiber, mm/mm/min (in./in./min).  $Z \simeq 0.01$

The load versus displacement was measured and a graph was drawn using the points obtained through out the specimen testing. For determining maximum flexural strength, the maximum load obtained in the graph was considered. The equation 3.2 gives the maximum flexural strength of a specimen when subjected under a three point bending.

$$\sigma_{f\max} = \frac{3P_{\max}L}{2bd^2} \quad (3.2)$$

where:

$\sigma$  = stress in the outer fibers at midpoint, MPa (psi),

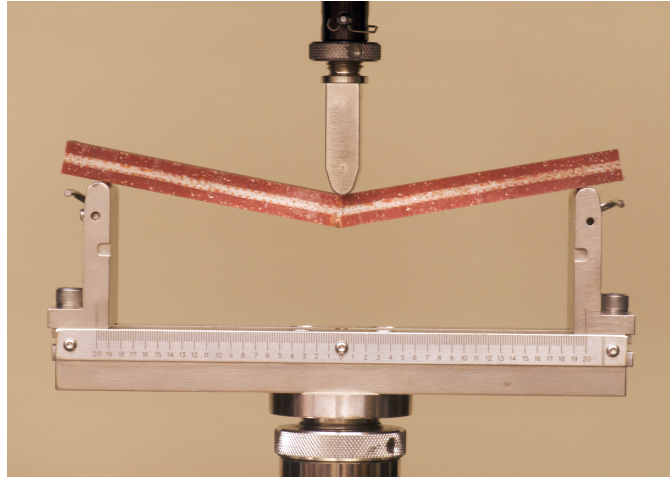


Figure 3.1: 3-point bend flexural test. Specimen: nylon–vinylester, FBBF

$P_{max}$  = maximum load obtained in the load-deflection curve, N (lbf),

$L$  = support span, mm (in.)

$b$  = width of beam tested, mm (in.) and

$d$  = depth of beam tested, mm (in.)

The flexural modulus of the specimen is the ratio of flexural stress to corresponding flexural strain when considered within the elastic limit. It was calculated using the following general equation 3.3, where the slope,  $m$ , was found by considering the steepest initial line on the load deflection curve.

$$E_B = \frac{L^3 m}{4bd^3} \quad (3.3)$$

where:

$E_B$  = modulus of elasticity in bending, MPa (psi),

$L$  = support span, mm (in.),

$b$  = width of beam tested, mm (in.),

$d$  = depth of beam tested, mm (in.), and

$m$  = slope of the tangent to the initial straight-line portion of the load defln. curve, N/mm (lbf/in.).



### 3.1.2 Screw pullout testing

In order to quantify the ability of these materials to be joined as structures, the screw pullout strengths were determined. Maximum screw pullout strength is the ultimate load resistance offered by the series of materials across the total specimen thickness on a cross sectional area, approximately equal to mean screw area, upon displacing the screw to a shearing length equivalent to one screw-pitch [35, 36]. Pallets for transport and storage uses are the typical applications.

For measuring the screw pullout strength, a new fixture was designed and developed which was very simple and convenient to test different thickness and category of specimens. Figure 3.2 depicts the setup of the screw pullout testing fixture with a nylon based FBBF laminate. ASTM D 7332/D 7332M - 07 [30] was considered as a reference for choosing the cross head motion rate (5 mm/min). A screw size of 1/4 inch x 3 inch [36] was selected and a minimum of 4 to 5 samples were chosen for conducting the test.

Samples were cut to the required dimension (2" x 2" x 0.5") from the composite structural laminates and a pilot hole was drilled to a size little less than the screw size at the center of the sample piece. A screw was then screwed into the sample to a particular pre-determined depth so to maintain consistency in testing on all the samples.

Two types of screw pullout tests were performed in this study. First tests were performed normally, that gave pullout strengths with partial shear on top layers. Since the fixture was initially designed with an entry recess in the bottom fixture to allow all different heights of specimens to be placed easily, tested samples exhibited only partial shearing in the top layer. Hence, second tests were performed with a washer to allow a full shear on the top layers of the samples. The equation 3.4 was used to find out the screw pullout resistance.

$$(\sigma_{SP})_{1,2 \max} = \frac{P_{\max}}{\pi \left( \frac{D_{\text{out}} + D_{\text{pilot hole}}}{2} \right) \times t} \quad (3.4)$$

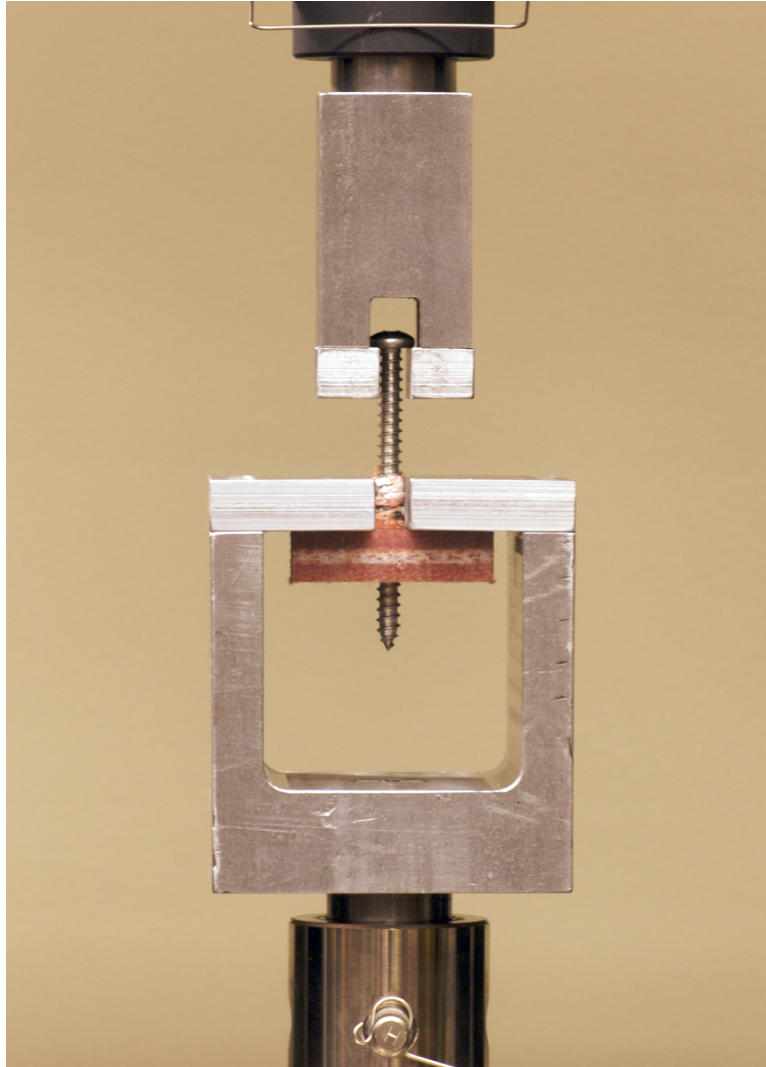


Figure 3.2: A nylon–vinyl ester, FBBF, sample without washer has been shown at failure in Screw pullout test.

where:

$\sigma_{SP,1}$  = screw pullout strength when top layer is partially sheared, i.e without washer, (MPa)

$\sigma_{SP,2}$  = screw pullout strength when top layer is fully sheared, i.e with washer, (MPa)

$P_{max}$  = maximum screw pullout load, N (lbf),

$D_{out}$  = outer diameter, mm (in.),

$D_{pilot\ hole}$  = pilot hole diameter, mm (in.) – recommended: 0.2 inch for 0.25 inch screw dia.,

$t$  = thickness of the sample, mm (in.).

## 3.2 Physical Property Tests

As for physical properties, density and thermal conductivity were chosen to be determined on the fabricated structural laminates. These physical properties help in selecting laminates for applications based requirements.

### 3.2.1 Density

Density can be defined as mass per unit volume. The mass can be generally measured using a weighing balance machine. Here the density of the samples was measured using a density measurement setup in the high precision (SARTORIUS) weighing machine with the use of following equation 3.5.

$$\rho = \frac{W_a}{W_a + W_w - W_b} (0.9975) \quad (3.5)$$

where:

$\rho$  is the density of sample, in gms/cm<sup>3</sup>,

$W_a$  is the weight of the specimen when hung in the air,

$W_w$  is the weight of the partly immersed wire holding the specimen,

$W_b$  is the weight of specimen when immersed fully in distilled water,

along with the partly immersed wire holding the specimen,

0.9975 is the density in gms/cm<sup>3</sup> of the distilled water at 23°C.

### 3.2.2 Thermal conductivity

In this study, an axial heat flow thermal conductivity setup (shown in figure 4) was used to find thermal conductivity [31, 32]. The temperature gradients across the in-line arrangement of the system (copper rod–carpet–polymer sample–copper rod) were determined to calculate the thermal conductivity of the carpet-polymer laminates. The thermal conductivity,  $k$ , of samples of size  $\phi 1 \times 0.5$  inch thick, were measured using equation 3.6 and 3.7. From the ASTM 1225 standard, equation 3.6 was used to calculate the heat flow,  $Q$ , on both sides of the specimen, that is represented as  $Q_{hot}$  and  $Q_{cold}$ . Subsequently, equation 3.7, the Fourier law of heat conduction, was used to find the thermal conductivity of the sample.

The setup uses eight T-type, high precision copper-constantan thermocouple probes (located in the hot and cold side of the sample on pure copper rods) to measure heat flow across the sample. Heat loss from the setup through conduction and convection in the circumferential direction was minimized by introducing thick teflon cylinder cum holder type insulation.

$$Q = -kA \left( \frac{\Delta T}{\Delta Z} \right) \quad (3.6)$$

$$k_{sample} = \frac{(Q_{hot} + Q_{cold})L_{sample}}{2A_{sample}(T_{hot} - T_{cold})} \quad (3.7)$$

The hot side input temperature was controlled using Omega CN132 temperature/process controller and the cold side input temperature was controlled by an analog controlled Cole Palmer chiller (model:12750-00). Source and sink of heat were located such a way that the exact temperature distribution/gradient can be measured across the samples. A thin and gummy layer of high thermal conductivity paste: Omegatherm 201, was used on both sides of the sample to improve the heat conduction between the sample and the hot- and-cold side

of the copper rods. Temperatures at different heights were recorded using an instrument, Fluke 53 series II digital storage thermometer, after the steady state conditions had been achieved in approximately 20 to 24 hrs.

The thermal conductivity of the carpet-polymer based composites becomes prominent when they are used as house roofs for multi-functional properties, such as, for hail-damage-resistant and low heat transfer properties. The former is very useful during spring/summer when heavy thunder storms strike, and the latter can be highly advantageous during summer.

### **3.3 Volume Fraction Measurement**

Volume fraction measurements are generally done to know the percentage of existence of individual materials in composites. These measurements sometimes form a basis for analyzing the behavior of composite materials.

There are different techniques available to measure fiber volume fraction in a composite, namely matrix digestion, ignition loss, areal weight, and image analysis methods. However, none of the above methods can be directly applied here nor be used to simply find the volume fraction of the carpet-polymer structural laminates, as the final laminates are not prepared by the same nature as the other composites are prepared.

#### **3.3.1 Fiber volume fraction**

A simple fiber volume fraction measurement was used in this study to find volume fractions of individual materials in the structural laminates. Square pieces of final laminates made from two carpet materials with two resins were taken individually for finding masses of all combination of samples. Two layers of raw carpet materials of same sizes were also weighed separately.

Approximate weight of the resins in the final laminates were determined by subtracting the final laminate weight from the two raw carpet materials weight. The face fibers and the

backing in each of the raw carpet layers were further separated for measuring the weight of the individual materials. After knowing all the individual material weights and densities, using the following appropriate formulae, volume fractions of each materials were determined. Fiber volume fraction is given as,

$$v_f = \frac{V_f}{V_f + V_m} \quad (3.8)$$

$$= \frac{\frac{M_f}{\rho_f}}{\left[ \frac{M_f}{\rho_f} + \frac{M_m}{\rho_m} \right]} \quad (3.9)$$

$$= \frac{\frac{w_f M}{\rho_f}}{\left[ \frac{w_f M}{\rho_f} + \frac{w_f M}{\rho_m} \right]} \quad (3.10)$$

$$v_f = \frac{w_f}{\left[ w_f + (1 - w_f) \frac{\rho_f}{\rho_m} \right]} \quad (3.11)$$

For our carpet structural laminates, the above equation can be expanded for face fibers, backing, and matrix as the following,

$$v_f = \frac{V_f}{V_f + V_b + V_m} \quad (3.12)$$

$$= \frac{\frac{w_f M}{\rho_f}}{\left[ \frac{w_f M}{\rho_f} + \frac{w_b M}{\rho_b} + \frac{w_f M}{\rho_m} \right]} \quad (3.13)$$

$$v_f = \frac{w_f}{\left[ w_f + w_b \frac{\rho_f}{\rho_b} + w_m \frac{\rho_f}{\rho_m} \right]} \quad (3.14)$$

Similarly,

$$v_b = \frac{w_b}{\left[ w_b + w_f \frac{\rho_b}{\rho_f} + w_m \frac{\rho_b}{\rho_m} \right]} \quad (3.15)$$

Also we know,

$$\rho V = \rho_f V_f + \rho_b V_b + \rho_m V_m \quad (3.16)$$

$$\Rightarrow \rho = \rho_f v_f + \rho_b v_b + \rho_m v_m \quad (3.17)$$

The density of the SC 79, nylon, and olefin are 1.116, 1.15, and 0.855 g/cc respectively.

For the density of the vinyl ester matrix, we have  $\rho_{\text{resin}} = 1.032\text{g/cc}$  and  $\rho_{\text{hardener}} = 1.004\text{g/cc}$

Density of the vinyl ester matrix is written as,

$$W_{\text{epoxy}} = W_{\text{resin}} + W_{\text{hardener}} \quad (3.18)$$

$$\rho_e V_e = \rho_r V_r + \rho_h V_h \quad (3.19)$$

$$\Rightarrow \rho_{\text{VE epoxy}} = \rho_r \frac{V_r}{V_e} + \rho_h \frac{V_h}{V_e} \quad (3.20)$$

$$\rho_{\text{VE}} = \rho_r v_r + \rho_h v_h \quad (3.21)$$

$$= \rho_r v_r + \rho_h (1 - v_r) \quad (3.22)$$

But  $v_r$  can be found as,

$$v_r = \frac{w_r}{w_r + (1 - w_r) \frac{\rho_r}{\rho_h}} \quad (3.23)$$

$$= \frac{0.988}{0.988 + (1 - 0.988) \frac{1.032}{1.004}} \quad (3.24)$$

$$= 0.98766 \quad (3.25)$$

$$\Rightarrow \rho_{\text{VE}} = \rho_r v_r + \rho_h (1 - v_r) \quad (3.26)$$

$$= 1.032 \times 0.98766 + 1.004 \times (1 - 0.98766) \quad (3.27)$$

$$= 1.03165 \text{ g/cc} \quad (3.28)$$

## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 Flexural Strength

##### 4.1.1 SC 79 and Vinyl ester neat epoxy-resins

Flexural strength on neat SC 79 and vinyl ester samples was tested before employing them on carpets. Figure 4.1 shows the load–displacement curve of neat samples. It is clear from the graph that SC 79 shows brittleness at failure, while the vinyl ester exhibits delayed failure showing a ductile nature. Table 4.1 lists the strength and modulus values and shows the vinyl ester samples have higher flexural strength than SC 79. However, flexural modulus of both the samples does not vary much.

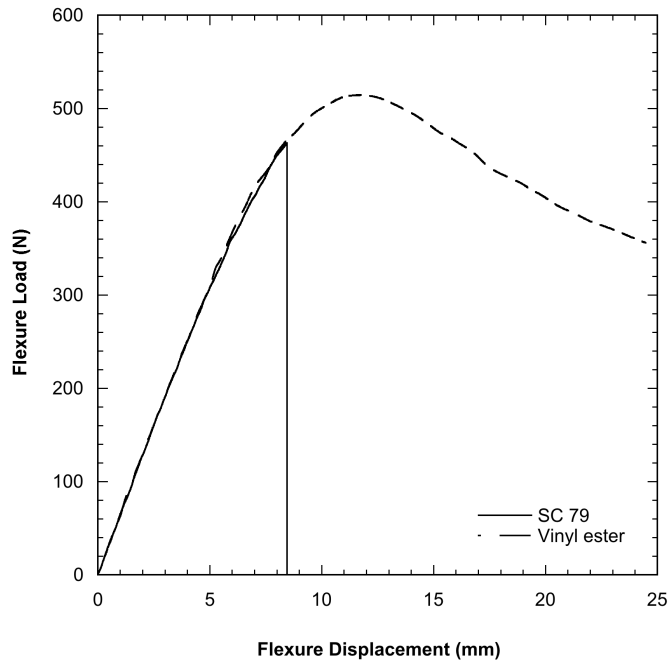


Figure 4.1: Load–displacement graph of neat epoxy-resins, flexural



<b>Resin</b>	$\sigma_{flexure}$ (MPa)	$E_{flexure}$ (MPa)
SC 79	$89 \pm 2.3$	$2970 \pm 145$
Vinyl ester	$95 \pm 2.2$	$2859 \pm 195$

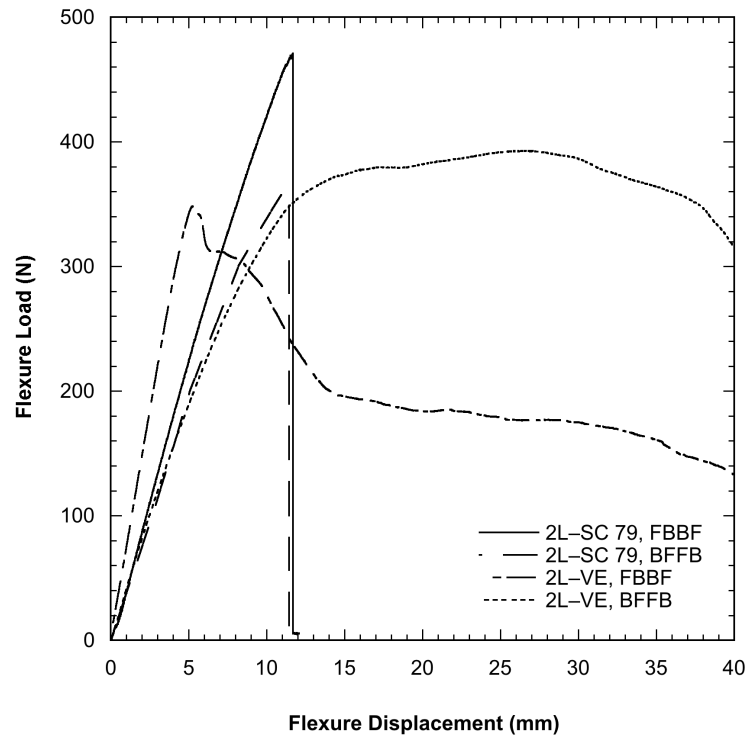
Table 4.1: Flexural properties of SC 79 and Vinyl ester neat epoxy-resins

#### 4.1.2 Nylon laminates – two layers

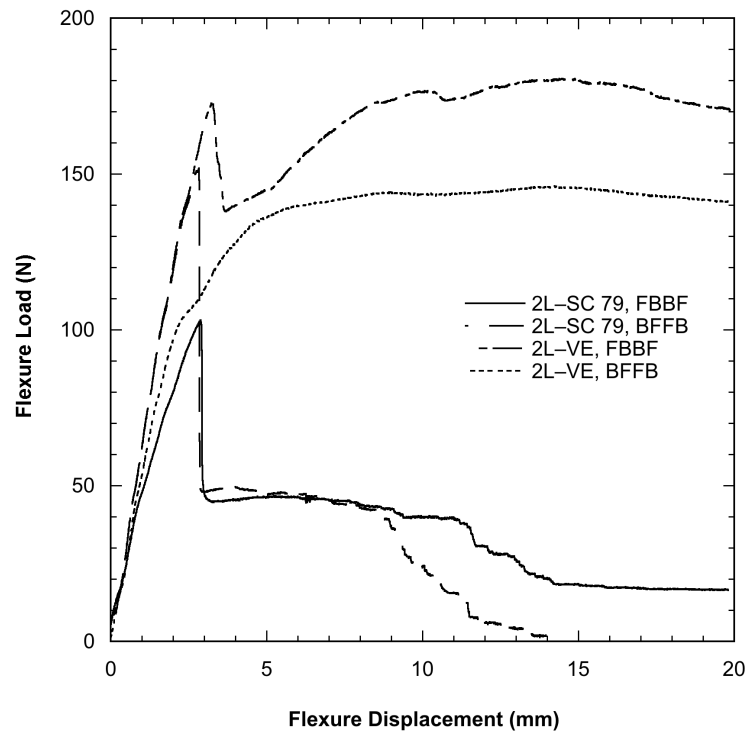
Figure 4.2, graph (a) shows that the laminates with SC 79 as matrix exhibit full brittle failure, and the laminates with vinyl ester as matrix exhibit extended ductility. The failure nature of these matrix samples confirm the same trend as the neat samples discussed before. However, it has to be noted that the maximum flexural strength and the pattern of failure were totally governed by the outer layer material. This material experiences different curing temperature with different resins before undergoing expansion under the three point bending load.

From table 4.2, it could be inferred that the nylon laminates with nylon face fibers at the top, employed with SC 79 matrix, offered better flexural strength than that of with vinyl ester matrix. This is because the reinforcement of nylon fiber with SC 79 at higher curing temperature (350 °C) was greater than that of vinyl ester matrix which was cured at room temperature. In other words, with nylon face fibers, the SC 79 offers higher strength than vinyl ester.

In nylon–SC 79 BFFB configuration, though the same increase in strength against vinyl ester matrix was expected, there was a decrease in strength value. This reduced strength suggests that degradation of olefin backing layer had occurred due to the influence of higher temperature curing process. Furthermore, from table 4.2, on the flexural modulus, the laminates with face fibers at the top (FBBF) exhibit higher flexural modulus against BFFB laminates with irrespective of the matrix employed.



(a) Nylon – Two layer laminate



(b) Olefin – Two layer laminate

Figure 4.2: Load–displacement graph of two layer nylon and olefin laminates, flexural

### 4.1.3 Olefin laminates – two layers

Figure 4.2, graph (b) shows again that the laminates with SC 79 as matrix exhibit brittle failure when compared with the laminates made with vinyl ester as matrix, except the fact that the failure here is quasi-brittle.

Table 4.2 reveals that, unlike the nylon laminates, the olefin laminates with olefin face fibers at the top (FBBF), employed with SC 79 matrix, offered lower strength than that of with vinyl ester matrix. This shows again that the higher temperature curing of SC 79 matrix had caused the degradation of olefin face fibers. On the contrast, olefin–SC 79 laminates with olefin backing layer at the top (BFFB) confirms the same strength pattern as that of nylon–SC 79 laminates.

#### Quasi-brittle phenomenon

The reason for the quasi-brittle nature with SC 79 matrix can be explained with the help of fig. 4.3, fig. 4.4, and fig. 4.8, single nylon laminate flexural testing. Figure 4.3 shows the flexural load versus displacement graph of single nylon–SC 79 laminate and double layer olefin–SC 79 laminate. One common thing to be noted from the graph is that both the samples failed approximately at a same load point of 150 N, and leveled-out finally to a same load of 50 N for some duration. This behavior suggests that both the polypropylene backing layers underwent the same nature of failure and expansion, but the material that is present beneath this outer layer has changed the post failure trends.

In case of the single layer nylon–SC 79 laminate (with backing in tension), the instantaneous matrix failure in the backing was followed by the extended ductile fashion failure of high resistant nylon-matrix compressive layers. When the load reached 50N, the fiber pull-out in the backing layer had started to contain the load—evident from graph (a) of fig. 4.4 and fig. 4.8. While with the two layer olefin–SC 79, BFFB, laminates, the sudden load drop was due to the fact that the olefin face fibers beneath the backing could not sustain the load, and thus broke rapidly. However, at the same 50 N load, the fibers in the olefin back-

ing have started stretching in both BFFB and FBBF laminates—evident from fig. 4.4, (b) and (c). Hence it is the pullout of polypropylene backing fibers that gives the quasi-brittle nature in two layer olefin–SC 79 laminates.

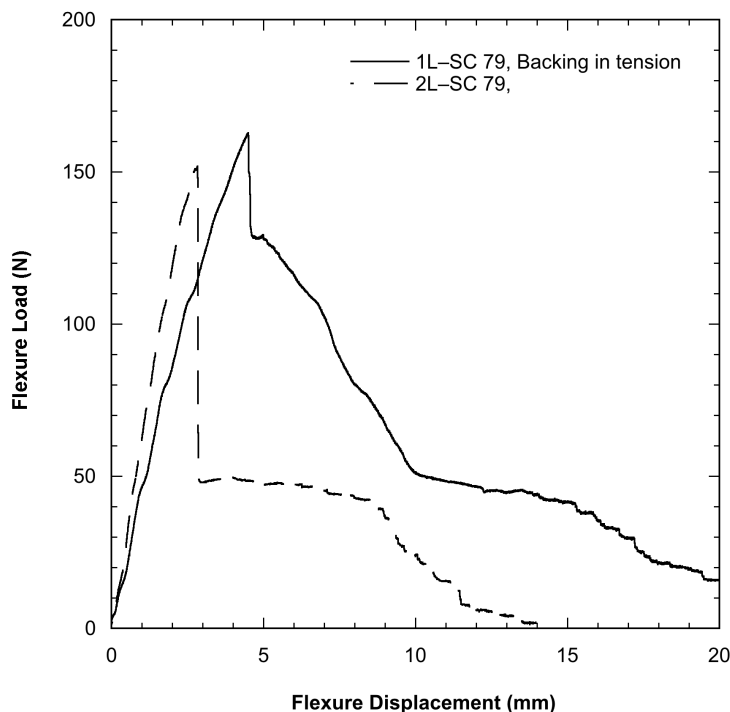
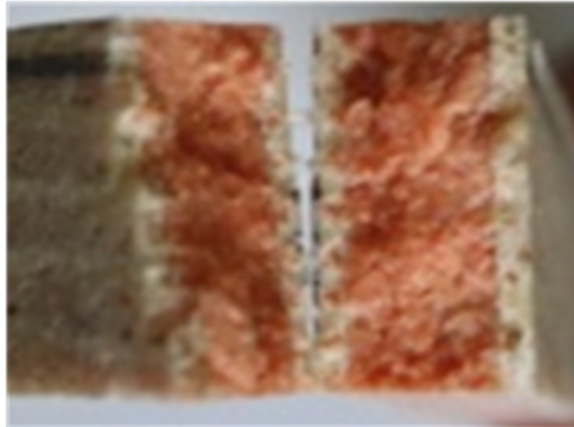


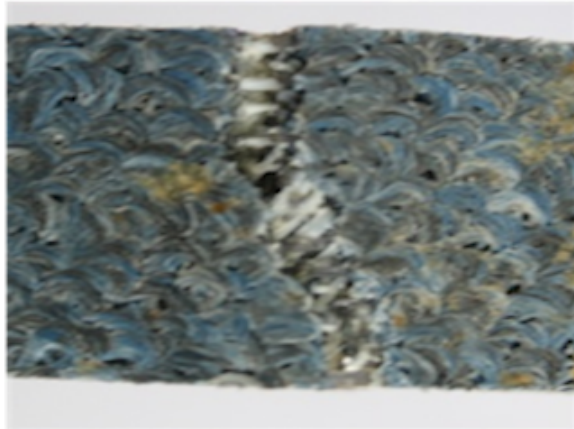
Figure 4.3: Load–displacement graph of single layer nylon and two layer olefin laminates, flexural

From table 4.2 for the flexural modulus, the olefin laminates with olefin/polypropylene backing layer at the top exhibit higher flexural modulus with both the matrices. In all, nylon fibers perform better than polypropylene backing, and polypropylene backing performs better than olefin face fibers. This shows that the relative toughness of the structural laminates could be controlled very effectively by an appropriate choice of the infusion resin. Thus the flexural properties allow for comparison with other structural materials.

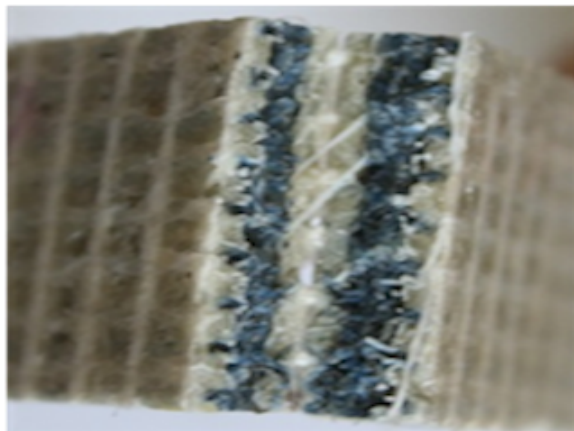
Flexural strength tested specimens are shown below.



(a) 2L Nylon-SC 79, BFFB

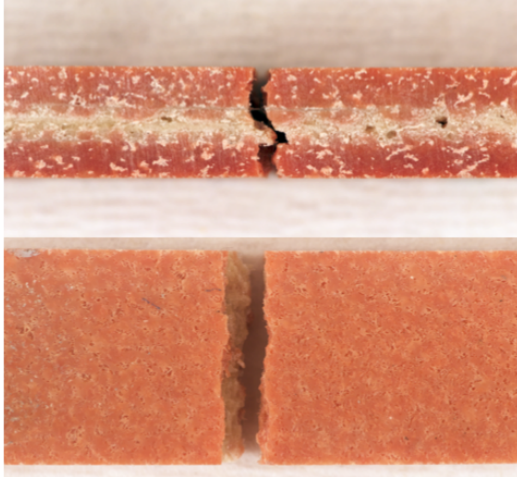


(b) 2L Olefin-SC 79, FBBF

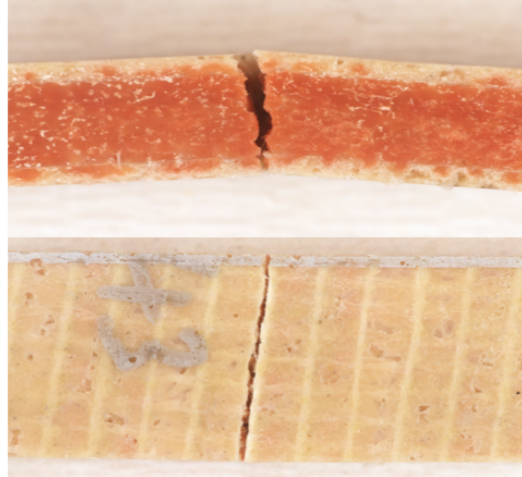


(c) 2L Olefin-SC 79, BFFB

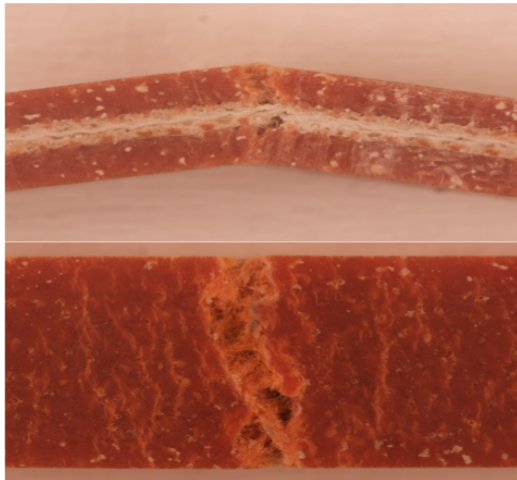
Figure 4.4: Fiber stretch in two layer laminates



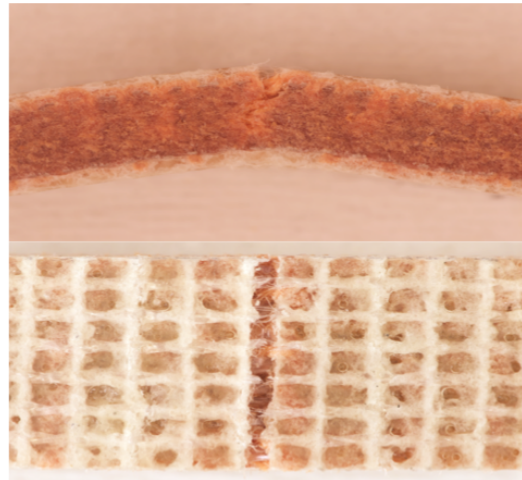
(a) SC 79 - FBBF



(b) SC 79 - BFFB



(c) VE - FBBF



(d) VE - BFFB

Figure 4.5: Fractured flexure samples of nylon based carpet

<b>Carpet</b>	<b>Resin</b>	<b>Configuration</b>	$\sigma_{flexure-2L}$	$E_{flexure-2L}$
Nylon	SC 79	FBBF	$35 \pm 1.3$	1635
Nylon	SC 79	BFFB	$24 \pm 0.3$	1375
Nylon	VE	FBBF	$27 \pm 0.7$	2340
Nylon	VE	BFFB	$28 \pm 1.5$	1330
Olefin	SC 79	FBBF	$19 \pm 0.5$	1570
Olefin	SC 79	BFFB	$24 \pm 0.8$	2060
Olefin	VE	FBBF	$28 \pm 1.0$	1860
Olefin	VE	BFFB	$29 \pm 0.7$	2210

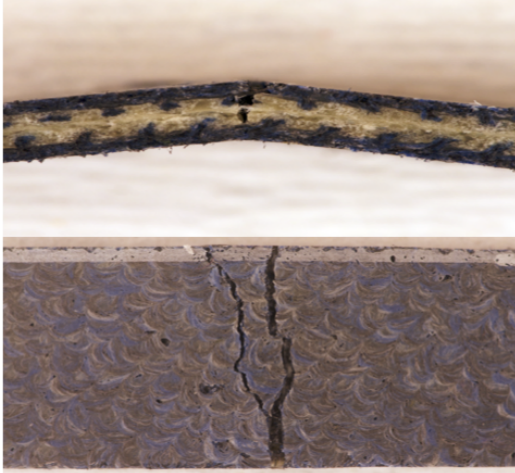
Table 4.2: Flexural properties of two layer nylon and olefin laminates.

Referring fig. 4.5 (c) and fig. 4.5 (d), the laminates with vinyl ester as matrix shows cracks that are not all the way through the thickness and are not sharp when compared with the specimens with SC 79 matrix in fig. 4.5 (a) and fig. 4.5 (b). Figure 4.6 (a) and fig. 4.6 (b) suggest that the failure in the outer layer material is brittle, but not throughout the thickness (quasi-brittle) as witnessed by the load–displacement graphs. Figure 4.6 (c) and fig. 4.6 (d) show clearly that the sample is ductile in nature.

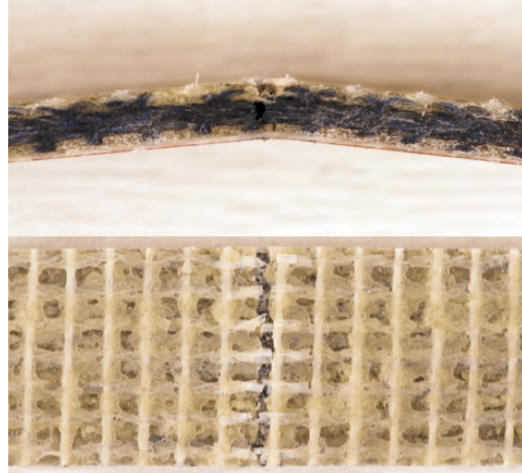
#### 4.1.4 Nylon laminates – single layer

The single nylon laminates were subjected to three point bend test to understand the failure response of each layer material—Nylon and backing, when they are under expansion. Several observations have been drawn in the following paragraph to get an in depth understanding of the property of nylon face fibers and polypropylene backing fibers under expansion and compression mode of testing.

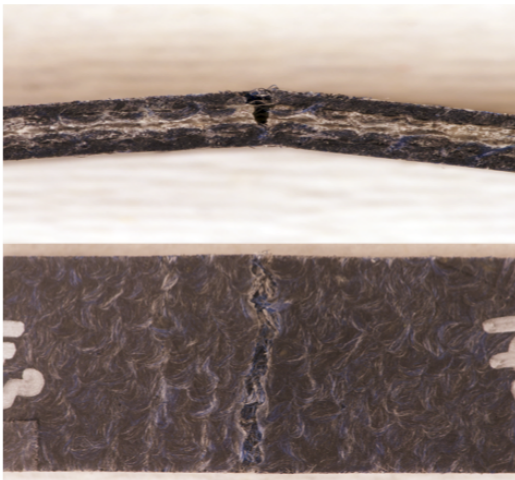
Comparing the graph (a) of fig. 4.2 with that of fig. 4.7, it is evident in SC 79 laminates that when the nylon fibers were under tension they failed in brittle mode. However, in



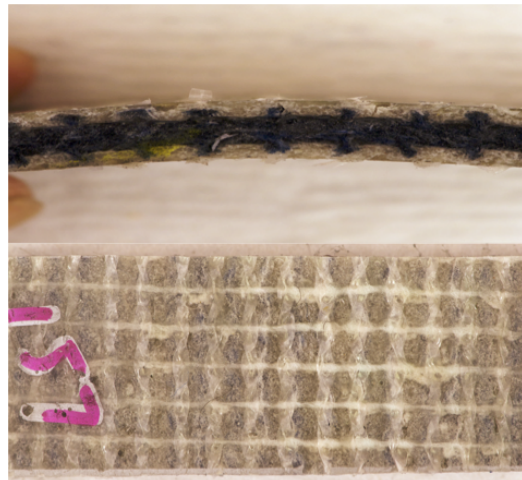
(a) SC 79 - FBBF



(b) SC 79 - BFFB



(c) VE - FBBF



(d) VE - BFFB

Figure 4.6: Fractured flexure samples of olefin based carpet



the case of single nylon laminate, the lower ultimate load of nylon face fibers has kept the compressive layer of polypropylene backing fibers intact and let them remain undisturbed as seen in fig. 4.8 (b).

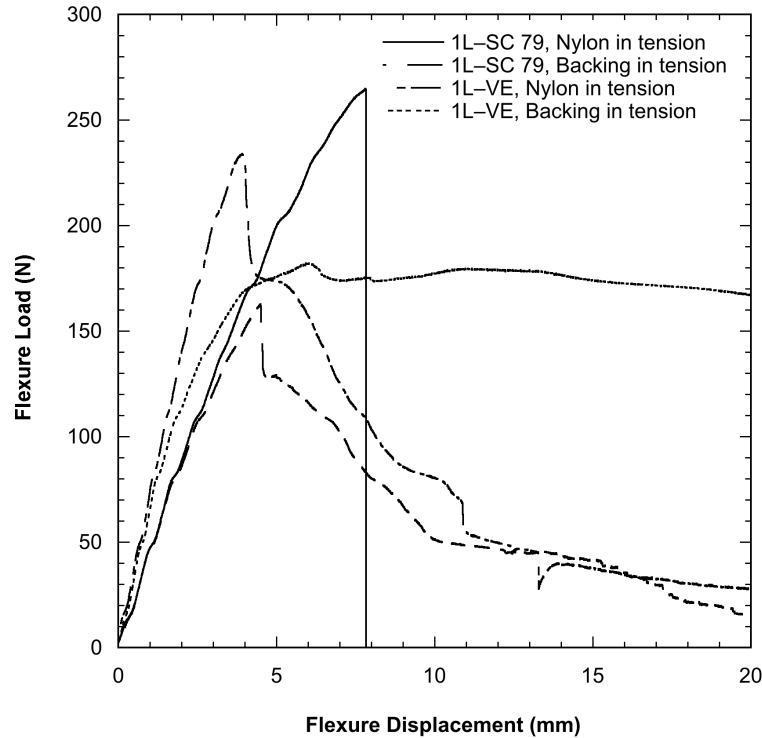


Figure 4.7: Load–displacement graph of single layer nylon laminate, flexural

Moreover, from fig. 4.7, with the same SC 79 matrix in single nylon laminate, when backing was under tension, the lower ultimate load value of backing–matrix does not allow the sample to fracture in brittle manner due to the backing fibers pullout—evident in fig. 4.8 (a). It shows that matrix in the backing has failed at a lower load, and was followed by fibers stretching.

However, in the similar BFFB configuration of double layer nylon–SC 79 laminate from graph (a) of fig. 4.2, the ductile fashion did not happen as in fig. 4.7, 1L–SC 79, Backing in tension. This was due to the fact that they were broken instantaneously at very high load values as shown by the drop to zero load values although the backing fibers were stretched—evident in fig. 4.4 (a).



(a) Backing under expansion



(b) Face fiber under expansion

Figure 4.8: Fiber stretch in single layer Nylon–SC 79 laminates

On the other hand, samples with vinyl ester as resin did not exhibit full brittle failure. From fig. 4.7, 1L–VE, Nylon in tension, the initial drop in load signifies the failure of outer layer nylon material. Thus the load value at the drop, 170N, is the resistance offered by the backing layer. It is to be observed that when the same samples tested with backing in tension mode (1L–VE, Backing in tension), they exhibited the same approximate maximum load resistance of 170N. Hence, when SC 79 is employed, it embrittles nylon at the cost of higher strength and degrades the backing performance compared to vinyl ester specimens.

Table 4.3 shows the flexural results of single nylon laminates with two matrices. It could be observed that the flexural strength values of single layer nylon laminates are closely comparable with the two layer nylon laminates. This shows clearly that the outer layer material is the decider of the flexural strengths irrespective of the number of laminates used.

<b>Carpet</b>	<b>Resin</b>	<b>Configuration</b>	$\sigma_{flexure-1L}$
Nylon	SC 79	Nylon in tension	$37 \pm 2.2$
Nylon	SC 79	Backing in tension	$23 \pm 1.1$
Nylon	VE	Nylon in tension	$29 \pm 0.9$
Nylon	VE	Backing in tension	$26 \pm 0.9$

Table 4.3: Flexural strength of single layer nylon laminates.

## 4.2 Screw Pullout Strength

### 4.2.1 Nylon laminates – two layers

Figure 4.9, (a) and (b), shows the trend of the screw pullout load versus screw displacement graph for single and two layer nylon based laminates with partial and full shearing of the top layer. The results from the nylon laminates, graph ‘a’, show that the SC 79 laminates reached its ultimate load at a screw displacement equivalent to screw pitch length. This

suggests that the failure is instant, or in other words, brittle. However, there is a significant difference in peak load between BFFB and FBBF configurations when top layer is not fully sheared (graph 'a'). While the vinyl ester laminates did exhibit some ductility before reaching the ultimate load. Unlike the SC 79 laminates, these laminates did not show any peak load difference between the two laminate configurations.

It should be understood that with the screw pullout in the existing designed setup, the top layer material does not undergo a full shear failure when compared to the bottom layer; Full shearing of top layer in the designed setup can be achieved with the help of a washer; The total pullout load is shared by all the 4 layers in some proportion depending on the individual layer strengths [35, 37]. Table 4.4 shows two different screw pullout strength of two layer laminate samples:  $\sigma_{SP-2L_1}$ —top layer with half shear and  $\sigma_{SP-2L_2}$ —top layer with full shear (with washer).

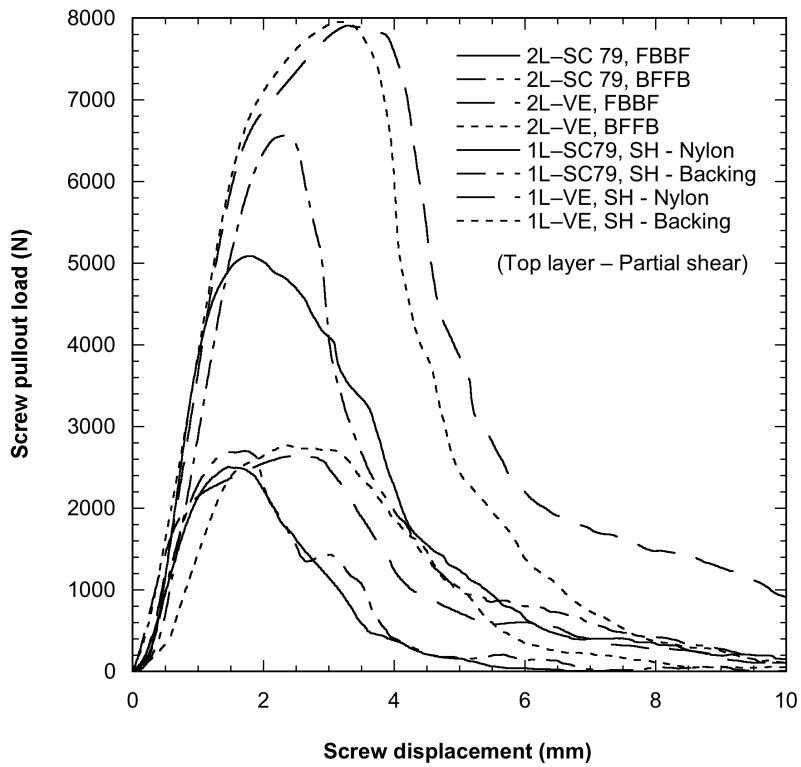
#### **Two layer nylon specimen screw pullout strengths – top layer partially sheared, $\sigma_{SP-2L_1}$**

In accordance with the graph (a) of fig. 4.9, the SC 79 laminates showed a (6 MPa) difference in strength between the two layer-style versions, while the vinyl ester specimens showed nil variation. The lowest strength value in the FBBF configuration was due to the fact that the face fiber at the top did not undergo full shear failure, and in addition, the high temperature curing of SC 79 degraded the backing that resulted in lower performance.

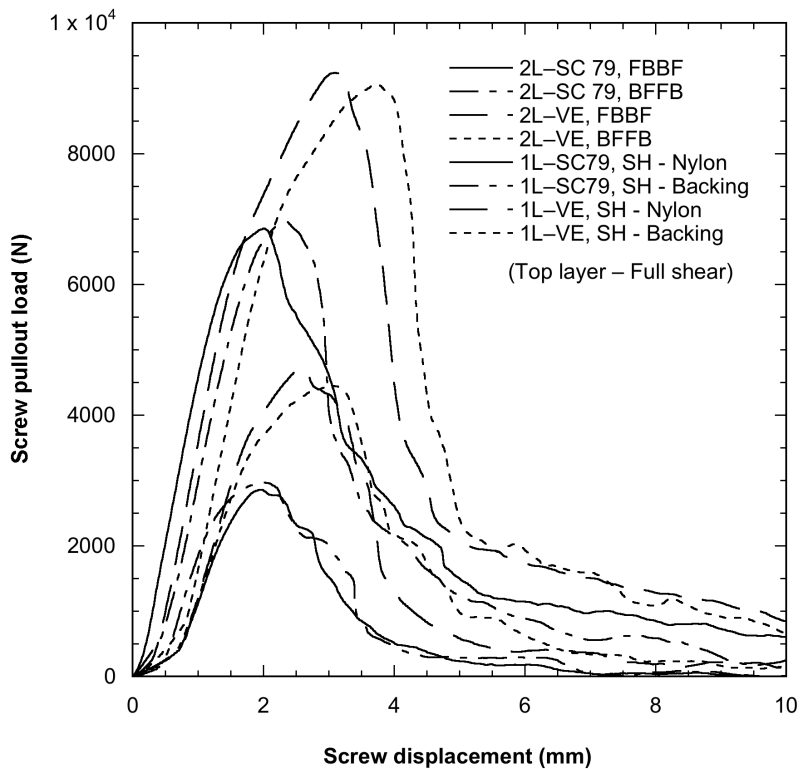
On the other hand, with the BFFB, the face fibers had undergone full shear—taking into account of degradation coupled with no full shear of outer backing layer—that led to an increased screw pullout resistance. However, vinyl ester specimens have better strength and less variation than the SC 79 laminates.

#### **Two layer nylon specimen screw pullout strengths – top layer fully sheared, $\sigma_{SP-2L_2}$**

A washer of size: OD-1.5”, ID-0.285”, and thickness 0.12”, was used to get full shear failure in laminates. Figure 4.10 shows the two layer nylon–SC 79 FBBF laminate with



(a) Nylon – Single and two layer laminates with partial shearing in top layer



(b) Nylon – Single and two layer laminates with full shearing in top layer

Figure 4.9: Load–displacement graph of single and two layer nylon laminates, screw pull-out

washer in place. Figure 4.11 (a) and (b) clearly shows the difference in top layer failure pattern with and without the incorporation of a washer in the screw pullout testing. Also, from table 4.4, it could be noted that, the pullout strengths with washer,  $\sigma_{SP-2L_2}$ , show that, a significant difference was achieved if the top layer was fully sheared when compared with a partially sheared top layer.



Figure 4.10: Two layer Nylon–SC 79 FBBF laminate with a washer in place

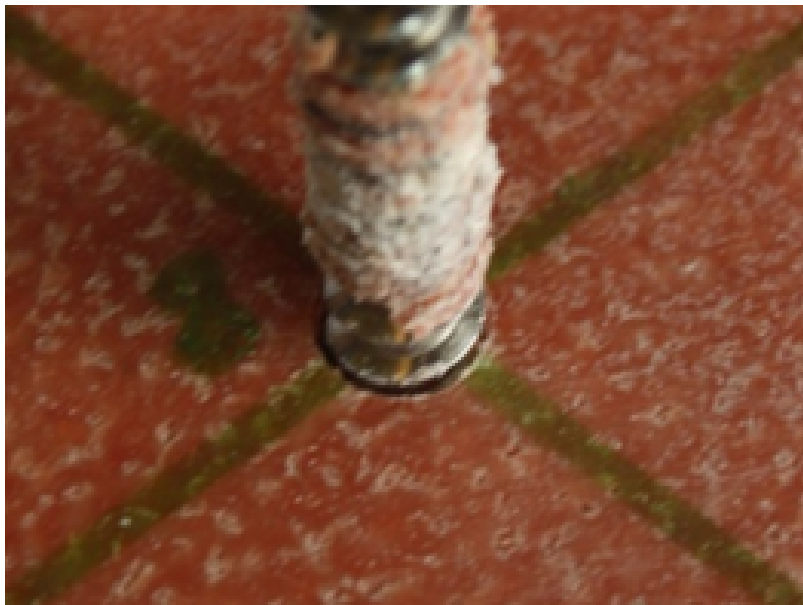
Furthermore, for a particular carpet–polymer laminate, a same pullout strength was achieved irrespective of the laminate configuration. Screw pullout strengths of vinyl ester specimens showed a 33% increase against SC 79 specimens.

#### 4.2.2 Olefin laminates – two layer

Though the olefin laminates are made with same compression ratio as nylon laminates, the final laminates are half the thickness of the nylon laminates. Nonetheless, from fig. 4.12, graph (a) and (b), a similar trend in curve-form and differences with SC 79 and vinyl ester



(a) Top layer in partial shear, FBBF



(b) Top layer in full shear, FBBF

Figure 4.11: Partial and full shearing of top layer in two layer Nylon–SC 79 laminates

could be seen against that of two layer nylon laminates.

**Two layer olefin specimen screw pullout strengths – top layer partially sheared,  $\sigma_{SP-2L_1}$**

As both the fiber and backing material are same here, and the number of threads in engagement is half, from table 4.4, only a little increase in strengths could be observed between BFFB and FBBF when compared to nylon based two layer laminates. However, specimens made with vinyl ester show a significant increase in strength against SC 79 specimens.

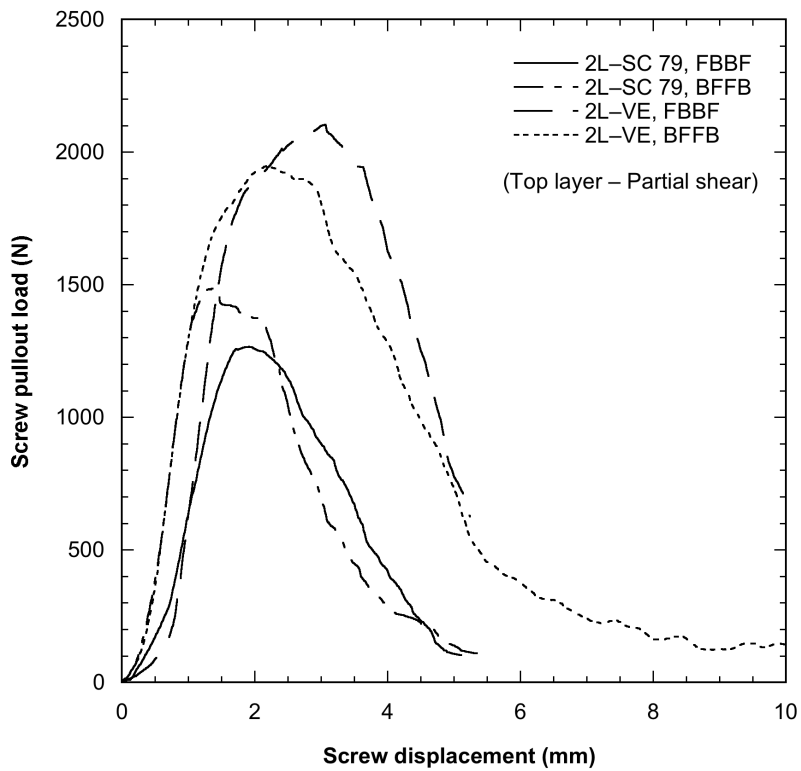
**Two layer olefin specimen screw pullout strengths – top layer fully sheared,  $\sigma_{SP-2L_2}$**

From table 4.4, it could be observed that the pullout strengths with washer,  $\sigma_{SP-2L_2}$ , show that a 95 % increase was achieved if the top layer was fully sheared when compared with a partially sheared top layer. In addition, similar to two layer nylon laminates, a same pullout strength was achieved irrespective of the laminate configuration. Screw pullout strengths of vinyl ester specimens showed a 95% increase against SC 79 specimens.

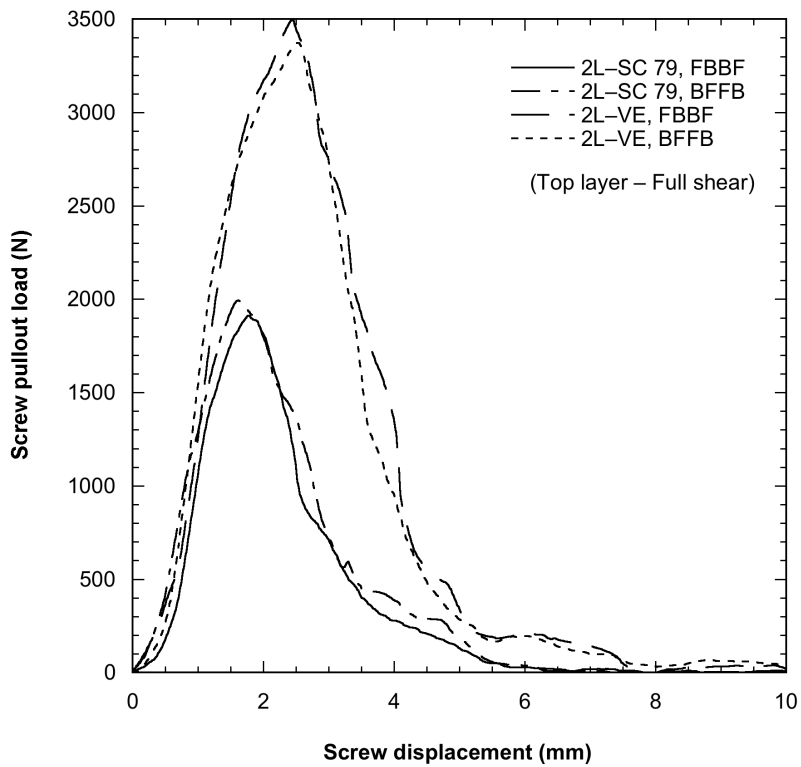
Carpet	Resin	Configuration	$\sigma_{SP-2L_1}$	$\sigma_{SP-2L_2}$
Nylon	SC 79	FBBF	25 ± 1.1	29 ± 2.4
Nylon	SC 79	BFFB	31 ± 1.3	30 ± 1.9
Nylon	VE	FBBF	33 ± 1.8	40 ± 1.4
Nylon	VE	BFFB	34 ± 2.6	40 ± 2.2
Olefin	SC 79	FBBF	10 ± 1.5	17 ± 1.3
Olefin	SC 79	BFFB	13 ± 1.6	19 ± 0.5
Olefin	VE	FBBF	18 ± 1.4	35 ± 1.8
Olefin	VE	BFFB	18 ± 3.3	35 ± 1.3

Table 4.4: Screw pullout strength of two layer nylon and olefin laminates.





(a) Olefin – Two layer laminates with partial shearing in top layer



(b) Olefin – Two layer laminates with full shearing in top layer

Figure 4.12: Load–displacement graph of two layer olefin laminates, screw pullout

### 4.2.3 Nylon laminates – single layer

The objective of the screw pullout testing on single layer nylon laminate was to understand what causes the difference in strength in SC 79 laminates. Single layer laminates were made with same compression ratio as two layer laminates. Thus the final laminate thickness is around 0.25 inches. Screw pullout performance of single nylon laminate specimens is super-imposed with two layer nylon laminates in figure 4.9. A trend in the shift of the peak loads on all the single and two layer vinyl ester samples could be seen against SC 79 samples. This shift in peak again confirms the ductile nature of vinyl ester samples.

#### **Single layer nylon specimen screw pullout strengths – top layer partially sheared,**

$$\sigma_{SP-1L_1}$$

Table 4.5 shows that there is no significance difference in strength values among the different laminates, as there is only a little difference between the SC 79 and vinyl ester matrix laminates. But when comparing with two layer nylon laminates, there seems a larger reduction in screw pullout strength. This may be due to the fact that, of the two layers, mainly the bottom layer contribution was significant in the total screw pullout strength, as the top layer did not undergo full shear.

#### **Single layer nylon specimen screw pullout strengths – top layer fully sheared, $\sigma_{SP-1L_2}$**

From table 4.5, it could be observed that, the pullout strengths with washer,  $\sigma_{SP-1L_2}$ , show that, pullout strength of single layer laminates matches exactly with that of two layer laminates. Thus fig. 4.9, graph (b), shows that, for a same screw pullout strength, the total load sharing of the single layer nylon laminates is as much half as that of the two layer laminates. However, there exists 20% and 35% difference between  $\sigma_{SP-1L_1}$  and  $\sigma_{SP-1L_2}$  in nylon–SC 79 and nylon–vinyl ester samples respectively.

Albeit the values of screw pullout strength differ from carpet and resin types, they are yet a substantial indicator of the materials that could be joined using standard screw-based

<b>Carpet</b>	<b>Resin</b>	<b>Configuration</b>	$\sigma_{SP-1L_1}$	$\sigma_{SP-1L_2}$
Nylon	SC 79	Screw head facing nylon	$24 \pm 0.6$	$30 \pm 1.4$
Nylon	SC 79	Screw head facing backing	$24 \pm 0.9$	$29 \pm 1.5$
Nylon	VE	Screw head facing nylon	$27 \pm 3.6$	$39 \pm 3.2$
Nylon	VE	Screw head facing backing	$26 \pm 2.8$	$38 \pm 2.2$

Table 4.5: Screw pullout strength of single layer nylon laminates.

fasteners.

### 4.3 Density and Thermal Conductivity

The density of the samples was found to be  $1.1 \text{ gms/cm}^3$  irrespective of the type of carpet and resin used. Also, the density of the neat resins is between  $1.03\text{--}1.12 \text{ gms/cm}^3$ . This shows that when the same resins were employed on the two carpets the resulting density was not affected by the carpet addition. Figure 4.13 shows the temperature distribution plot of copper rods and the given specimen from hot side temperature to cold side temperature as a function of distance. The hot and cold side linear curves were extrapolated to determine the temperatures,  $T_{hot}$  and  $T_{cold}$ , at the specimen interfaces. Using this, a slope was drawn in the middle. This slope shows the temperature gradient of the sample and was utilized to find the thermal conductivity of the given specimen.

The density and thermal conductivity of the different carpet-polymer samples with different laminate configurations are listed in table 4.6. As listed, the material constituents or laminate configurations did not have an effect on the material density or the thermal conductivity. This is good, as it allows flexibility in design. Thus different material strengths can be achieved by changing constituents or laminate configurations without paying a single penalty on the physical properties.

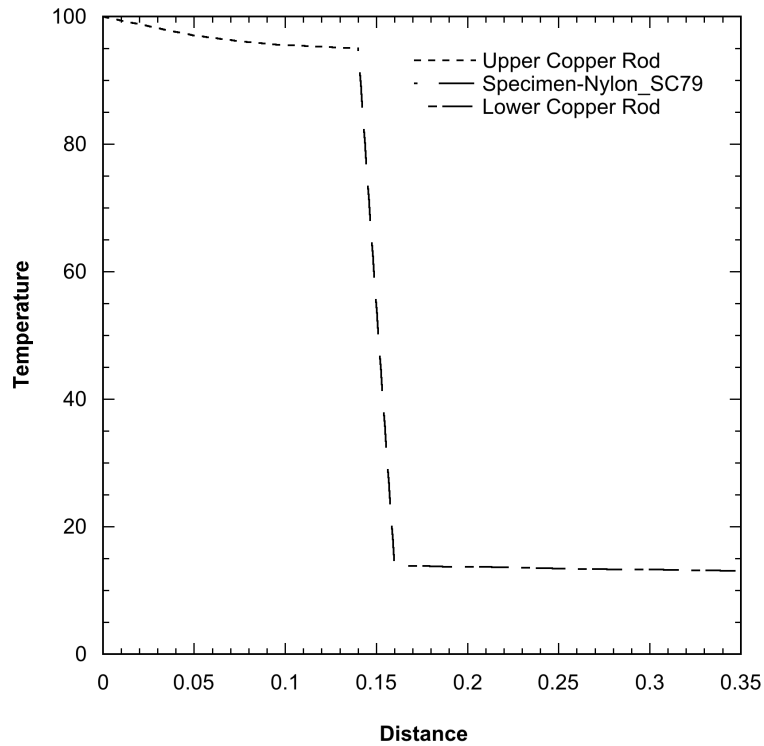


Figure 4.13: Thermal conductivity graph of a nylon-SC 79 laminate

Carpet	Resin	Configuration	$\rho$	$k$
			(gms/cm <sup>3</sup> )	(W/mK)
Nylon	SC 79	FBBF	1.1 ± 0.1	0.7 ± 0.05
Nylon	SC 79	BFFB	1.1 ± 0.1	0.8 ± 0.05
Nylon	VE	FBBF	1.2 ± 0.2	0.7 ± 0.03
Nylon	VE	BFFB	1.2 ± 0.2	0.7 ± 0.04
Olefin	SC 79	FBBF	1.1 ± 0.1	0.7 ± 0.05
Olefin	SC 79	BFFB	1.1 ± 0.2	0.6 ± 0.04
Olefin	VE	FBBF	1.1 ± 0.2	0.6 ± 0.03
Olefin	VE	BFFB	1.1 ± 0.2	0.7 ± 0.04

Table 4.6: Density and thermal conductivity values of two layer nylon and olefin laminates.

#### **4.4 Fiber Volume Fraction**

The weight measurements, and weight and volume fractions for all the discussed carpet–polymer structural laminates are listed in table 6.1 and table 6.2, respectively. From table 6.2, it can be inferred that for all the samples the carpet fibers are occupying approximately 33% and the remaining 67% are matrix by volume. Also, the higher percent (72%) of vinyl ester matrix by volume with olefin fibers shows higher wetting tendency compared to other laminates.

## CHAPTER 5

### CONCLUSIONS

Carpet based structural laminates were fabricated using simple vacuum assisted resin infusion technique. This technique did not require any energy intensive processes that other conventional methods require. Utilization of three dimensional architecture of carpet fibers was achieved to get superior mechanical properties with low cost process.

The fabricated laminates were studied for two mechanical properties: flexural strength and screw pullout strength. From the flexural strength results, it was apparent that the flexural strength of a Carpet–polymer laminate was mainly affected by the outer layer material that is under expansion. The difference in curing temperature, as between SC 79 and vinyl ester, changes the failure property of the material to be either a brittle or ductile. Further, laminates with SC 79 degrades the olefin backing layer which leads to quick destruction of total laminate. However, at lower ultimate loads, the criss-crossed olefin backing fibers prevent brittle failure of composites by undergoing stretching—as the case of quasi-brittle of two layer olefin laminates. This was witnessed in the single layer nylon laminates in addition to the two layer nylon and olefin laminates. The difference in the material failure response showed that the relative toughness of the structural laminates could be controlled very effectively by an appropriate choice of the infusion resin. Thus the flexural properties allow for comparison with other structural materials.

As for the screw pullout test measurements, two different types of screw pullout strength measurements were carried out—partial and full shear in the outer layer. Full shear mode test was performed with the help of a washer. From the results, it was found that tests with outer layer partial shear exhibited lesser strength than tests with fully sheared lam-

inates. Moreover, with the partial shear mode, a notable difference was present between the stacking configurations in case of SC 79 laminates. Since the outer layer materials did not undergo full shearing, their contribution towards the pullout load sharing was minimal. Hence the strength of the materials were majorly determined by the successive layers. In addition to the above, the degradation of backing material due to the higher temperature curing process, as with the case of SC 79, gave lesser strength with FBBF configuration. With the vinyl ester resins, there was no such high temperature process, and that left the backing unaffected with no difference between the configurations. While the laminates tested with full shear exhibited same screw pullout strength irrespective of the stacking configuration and the number of layers employed.

In all in all, the nylon face fibers have better flexural and screw pullout properties than olefin backing and face fibers. However, when comparing to the post-consumer carpet waste based nylon structural laminates [16], they do not vary much in strength. Although the screw pullout strengths differ from resin types and layer styles, they are yet a substantial indicator of the materials that could be joined using standard screw-based fasteners.

The physical properties—density and thermal conductivity—show that the material constituents or laminate configurations did not have an effect on the carpet–structural laminate density and thermal conductivity. Moreover, there is no significant variation in density between neat resin and carpet–polymer samples. This is advantageous, as it allows flexibility in designing the combination of material constituents. Thus, different material strengths could be achieved by changing constituents and laminate configurations without paying a single penalty on the physical properties.

Fiber volume fraction experiments were done and results have been reported. From the results it was seen that matrix occupied 67% by volume and the remaining was carpet. The olefin fibers with vinyl ester matrix showed higher matrix volume percentage and that signifies that it has higher wetting tendency.

In short, studies from the virgin carpet based laminates show that there is no apparent

difference in the strength and physical properties with that of post-consumer carpet waste based laminates [16]. Hence, the technique to convert the post-consumer carpet waste into structural laminates using the vacuum assisted resin infusion technique would be a promising work for the recycling and the composite market.



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## CHAPTER 6

### APPENDIX

<b>Carpet</b>	<b>Resin</b>	<b>Config.</b>	<b>Face fibers</b>	<b>Backing</b>	<b>Raw carpet</b>	<b>Matrix</b>	<b>Composite</b>
Nylon	SC 79	FBBF	3.556	2.448	6.004	11.537	17.541
Nylon	SC 79	BFFB	3.056	2.246	5.302	11.006	16.308
Nylon	VE	FBBF	3.272	2.734	6.006	12.768	18.774
Nylon	VE	BFFB	3.710	2.950	6.660	12.635	19.295
Olefin	SC 79	FBBF	1.160	2.066	3.226	4.812	8.038
Olefin	SC 79	BFFB	1.084	1.996	3.080	4.224	7.304
Olefin	VE	FBBF	1.098	2.374	3.472	5.302	8.774
Olefin	VE	BFFB	1.308	2.580	3.888	5.594	9.482

Table 6.1: Weight measurements of two layer laminates in grams.

<b>Carpet</b>	<b>Resin</b>	<b>Config.</b>	$w_f$	$w_b$	$w_c$	$w_m$	$v_f$	$v_b$	$v_c$	$v_m$
Nylon	SC 79	FBBF	0.20	0.14	0.34	0.66	0.19	0.17	0.36	0.64
Nylon	SC 79	BFFB	0.19	0.14	0.33	0.67	0.18	0.17	0.35	0.65
Nylon	VE	FBBF	0.17	0.15	0.32	0.68	0.17	0.16	0.33	0.67
Nylon	VE	BFFB	0.19	0.15	0.34	0.66	0.18	0.17	0.35	0.65
Olefin	SC 79	FBBF	0.14	0.26	0.40	0.60	0.17	0.17	0.34	0.66
Olefin	SC 79	BFFB	0.15	0.27	0.42	0.58	0.17	0.17	0.34	0.66
Olefin	VE	FBBF	0.13	0.27	0.40	0.60	0.14	0.14	0.28	0.72
Olefin	VE	BFFB	0.13	0.27	0.40	0.60	0.15	0.15	0.30	0.70

Table 6.2: Weight and volume fractions of two layer laminates.

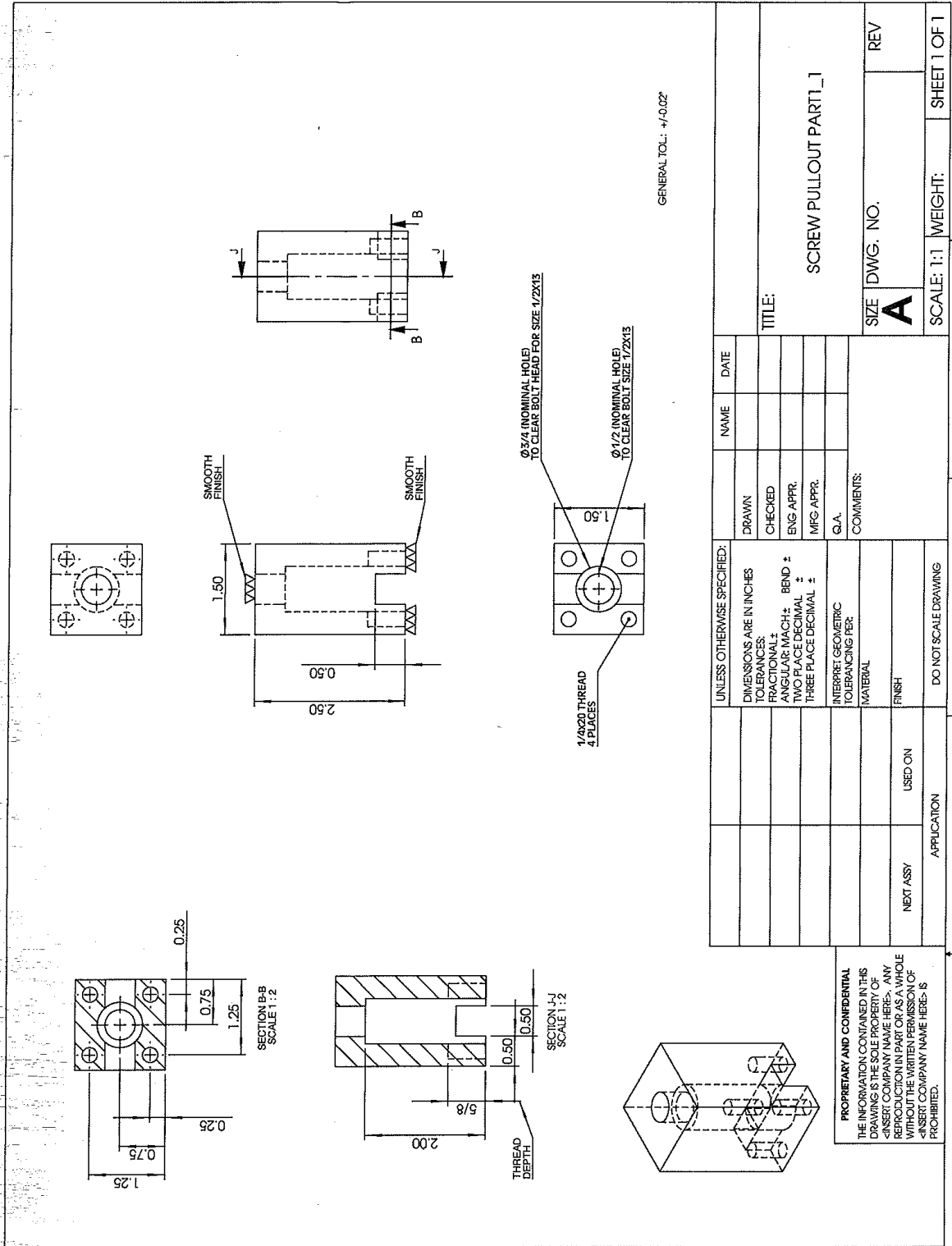


Figure 6.1: Screw pullout fixture, top-part 1-1

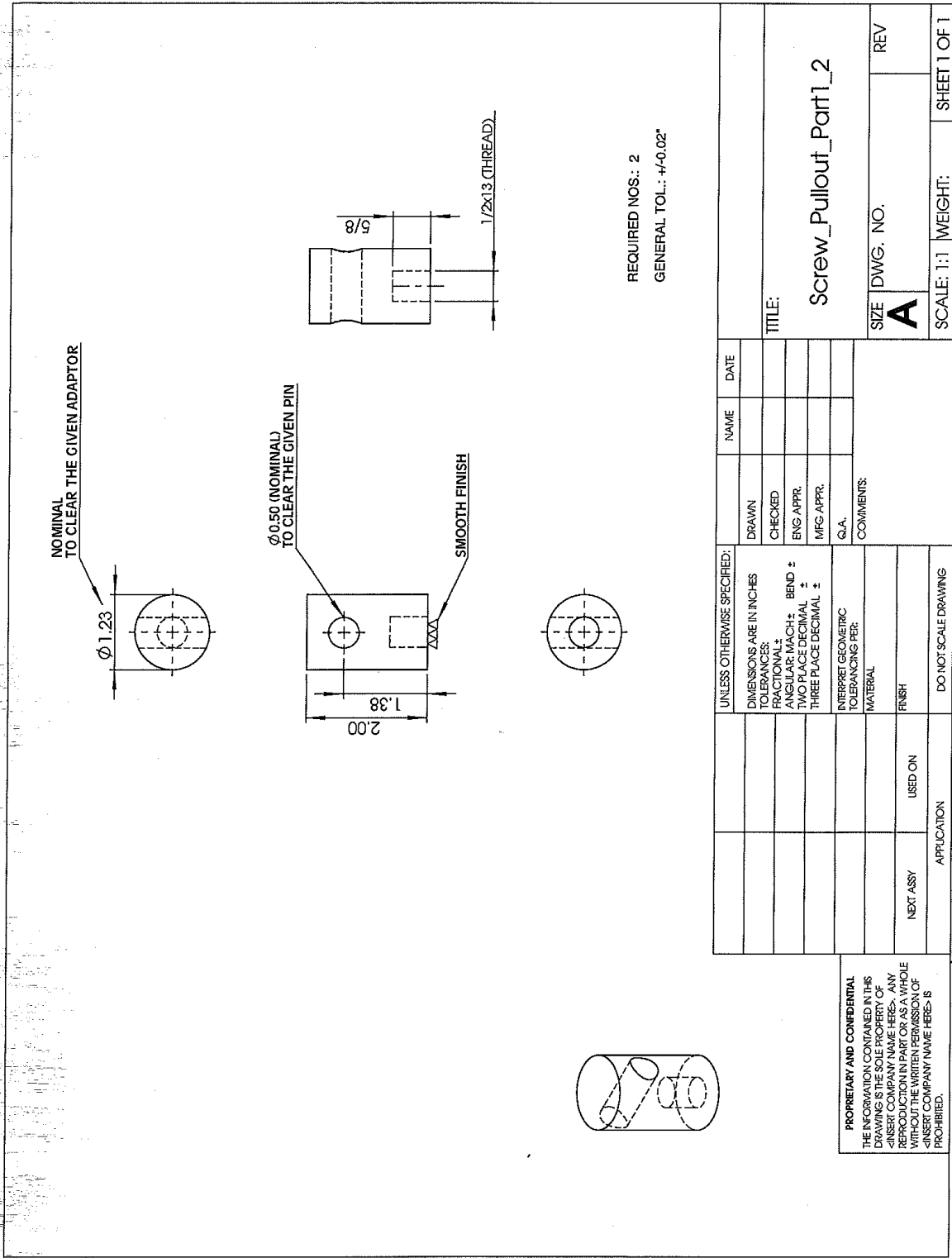


Figure 6.2: Screw pullout fixture, top-part 1-2



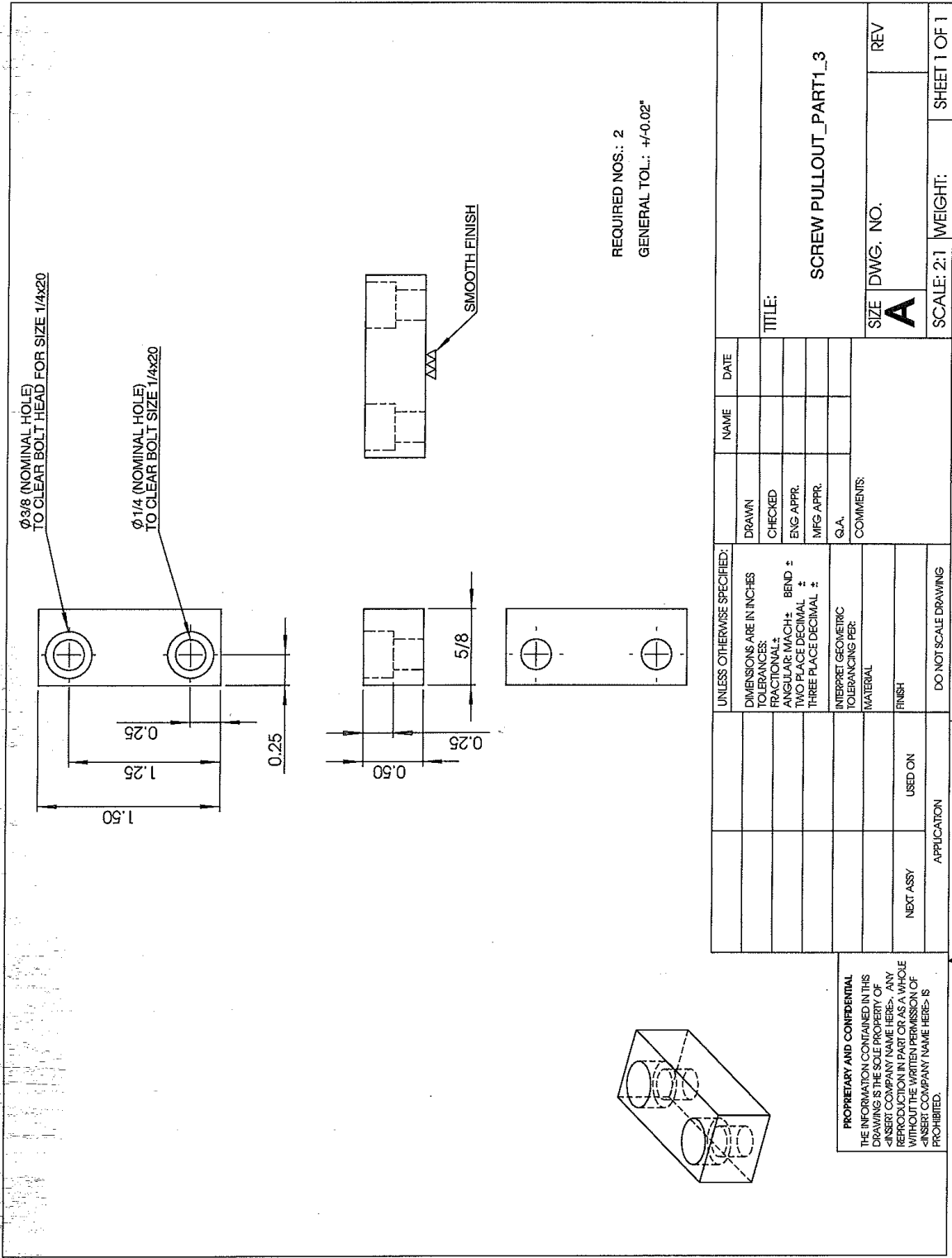


Figure 6.3: Screw pullout fixture, top-part 1-3



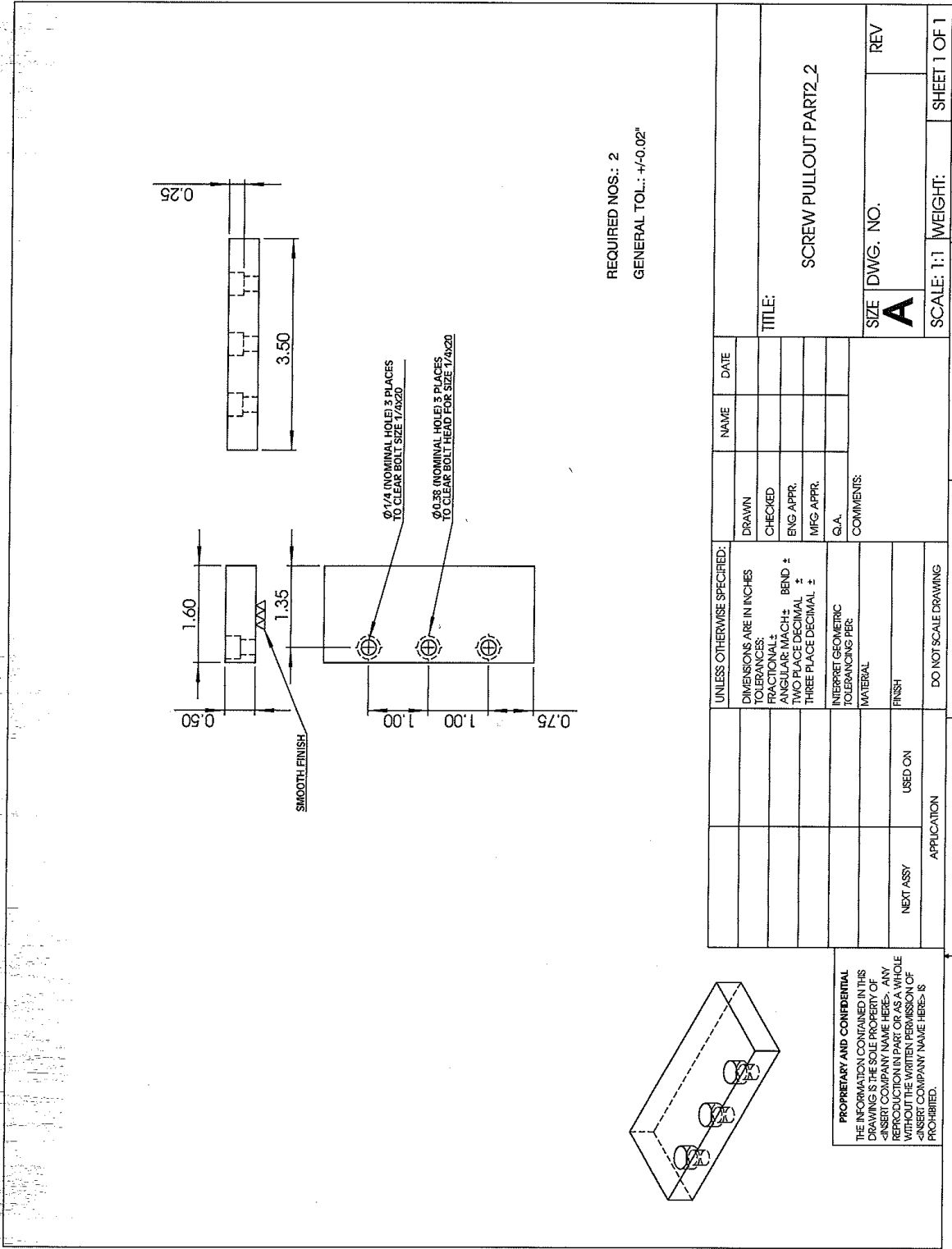


Figure 6.5: Screw pullout fixture, Bottom-part 2-2

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Post-consumer carpet waste recycling is in its infant stage in the United States. Currently, a number of initiatives have been taken to recycle carpet waste with an effort to divert away from landfill and incineration. Some of the current and previous methods suggest that waste carpets can be chopped or shredded and reused, or melt blended to form into a desired product shape. However, none of these methods was simple enough to reduce the energy and the total cost involved. A recent technique proposed by Singh *et al.* (Patent pending), suggests the use of simple resin infusion technique to convert the post-consumer carpet waste into useful structural laminates. The initial study that was done on nylon fiber based post-consumer waste carpet-structural laminates, using vacuum infusion technique, showed promising results on mechanical and physical properties. In an attempt to perceive the deterioration of carpet fibers upon its long usage, this study has been primarily aimed at establishing reference properties using virgin carpet-polymer based composites that can further be utilized to create a comprehensive database.

Most of the manufactured carpets today consist of one of these six pile fibers: nylon, olefin, polyester, acrylic, cotton, or wool. Of these, nylon and olefin are by far the best all-around materials with better multi-resistant properties. This study is directed at utilizing the three dimensional architecture of virgin nylon and olefin fiber based carpets, and converting them into realtime-application based structural laminates. Two VARTM-able epoxy resins, SC 79 and vinyl ester, are employed as matrix for making such laminates. Materials are fabricated using a simple, vacuum infusion based, fabrication technique. Subsequently, these structural laminates are tested for different mechanical and physical properties. Using the test results, a reference property is established, and a clear understanding of the failure mechanisms of the discussed carpet-polymers with two different laminate design configuration styles, BFFB and FBBF, is achieved. [Note: BFFB – Backing-Face fiber-Face fiber-Backing, FBBF – Face fiber-Backing-Backing-Face fiber.]

ADVISOR'S APPROVAL: Dr. Raman P. Singh