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Abstract

Common Fibers, a company founded by Cal Poly alumni, produces carbon fiber wallets. The invention of their built-in fiber-matrix composite hinge reduces the need for extra complexity and added mass that is inherent with using standard metal hinges to join standard composite panels. Replacing the polyurethane tape on the wallet hinge allows for improved protection while maintaining flexibility and other performance properties is critical to the success of such a design. The most important material property in this project is the bond strength between carbon fiber and a variety of flexible resin candidates. The silicone and urethane based elastomer resins include CF19-2615, Encapso K, Flex-It 10, and Econ 80, which were chosen as a partially representative sample of the wide range of flexible resin systems. A fiber bundle pull out test was designed and implemented to directly and quantitatively measure and compare fiber-matrix bond strength. Additionally, two separate methods for applying the resin to a hinged panel were investigated: resin transfer molding (RTM) and vacuum bagging. A modified RTM was designed and fabricated in-house, and a standard vacuum bagging setup was assembled. In order to determine the best overall application method, several criteria were selected based on the wetting of the fibers and the overall aesthetic feel and appearance. Based on these criteria, the best and most efficient method is vacuum bagging. Econ 80 displayed a significantly higher mean bond strength compared to all other resins.

Keywords: Composite, Hinge, Carbon Fiber, Flexible Resin, Bond Strength, Resin Transfer Molding, Vacuum Bagging, Materials Engineering, Fiber Bundle Pull Out Test
1. Background

Composites are material systems composed of fibers and a matrix. The fibers act as the reinforcement and carry the load. The matrix, on the other hand, transfers the load to the fibers, provides the component’s shape, and protects the fibers. There is a large variety of fibers and matrices to choose from when manufacturing a composite. The choice of these constituents is imperative to the properties need and the application. Material selection specifically depends on the loading, mode of loading, service life, service environment, interaction with other components, manufacturing process, and cost [1]. The cost includes not only the material cost, but also the manufacturing and assembly cost of the final product. For many applications weight reduction is critical. The two most common fibers used in applications are glass and carbon fibers. Glass fiber reinforced polymers (GFRP) are the cheapest option, but carbon fiber reinforced polymers (CFRP) have greater tensile strength and stiffness. Carbon fibers cost 5 times as much as glass fibers [1]. These two composite systems are used in a variety of applications including aircraft, boat hulls, and automotive parts. Composite laminates can come in a variety of forms including unidirectional continuous fibers, bidirectional continuous fibers, multidirectional continuous fibers, unidirectional discontinuous fibers, and random discontinuous fibers.

1.1 Carbon Fiber

The structure of carbon fiber consists of both amorphous and graphitic carbon. The carbon atoms are arranged in parallel planes with each plane consisting of interconnecting regular hexagons in which the carbon atoms are at the corners. Carbon atoms are bonded covalently in plane. The parallel planes are connected by weak secondary bonds called van der Waals forces, allowing the planes to slide by each other. The resulting carbon fibers are highly anisotropic. The structure of a typical carbon fiber is folded sheets (ribbons) of carbon graphitic planes (Figure 1).
1.1.1 Carbon Fiber Manufacture

Both textile and pitch precursors are used to manufacture carbon fiber. The most common precursor is polyacrylonitrile (PAN), a synthetic semi-crystalline organic polymer resin (Figure 2). It does not melt under normal conditions, even though it is a thermoplastic [3]. Besides carbon fibers, a large variety of products such as filtration membranes, hollow fibers for reverse osmosis, fibers for textiles, and oxidized flame retardant fibers are produced from PAN [3].

The manufacture of carbon fiber begins with a solution of PAN that is wet spun and stretched followed by heat stabilization in air at 200°C-300°C for about 2 hours. The resulting PAN filament structure consists of a rigid ladder structure with a high glass transition temperature. The PAN filaments are then heated and stretched at 1000°C-2000°C for about 30 minutes in a process called carbonization. To avoid burning
fibers, the process is done in an inert atmosphere \([4]\). “The high temperature causes the atoms in the fiber to vibrate violently until most of the non-carbon atoms are expelled \([4]\).” In order to prevent shrinking and improve molecular arrangement, tension is maintained on the filaments \([1]\).

The last phase, called graphitization, consists of heating the filaments above 2000°C with or without stretching. Unstretched carbon fibers have a relatively high-modulus, whereas stretched fibers have improved tensile strength. By removing defects, such as vacancies or impurities, and controlling crystallinity, other properties of carbon fibers can also be improved \([1]\). A less common and low cost precursor is pitch, a byproduct of petroleum refining or coal coking. The basic forms of commercially available carbon fiber are long and continuous tow, chopped (6–50 mm long), and milled (30–3000 mm long) \([1]\). The tows may also be used to produce various styled two-dimensional woven fabrics \([1]\).

1.2 Polymer Matrix

Polymers, long chained molecules containing one or more repeating units of atoms, are joined together by strong covalent bonds. Common polymers are divided into two categories: thermosets and thermoplastics. Unlike thermosets, thermoplastics are not chemically joined together. Weak secondary bonds, such as Van der Waals bonds and hydrogen bonds, hold them in place. The molecules can slide by each other with the application of heat. Unlike thermosets, thermoplastics can be heat-softened, melted, and reshaped as many times as desired. In thermosets, the molecules are chemically joined together by crosslinks that are formed during the polymerization reaction known as curing. These crosslinks are primary molecular bonds that join the polymer chains together, increasing strength and stiffness. Crosslinking behavior inhibits the polymer from being re-melted, and contributes significantly to the mechanical properties of the polymer (Figure 3).

![Cross-links](image)

**Figure 3.** Structure of thermoplastic vs thermoset \([5]\).
The most widely used thermoset matrices are polyester resin and epoxy. Typically resin systems consist of a base and a hardener. When mixed together, the resin will cure at a particular temperature and time. Epoxy has many advantages over other thermosets in that there is a wide variety of properties, absence of volatile matter during cure, low shrinkage during cure, excellent chemical resistance, and excellent adhesion to fibers [1]. However, epoxy is more expensive and has a long cure time. The most commonly used thermoplastic matrix is polyether ether ketone (PEEK). In addition to lower water absorption, PEEK has a high fracture toughness that is 50-100 times higher than that of epoxies [1].

1.2.1 Flexible Resin Matrix

Elastomers are amorphous polymers characterized by their remarkable ability to stretch and flex elastically under an applied load for several hundred percent strain before experiencing permanent deformation (Figure 4) [6].

![Stress-strain curve](image)

**Figure 4.** Stress-strain curve showing the tensile behavior of two elastomers, vulcanized rubber and poly-glycerol sebacate (PGS), compared to a standard semicrystalline thermoplastic, poly-4-hydroxybutyrate (P4HB) [6].

This unique property is directly related to the crosslinked structure of the polymer on the molecular level. The tangled polymer chains are held together by primary chemical bonds, which allow the elastomer to retain its permanent shape following elastic deformation. These chemical bonds are commonly formed during processing and curing by introducing a crosslinking agent to an elastomeric base polymer. The crosslinks act as a bridge between chains and promotes chemical restructuring to form additional primary bonds (Figure 5) [7].
Polysiloxanes (or silicones), named as such because of their silicon and oxygen content, are among some of the more intriguing elastomers currently in use. They are present in cosmetics, cleaning products, medical equipment, and many other common applications. The versatility of siloxanes is a result of their unique structure, namely the composition of their polymer chains. Most common polymers consist of chains with carbon-based backbone structures, however siloxanes are composed of alternating silicon and oxygen atoms. Silicon has similar bonding characteristics to carbon, however one key difference is the energy required to rotate about a bond. Rotation of carbon-carbon bonds require a significant amount of energy (13.8 kJ/mol for polyethylene, 19.6 kJ/mol for PTFE), several times the required input to rotate Si-O bonds. This difference originates from the atomic bonding patterns of Si and O. Si-O bonds have an unusually large bond angle compared to typical sp³ hybridized bonds, because of electron interaction between silicon and oxygen. This results in a shorter bond length than predicted and low energy requirements to deform the bond angle [8]. This structural difference gives polysiloxane materials an even greater range of flexibility compared to standard polymers.

In typical fiber-reinforced polymer matrix composites the matrix is mainly responsible for transferring any applied loads to the fibers via the interface between the two materials. The quality of this bond is crucial in determining successful fiber-matrix combinations as it dictates the resistance of the composite to fail from interfacial shear stresses.

Figure 5. A chemical reaction between a siloxane base and a crosslinker showing the resulting crosslinked structure for a silicone elastomer [7].
1.3 Application Background

Common Fibers (Kent, WA), a start-up company comprised of Cal Poly graduates, has been producing carbon fiber wallets on the consumer level since March 2014 when they launched a Kickstarter campaign to fund their initial production run [9]. The traditional wallet design requires a material and shape that allow the wallet to bend and flex significantly and return to its folded state as part of its main function. Carbon fiber is typically considered for structural applications due to its exceptionally high specific stiffness, a property that does not directly lend itself to the requirements of a wallet. Common Fibers has resolved this issue by inventing a hinge in the carbon fiber sheet that allows for near 360° flexibility while preserving much of the strength of the original panel [10]. This hinge is fabricated by using a CO2 laser to selectively ablating the polymer matrix across a portion of the composite panel. This process leaves the bare fiber intact and leaving a region of flexibility comparable to that of a wallet. This processing method and end product, named the CF-Lex™ hinge, has been patented by Common Fibers and has become a staple of their products and future designs (Figure 6) [11].

![Figure 6. Common Fibers standard carbon fiber wallet design, complete with hinge [11].](image)

The initial goal of the Kickstarter campaign was to provide Common Fibers with funding to pursue additional applications of their CF-Lex™ hinge. The wallet campaign was so successful that it has allowed them to continue producing wallets and explore other applications concurrently. These additional prospective applications include carbon fiber skis that can fold up for ease of transportation and several hinged components in non-critical aerospace components like tray tables, overhead compartments, and flight attendant carts. This novel hinge design would eliminate the need for metal hinges affixed to composite doors and panels, and allow manufacturers to streamline their processes.
One of the first steps in determining the feasibility of a fiber-reinforced composite hinge in applications other than wallets is to obtain and compile information relevant to the various mechanical stresses it will undergo. One property which is of the utmost importance in fiber-matrix composite fabrication is the interaction between the polymer matrix and the fibers, traditionally quantified as the bond strength of the interface. This interaction is primarily dictated by the selection of matrix material and the method by which it is applied to the fibers and subsequently cured.

1.4 Manufacturing Methods

The overwhelming majority of fiber-reinforced composite products and research are present in situations where high specific strength and stiffness are required. When an application requires significant flexibility instead of stiffness from a fiber-matrix composite, however, there are concerns regarding materials selection and processing. Because of this, the testing and application methods designed for a flexible secondary polymer matrix will deviate from most of the available literature in some way. This is further complicated by the fact that the CF-Lex™ hinge has not been extensively tested due to its recent discovery and patented status. The process of selectively removing matrix portions by laser ablation is a relatively new and unexplored field. Most composites are manufactured from a sheet(s) of woven, dry fiber which is fully coated in resin during the molding and curing processes. The Common Fiber hinged wallet samples used in this experiment, however, consist of rigid, cured panels of carbon fiber composite joined by a small section of dry fibers. Given these concerns and requirements, the following resin application methods appear the most promising and feasible.

1.4.1 Resin Transfer Molding

Resin transfer molding (RTM) is the process of infusing liquid resin under pressure into a layer of fibers under compressive forces in a two-part mold and has become an important tool in the hands of many composite manufacturers. As the focus of materials continues to trend towards weight-reducing solutions, the ability to manufacture complex composite structures becomes increasingly important. Resin transfer molding allows the operator to fabricate large 3-dimensional structures with tolerances and finishes that are well suited for numerous areas of application. Typical RTM procedures involve laying up a composite preform onto a rigid metal 2-part mold and sealing layers of fibers, bleeder/breather layers, and release fabrics inside using pressure and/or a sealing gasket (Figure 7) [12].
This compacts the layers to the final desired shape and the rigid structure ensures the proper dimensions are adhered to through the injection and curing stages. Resin is then injected under pressure to force out air and completely impregnate all of the fibers [13]. The injection phase can be supplemented by a vacuum, which pulls resin out of the injection site and throughout the entirety of the mold’s volume. This acts as an additional measure to ensure full fiber wetting [14].

1.4.2 Vacuum Bagging
Vacuum bagging represents an effective application method that can reduce the cost of manufacturing expensive carbon fiber composites. There are no expensive molds or heated presses involved, significantly reducing the machinery costs of fabrication. In vacuum bagging, resin is applied to a fiber reinforcement by hand and then conformed to a given mold between various optional bleeder and breather layers by hand (Figure 8) [15].
The entire setup is enclosed in an airtight bag and then subjected to a vacuum. This process compacts the composite and spreads the resin through the system. Vacuum bagging can exist as a stand-alone technique or it can be supplemented by elevated temperature and outside pressure to decrease curing time or increase impregnation [16]. The advantages of vacuum bagging include the process of applying the vacuum to remove any volatiles that may be present in the resin left over from mixing the hardener and base polymers. This removal decreases the void content of the finished product, increasing strength and quality. Additionally, the constant pressure of the vacuum causes resin to travel through the boundaries between layers in the prepreg, reducing the chance of delamination. Finally, the layers of absorbent material surrounding the prepreg laminate that are inherent in vacuum bagging will absorb a significant amount of resin, reducing the thickness and weight of the finished part and increasing the fiber to resin ratio while maintaining similar mechanical properties [17].

1.4.3 Preliminary Application Method

The limitations inherent with wetting a small strip of dry fibers surrounded by cured matrix are most easily overcome with application methods where the sample can be held firmly between molds that will ensure the resin will adhere to the intended shape of the wallet. In order to implement these design criteria, a method derived from resin transfer molding and hot press molding has been designed as a preliminary test. Initially, resin will be applied to the hinged area using standard hand lay-up procedures. The impregnated samples will be secured between release cloth and a set of aluminum platens, which will be subjected to constant compressive forces using a vertical press. This compression will prevent resin from leaking from the hinged area and aid in producing a superior finish compared to applying resin by hand. A flat profile flush with the rigid carbon fiber panel is essential to preserve the look and feel of the hinge design.

1.5 Fiber-Matrix Bond Strength Testing

Several mathematical models have been developed for characterizing fiber-matrix bond using fracture mechanics and stress-based approaches. However, these models assume the force-displacement testing is done by the microbond or single fiber pull-out test. By using a pull-out test or microbond test, the apparent interfacial shear strength (IFSS) can be calculated using the relationship between the force required to pull out the fiber and the interfacial contact area [18]. However, it is difficult to perform these tests without individual fiber handling capabilities and specialized equipment.
There are other methods to characterize fiber-matrix bond strength. For the fiber bundle pull-out test, instead of a single filament and a single polymer droplet, a fiber bundle and polymer disk are used. There are many steps associated with the test procedure. First, a bundle of fibers is impregnated with resin and the extra resin is wiped off. Next, the bundle is placed in a silicone rubber mold which is filled with resin and cured to form a polymer disk. A test fixture is threaded onto the narrow parallel part of specimen. Then a dumbbell-shaped part of the specimen is formed using a rubber mold and curing process. Fibers protruding from the disk are cut and the bottom of the disk is polished using emery paper (220 grit) without water. The specimen is clamped using screw grips at the dumbbell and loaded against a supporting test fixture, placed in a frame clamped by screw grips, which hold the polymer disk [19]. Lastly, load displacement curves are obtained.

The fiber-matrix interface plays a critical role in determining the performance of fiber-reinforced composites. Macromechanical testing methods, unlike micromechanical tests that measure IFSS, are indirectly related to fiber-matrix adhesion. One of these tests, a transverse fiber bundle (TFB) test can be used to characterize fiber-matrix bond strength. This test method is sensitive to changes at the interface and a major concern is the effect of residual stresses. Residual stress makes the TFB test complex for data interpretation and can cause premature failure of specimens. In polymer fiber reinforced polymer interfaces, bond strength is weaker than the individual strengths [20]. Therefore, under tensile or shear loads, failure of interfaces occurs first and introduces a catastrophic fracture of specimen. Under this circumstance, the failure stress of specimen can be equivalent to the fiber-matrix bonding strength [20].

The manufacture of TFB specimens follows ASTM standard D638 [20]. First, rubber molds in shape of tensile “dog bone” are obtained. Two cuts are made into the side walls in the middle, reaching the bottom of the cavity of the mold. The fiber bundles are arranged parallel by sticking them onto two pieces of plastic tape at two ends to form a single ply of threads. Then it is transversely inserted into the cuts crossing the cavities and the epoxy resin is cast into the cavities and cured. The cured specimen is demolded and milled on both upper and lower surfaces using a surface grinder to reduce surface roughness and remove possible defects (Figure 9).
Figure 9. Tensile specimen with polymer thread bundles embedded in the middle of the specimen [20].

For the mechanical test, an Instron testing machine, longitudinal extensometer (gauge length=50mm), and transverse extensometer are used. A 10kN load cell is used and the crosshead rate is 1mm/min. Specimens which fail outside the fiber bundles are invalid for TFB. Premature failures occur prior to reaching the failure mode of the matrix, accompanied by a sudden drop in tensile stress. Once the applied stress reaches the normal bonding strength of the polymer fiber-epoxy interface, tiny cracks form as a result of debonding at multiple locations [20]. These cracks spontaneously coalesce into larger (critical) cracks, which triggers tensile failure. Theoretically, the stress at specimen failure is equivalent to bonding strength of the fiber-matrix interface

2. Materials and Methods

2.1 Carbon Fiber-Epoxy Matrix Panels

Sample panels and loose carbon fiber tows were produced from aerospace grade T300B carbon fibers, manufactured by Toray Industries, Inc. The carbon fibers were grouped into 3k tows and made into a woven fabric. The resin used in the composite panels was an 820 Epoxy Resin produced by CASS Polymers. The composite panels used to this project were produced by Protech Composites. Common Fibers produced the hinges on the samples using their patented laser ablation system. Common Fibers the next step in the traditional Common Fibers assembly line is to protect the bare fibers of the hinge with a form of polyurethane tape. However, for the purposes of this project the hinges were left without
polyurethane tape to allow access to the bare carbon fibers. The cured and hinged carbon fiber panels were cut to wallet sample sizes using a waterjet cutting tool (Figure 10).

![Figure 10. Representative hinged carbon fiber wallet sample used for vacuum bagging and resin transfer molding.](image1)

For the purposes of this project, samples similar to the “Slim” wallet size were used. Samples of unidirectional carbon fiber were also fabricated and cut at a 45° offset, with dimensions adhering to the standard tensile bar shape as listed in ASTM Standard D3039. These dimensions were modified slightly due to the fact that the hinge is the obvious point of failure during a tensile test, and as such the standard coupon length is not crucial to the integrity of this test (Figure 11).

![Figure 11. Dimensions of unidirectional coupon samples (not to scale).](image2)
2.2 Flexible Resin Systems

Several 2-part silicone and urethane elastomeric resins were used in the project (Table I).

<table>
<thead>
<tr>
<th>Resin</th>
<th>Mixed Viscosity (cP)</th>
<th>Pot Life (min)</th>
<th>Cure Time (hrs)</th>
<th>Shore A Hardness</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encapso K</td>
<td>500</td>
<td>60</td>
<td>24</td>
<td>20</td>
<td>Water clear</td>
</tr>
<tr>
<td>Flex-It 10</td>
<td>500</td>
<td>30</td>
<td>24</td>
<td>10</td>
<td>Semi-clear</td>
</tr>
<tr>
<td>Econ 80</td>
<td>1200</td>
<td>13</td>
<td>24</td>
<td>80</td>
<td>Translucent</td>
</tr>
<tr>
<td>CF19-2615</td>
<td>1300</td>
<td>240</td>
<td>0.5 (at 150°C)</td>
<td>30</td>
<td>Optically clear</td>
</tr>
</tbody>
</table>

Encapso K, manufactured by Smooth-On, is a water clear silicone rubber that looks just like water and is ideal for a variety of encapsulation and display applications. Encapso K is easy to use, UV resistant and non-hazardous. It also cures with minimal bubble entrapment and without generating any dangerous heat or fumes. Flex-It 10, produced by Specialty Resin and Chemical LLC., is a highly flexible urethane casting resin designed for casting flexible molds, seals, gaskets, models, prototypes, and miscellaneous parts. It has excellent tear strength, elongation, tensile strength, and good chemical resistance. Econ 80, manufactured by Smooth-On, is an economical urethane rubber suitable for a variety of mold making and industrial applications (Figure 12).

![Figure 12](image-url)
Econ 80, however, can produce a significant amount of vapors which can cause lung damage and sensitization; adequate ventilation is needed. CF19-2615, manufactured by NuSil Technology LLC., is an optically clear potting and encapsulating silicone elastomer. It offers good physical and electrical stability across a broad range of temperatures. CF19-2615 provides protection of electronic components and assemblies against shock, vibration, moisture, ozone, dust, chemicals and other environmental hazards.

2.3 Application Methods

Out of the many of resin application and composite manufacturing methods, resin transfer molding (RTM) and vacuum bagging were selected as the most feasible for the purposes of this project and for the potential implementation into the Common Fibers production line in the future.

2.3.1 Resin Transfer Molding

Due to the complexity of current setups, a resin transfer mold (RTM) was designed and manufactured in-house. The design of these molds was done to maximize the likeness of the RTM in this project to those in commercial use, all while maintaining the ability to apply resin selectively to the hinged area of the samples.

2.3.1.1 Setup

Fabrication and assembly of the resin transfer mold was done in the Cal Poly Student Project Machine Shop. Aluminum panels were milled to size (4 in. by 2 in., 0.625 in. thick) and to incorporate the average hinged wallet sample (2.53 in. wide, 0.0195 in. thick). An additional mold was fabricated to accommodate the size of the unidirectional 45° offset samples, following similar procedures to those described previously. This design included a resin injection port on the channeled (top) plate and a set of two air holes on the bottom plate to promote the flow of resin during operation. All additional hardware was purchased from Home Depot, including zinc-plated hex bolts, nuts, and washers. A neoprene gasket was attached to the aluminum plate around the injection port in order to mitigate the backflow of resin during the injection process. Samples were wrapped in a transparent cling wrap (provided by Common Fibers) in order to reduce the amount of resin flowing and subsequently curing on the unhinged portions of the sample still encased in the mold (Figure 13).
2.3.1.2 Sample Fabrication

Samples for resin transfer molding were prepared by mixing each resin for 5 minutes and allowing a reasonable amount of time for entrapped air to escape. Mixed resin was poured onto the center of the hinge and manually brushed into the fibers through the use of a squeegee tool. Manual fiber pre-wetting was done thoroughly to both sides of the sample, at which point the sample was placed inside the RTM mold. A 3mL medical syringe was used to inject pre-mixed resin into the injection port of the RTM mold. The syringe was held tightly against the neoprene gasket to eliminate the possibility of back-flowing resin. Constant pressure was applied to the plunger of the syringe until resin began seeping out from the sides of the mold. This serves as an indication that the resin had reached all of the fibers of the hinge (Figure 14).
Samples were left inside a fume hood to cure for at least 24 hours before removal and inspection. After the full curing time had elapsed, samples were released from the mold and inspected. The mold was cleaned of any residual resin before each subsequent use.

2.3.2 Vacuum Bagging

The vacuum bagging setup used in the execution of this project closely followed a standard vacuum bagging procedure, but was modified slightly to accommodate the hinged wallet design.

2.3.2.1 Setup

Fabrication of vacuum bagging samples began with the standard setup. First the vacuum bagging material, bleeder/breather cloth, and release cloth were cut to size. The size of each material depended on the number of samples being fabricated in the same bag. Originally both sides of the setup were composed of vacuum bagging material. However, this was later changed to only have one side be the material and the other side being a work surface, in this case a large unused composite panel. Tacky tape was laid out along the edges of the bag. A hole was punctured in the bagging material in order to insert a vacuum connector valve. This valve was produced from common parts readily available at any hardware store. Parts included neoprene O-rings, zinc-plated washers, brass barb connector, and brass nut. Once the
valve was inserted, release cloth and bleeder/breather cloth were laid down. Later this was changed to only have release cloth on the work surface (Figure 15).

![Figure 15. Vacuum bagging setup.](image)

### 2.3.2.2 Sample Fabrication

Hinged samples were laid out under a fume hood. Parts A and B of each resin were mixed for 5 minutes and poured on the center of the hinge and manually brushed into the fibers with a squeegee. Then the samples were carefully placed, shiny side up, on the release cloth and covered with another layer of release cloth and bleeder cloth. The bagging material was sealed to the work surface with tacky tape. The vacuum tube was connected to the valve and the pump was turned on for 1 hour. The gap between the tube and connector was also sealed with tacky tape. Any air leaks, holes, gaps in the bag were sealed as soon as possible. After turning off the pump, the samples were left to cure in the sealed bag for at least 24 hours. The samples were removed from the bag and inspected. The connector valve was removed from the bag and the bagging material and cloth were discarded. 3 Encapso K samples, 2 Flex-It 10 samples, 2 Econ 80 samples, and 1 CF19-2615 sample were fabricated in total (Figure 16).

![Figure 16. The vacuum pump sucking the air out of the bag. This trial contained 4 samples each with different resin.](image)
CF19-2615 was advertised as a resin that cures at either room temperature or elevated temperature, however the only detailed information listed the standard curing parameters as 30 minutes spent at 150°C. Through correspondence with a NuSil representative it was learned that given a small volume of resin it was possible to begin the reaction with a relatively small heat input (using a hair dryer, for instance), and allowing the resin to cure over a longer time scale (~24 hours). While the vacuum was engaged the CF19-2615 sample was subjected to several minutes of heat from a MATE Department hair dryer, and then left the vacuum to run for the remaining 1 hour (Figure 17).

**Figure 17.** It was hypothesized that heat input during vacuum bagging would allow the CF19-2615 resin to begin crosslinking.

### 2.4 Bond Strength Testing

#### 2.4.1 Unidirectional 45° Offset Tensile Test

This test was developed as a way to characterize the fiber-matrix bond strength based on other testing methods present in the literature. However, it was acknowledged that this test may not be able to accurately measure the interfacial bond strength. In order to determine the validity of this tensile test, a set of control samples was fabricated to be tested and compared with results from a set of samples containing resin at the hinge. It was hoped that this preliminary test could establish both a significant difference in the mean load values of these two groups, and identify a significant difference in the variance of the two
data sets, if one existed. Because there existed the possibility that this test would not provide a sufficient method for characterizing bond strength, it was critical to determine the validity of this testing method with a reasonable number of samples. As such, it was decided to use the flexible resin with the highest Shore A Hardness value as the experimental group. This resin, Econ 80, was chosen due to an assumption that it had the highest chance of displaying a statistically significant difference in mean load value compared to the control samples. In other words, if a resin with low bond strength was used, a risk was run of not seeing a significant difference in mean load compared to the control, and prematurely disregarding the entire test method due to incorrect/incomplete data analysis. It was also assumed that there was at least somewhat of a positive correlation between hardness and bond strength.

2.4.1.1 Sample Fabrication
Eight coupons were laid out under the fume hood. Both parts of the Econ 80 resin were mixed together for 5 minutes, as per the manufacturer’s instructions. Mixed resin was hand-applied using a squeegee method. The coupons were left to cure for 24 hours (Figure 18).

![Image of coupons with resin applied](image)

**Figure 18.** Econ 80 was applied to the hinged portion of each coupon.

2.4.1.2 Testing Procedure
Each sample was tensile tested using the Instron tensile tester. First, the testing method was setup with Bluehill 3 software. The Instron machine was covered with a plastic sheet for protection from any breaking fibers. Each sample was loaded into the fixture and the test ran until failure. A series of hinged coupon samples with no resin were also tested as a control.
2.4.2 Fiber Bundle Pull-Out Test

Originally developed as a backup for the unidirectional tensile test, a fiber bundle pull-out test was developed to characterize the fiber-matrix bond strength. It was hypothesized that the load at which the fibers debond from the resin is relative to the bond strength.

2.4.2.1 Sample Fabrication

First, a large number of 3mL medical syringes were obtained. 3k tows of carbon fiber were pulled out of a woven mat. Each tow was carefully threaded through the end of each syringe. Each fiber bundle was aligned along the longitudinal axis of the syringe. The samples were hung in a homemade wooden stand as to keep the fibers taught. Parts A and B of each resin were mixed. About 2mL of mixed resin was injected into each syringe. In order to prevent the leaking of resin, plastic wrap was attached by a rubber band to the bottom of the syringes. Encapso K, Flex-It 10, and Econ 80 resins were left to cure for 24 hours. Due to CF19-2615’s cure time (and temperature), those samples were left to cure for 72 hours. Ten samples were produced for each resin system (Figures 19, 20, and 21).

![Figure 19](image.png)

*Figure 19.* Wooden fixture used to hold syringes upright. Taut fibers are aligned along the center axis of the syringe.
2.4.2.2 Testing Procedure
Given the resin-fiber combination could not be removed from the syringe without pulling out the fibers, it was decided that the syringe itself would be used as part of the sample. The relative fiber-matrix bond strength was determined quantitatively through a fiber-bundle pull-out test performed on a Mini 55 Instron Tensile Tester. First, a method was setup with Bluehill 3 software. The resin encapsulation length within each syringe was noted. A washer was fed over one end of the syringe to the other end. The bottom end of the syringe was faced upward and loaded into an asymmetrical jaw fixture in order to minimize the
effect of unintended forces on the bond strength measurements. Fibers were gripped at the top of the fixture. Each syringe sample was pulled to failure. Peak load was recorded as a measurement of the point at which fibers either fully debonded from the resin or fractured (Figures 22, 23, and 24).

Figure 22 and Figure 23. Rubber faces in the center of the jaws grip the loose fiber-end of the samples (left), bottom portion holds flanges of the syringe (right).
3. Results and Analysis

3.1 Application Method Results

In order to determine the best overall application method, several criteria were selected based on the wetting of the fibers and the overall aesthetic feel and appearance. These specific parameters were selected because of their perceived importance both in the implementation of this solution as a wallet hinge and for hinges in future applications. Samples were examined in a random fashion in order to reduce any bias from the examiner. Samples were ranked on a scale of 1-5 (excluding the neutral value of 3) for each criterion, and the sum of a samples rankings was used to determine its overall score (Table II).

Table II. Individual Criteria and Total Score Ranking of Application Method – Resin Combinations

<table>
<thead>
<tr>
<th>Random Sample</th>
<th>Resin System</th>
<th>Application Method</th>
<th>Flexibility</th>
<th>Edge Fiber Containment</th>
<th>Total Encapsulation</th>
<th>Surface Feel</th>
<th>Surface Appearance</th>
<th>Total Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Encapso K</td>
<td>VB #2</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>CF19-2615</td>
<td>RTM</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>
The numbers in the “Application Method” column differentiates sample combinations that were attempted on multiple occasions. The average total for vacuum bagging was 19.4 while the RTM average was 17.2. Based on these criteria, the best and most efficient method was vacuum bagging, however the quality of application greatly varied across resins and both methods.

3.1.1 Vacuum Bagging

The first sample that was fabricated, Encapso K, had the closest profile to that of the cured carbon fiber epoxy matrix panels with near perfect coverage. Compared to the RTM sample, there was a little buildup of resin. Additionally, there was almost no excess resin on the unhinged portions of the sample past the hinged area (Figures 25 and 26).

![Image](image_url)

**Figure 25.** The vacuum bagging resin profile of the hinge closely follows that of the composite panels, with little to no resin outside of the hinge area (Encapso K).
Figure 26. Close-up view of the hinged area. Some of the texture of the carbon fiber has telegraphed to the surface of the relatively thin layer of resin (Encapso K).

The bleeder and release cloth appeared to have absorbed the excess resin as the vacuum pulled the resin directly into the fibers. There was better fiber containment on the edges of the hinge. For the second Encapso K vacuum bagging sample, the resin does not appear to have entered as deeply and completely into the fibers. There are uncovered areas throughout the hinge, and the edges of the hinge were noticeably absent of a resin as well (Figure 27).

Figure 27. Encapso K vacuum bagging sample from the 3-resin test. Resin does not appear to have entered as deeply and completely into the fibers. There are uncovered areas throughout the hinge, and the edges of the hinge are noticeably absent of a resin as well.
It was clear from the results of the first Flex-It 10 and Econ 80 samples that the size of the release cloth used in the vacuum bagging process must be larger than that of the sample to prevent any resin from unexpectedly joining the breather/bleeder layer and the sample, as happened in the first Econ 80 test. Econ 80 samples in particular exhibited stiff hinge areas with some amount of preferential bending at the hinge. It was also realized that a portion of the large breather/bleeder cloth had become attached to the cured panel portion of the Econ 80 samples (Figure 28).

![Figure 28. Econ 80 vacuum bagging sample from the 3-resin test. Econ 80 bonds well to carbon fiber as well as bleeder/breather cloth (right).](image)

The surface finish and feel of the first Econ 80 sample was of the smoothest and most conformal to the shape of the current panels so far. There was also no sticky or tacky sensation when a finger or other object was laid or dragged across it. This is in contrast to Flex-It 10 samples, which retained a noticeable level of adhesion after fully curing (Figure 29).
Figure 29. Flex-It 10 vacuum bagging sample from the 3-resin test. This sample experienced much more uniform resin distribution and adhesion, however Flex-It 10 is much sticker in general, as shown by the dust and hair adhered to the hinged area of the sample.

3.1.2 Resin Transfer Molding
Resin transfer molding had a fundamentally different resin application appearance compared to vacuum bagging. While the design of the mold was such that it fixed specifically over the hinged area of the sample, there were portions of the milled slot in the mold that resided over epoxy composite panel sections of the samples during the injection and curing processes. Because of this, resin tended to evenly form over this entire range, which spanned a significantly greater distance than simply the width of the hinge (Figure 30).

Figure 30. Resin coverage of a Flex-It 10 RTM sample, clearly showing the application of resin far past the boundaries of the hinge.
Additionally, because there was no absorbent layer inside the resin transfer mold and the cavity was slightly deeper than the thickness of the samples, the resin applied over the hinge cured to fill the entirety of the cavity. This means that the resin layer was slightly thicker than the surrounding panel, and that the surface finish of the inside of the mold appeared on the surface of the resin due to their direct contact (Figure 31).

![Figure 31](image1.png)

**Figure 31.** The marks still present on the mold surface from the milling process have been imprinted on the surface of the resin.

These trends were consistent across all RTM samples and occurred independently of resin system used. Each resin system had similar relative ease of squeegee pre-wetting and injection. However, resins which ended up having higher bond strengths exhibited greater adhesion to the surfaces of the mold, and displayed greater resistance to being removed from the confines of the mold (Figure 32). Despite this, all samples remained intact during the curing, removing, and observation steps.

![Figure 32](image2.png)

**Figure 32.** Flex-It 10 RTM sample showing strong adhesion to the inside of the mold during removal.
3.2 Bond Strength Testing Results

3.2.1 Unidirectional 45° Offset Tensile Test Results
16 unwetted hinged control samples were pulled to failure using standard tensile testing procedures. Eight additional samples which had been hand-wetted with Econ 80 were pulled to failure as experimental trials. Load (kN) - extension (mm) curves were compiled for both trials, and the peak load measurements were used to characterize resin-fiber bond strength (Figures 33 and 34).

![Figure 33](image1.png)

**Figure 33.** Load-extension curve for control hinged samples of unidirectional, 45° offset coupons.

![Figure 34](image2.png)

**Figure 34.** Load-extension curve for Econ 80 hand-wetted samples.
Upon observations of the curves produced and a comparison of the average load values, it was determined that no significant difference existed (Table III).

| Table III. Comparison of Peak Load values of Unidirectional 45° Offset Tensile Test |
|---------------------------------|-----------------|-----------------|
| Mean Peak Load (kN)             | 0.961           | 0.918           |
| Standard Deviation (kN)         | 0.088           | 0.737           |

Overall, it was concluded that the unidirectional 45 offset tensile test was not an appropriate method to characterize resin-fiber bond strength. After comparing the results of Econ 80 and the controls, the results were not significantly different, and there was even a small decrease between control and experimental trials. Therefore, the fiber bundle pull-out test was pursued further.

3.2.2 Fiber Bundle Pull Out Test Results

The fiber bundle pull out test displayed some interesting results: In all resin samples excluding Econ 80, the fibers were pulled until they debonded from the resin. For Econ 80, on the other hand, the fibers either fractured inside or outside of the syringes (Figure 35). During testing, it was observed that voids nucleated on the surface of the fibers, specifically in the Encapso K and CF19-2615 samples (Figure 36). The bubbles in the other resin samples, however, were formed during fabrication (Figure 37). These bubbles could have had an effect on the bond strength results for these resins.

Figure 35. A representative Econ 80 sample post-tensile testing. It is clear that the main method of failure in these samples is fracturing of fibers rather than pulling out of the resin. This image also shows the large amount of trapped air in the Econ 80 sample as a result of mixing.
Figure 36. Close-up of Flex-It 10 fiber bundle pull-out sample. The bubbles were present in the sample from curing.

Figure 37. Close-up of Encapso K fiber bundle pull-out sample. The voids formed on the fibers during testing.

All of the resins had different peak loads and standard deviations, some more similar than others. Econ 80 exhibited an extremely large mean peak load of 113N. Along with a much higher average peak load,
Econ 80 samples had a disconcertingly large variance between samples, with multiple values as high as 164 N and as low as 42 N. Encapso K had lowest mean peak load of 12.6 N. With the exception of Encapso K, the mean peak loads correlated with the resins’ Shore A hardness value (Table IV). Further statistical analysis was conducted to determine the significant differences across all resin systems.

### Table IV. Data from Fiber Bundle Pull-Out Testing

<table>
<thead>
<tr>
<th>Sample</th>
<th>Encapso K Peak Load (N)</th>
<th>Flex-It 10 Peak Load (N)</th>
<th>Econ 80 Peak Load (N)</th>
<th>CF19-2615 Peak Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.94</td>
<td>22.37</td>
<td>164.23</td>
<td>29.22</td>
</tr>
<tr>
<td>2</td>
<td>13.81</td>
<td>18.41</td>
<td>88.48</td>
<td>41.24</td>
</tr>
<tr>
<td>3</td>
<td>14.98</td>
<td>46.70</td>
<td>164.90</td>
<td>34.42</td>
</tr>
<tr>
<td>4</td>
<td>13.06</td>
<td>38.23</td>
<td>99.07</td>
<td>39.23</td>
</tr>
<tr>
<td>5</td>
<td>12.12</td>
<td>41.93</td>
<td>135.33</td>
<td>35.38</td>
</tr>
<tr>
<td>6</td>
<td>23.10</td>
<td>22.16</td>
<td>42.81</td>
<td>30.15</td>
</tr>
<tr>
<td>7</td>
<td>13.01</td>
<td>27.78</td>
<td>77.89</td>
<td>42.68</td>
</tr>
<tr>
<td>8</td>
<td>9.29</td>
<td>36.38</td>
<td>118.45</td>
<td>54.17</td>
</tr>
<tr>
<td>9</td>
<td>12.52</td>
<td>30.98</td>
<td>119.75</td>
<td>33.31</td>
</tr>
<tr>
<td>10</td>
<td>4.46</td>
<td>31.91</td>
<td>121.14</td>
<td>31.79</td>
</tr>
<tr>
<td>Mean</td>
<td>12.63</td>
<td>31.69</td>
<td>113.20</td>
<td>37.16</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>4.74</td>
<td>9.22</td>
<td>37.88</td>
<td>7.51</td>
</tr>
</tbody>
</table>

In an attempt to reduce the variability in fiber bundle pull out data, new samples of Flex-It 10 and Econ 80 were produced. Directly after the resin mixing stage the resins were placed inside a vacuum chamber for 5 minutes with the hopes that the vacuum pressure would pull the air bubbles out that had been introduced through mixing. The resin was then poured into prepared syringes using standard procedures. Unfortunately, the pouring process (which involves the use of an additional syringe to suck up and inject the resin into the sample syringes) introduces bubbles as well, which could not be eliminated with the vacuum chamber method. These samples were then pulled using standard procedures. There was no statistically significant difference in mean load or in standard deviation, suggesting that this method for bubble elimination is not entirely effective.

3.2.2.1 Statistical Analysis

Peak load values were analyzed further using Minitab Statistical Software in order to determine any significant differences between resin types. Several integral assumptions must be made in order to
perform one-way Analysis of Variance (ANOVA). These include assumptions that the data points are normally distributed and have equal variances between resin types. In its current form, the raw peak load data did not pass either test (Figures 38 and 39).

**Figure 38.** Failed test for normality of all 40 fiber bundle pull out peak load values.

**Figure 39.** Failed test of equal variances of all 40 fiber bundle pull out peak load values.
However, this data was then altered by subjecting it to a base 10 logarithm. This data was then put through the sample normality and equal variances test, and it passed successfully (Figures 40 and 41).

**Figure 40.** Successful test showing a normal distribution of the $\log_{10}$ of all 40 fiber bundle pull out peak load values.

**Figure 41.** Successful test showing a normal distribution of the $\log_{10}$ of all 40 fiber bundle pull out peak load values.
The successful tests for normality and equal variances allowed for a one-way ANOVA test, specifically with Tukey Pairwise comparisons (Table V).

**Table V. Tukey Groupings of Bond Strength data by Resin Type**

<table>
<thead>
<tr>
<th>Resin Type</th>
<th>Tukey Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Econ 80</td>
<td>A</td>
</tr>
<tr>
<td>CF19-2615</td>
<td>B</td>
</tr>
<tr>
<td>Flex-It 10</td>
<td>B</td>
</tr>
<tr>
<td>Encapso K</td>
<td>C</td>
</tr>
</tbody>
</table>

It can be confidently stated that Econ 80 has a significantly higher bond strength than all other resins. CF19-2615 and Flex-It 10 have statistically similar values, while Encapso K has the lowest bond strength values.

**4. Discussion**

**4.1 Application Method**

**4.1.1 Resin Transfer Molding**

Overall, the resin transfer molding process consisted of significant trial, error, and reiteration. The greatest strength of the RTM approach was its simple setup and process. The mold fixture was small and so the space taken up inside a fume hood during the 24-hour curing process was not excessive. In addition, there was no waste of materials, unlike vacuum bagging. The most significant disadvantage of the process was that only one sample could be fabricated every 24-hour period.

The samples fit the mold fixture relatively well, but there were spaces vertically and horizontally on both sides. A perfectly fit sample would have reduced pooling on the top of the samples and improved the edge fiber containment. However, not all samples were cut to the exact same size. In other words, even if the mold fit one sample, it might not fit another. Aluminum was a good choice for the mold material. The surface finish of the mold could have been improved to reduce the amount that was telegraphed to the surface of the samples. RTM is feasible for future research, but the mold must be redesigned in order to obtain the best surface feel and appearance, the primary drawback of this application method in terms of
sample observations. In addition, it would be advantageous to develop a method to produce multiple samples at one time as this would be the only way to make this method feasible on a larger scale.

4.1.2 Vacuum Bagging
The vacuum bagging process used in this project was a standard, simple procedure, which was iterated several times. These changes include altering amounts of various release and breather/bleeder layers, the work surface, and placement of the vacuum port. The final iteration of the vacuum bagging design produced samples that displayed better appearance, better encapsulation and fiber containment, and better consistency than resin transfer molding. An improvement of this method is certainly possible, and is important for finally determining the best application method for selectively encapsulating the hinge fibers. Specifically, upgrading the work surface to smoother metal surface and using a non-porous release cloth will aid in the overall aesthetic appearance of the flexible resin. This is important for matching the profile and appearance of the rest of the composite panel.

In addition to improving the aspects of the vacuum bagging design, the accuracy of the current procedure is important to consider. During sample fabrication trials samples of multiple resins were placed inside the same bagging setup as a method to reduce the overall disposable material use and to make most efficient use of the vacuum pump. However, the effect of either multiple samples per vacuum bag or multiple resins per vacuum bag were not investigated in any detail. While there appeared to be no interaction from standard observation procedures, it cannot be said with absolute confidence that this has no effect on the final product.

For future research, vacuum bagging currently appears to be the most promising of the two methods explored in this project. The current design is sufficient for use in preliminary work, and it can be easily improved upon to improve quality, efficiency, and consistency. It is possible that the standard vacuum bagging process has an upper limit to the quality of sample it produces, however this is not presently known. One of the goals of this project was to explore potential options for future implementation by Common Fibers, vacuum bagging may not be the most efficient on a larger production scale. Additional research into the field of large scale composite manufacturing may be beneficial.

4.2 Bond Strength Testing
The fiber bundle pull out test was effective at determining the bond strength between the carbon fiber bundle and the selected flexible resins. Fabricating the samples was not a difficult procedure and it was
possible to make a large quantity at once. The tensile test was easy to execute since it only involved placing our cured samples in the fixture and pulling them to failure.

For a majority of the resins used, the test was relatively consistent with a small standard deviation between peak loads. The results can be seen as relatively accurate because of this. The test showed enough of a difference across resins and samples to make basic conclusions about bond strength. In addition, it was helpful to use the syringes since they were transparent and one could actually see the fibers debonding from the resin. However, in some samples there were a large number of bubbles. A different sample fabrication method could be useful to remove these bubbles, but the problem is more resin specific, particularly Econ 80 and Flex-It 10. These were formed during sample fabrication. Due to the short work time of the resins used, there was not enough time for the resin to settle in the syringes and allow bubbles to escape. Although, the fiber bundle pull out test was an accurate way of testing bond strength, the data showing that resin amount does not affect peak load is not entirely conclusive.

In the future, even though syringes are inexpensive and disposable, there needs to be a more sustainable resin curing method. Reducing the bubbles could produce more consistent results with these resins and a smaller standard deviation. Instead of placing the mixed resin in the evacuation chamber, producing samples of a smaller size could allow the bubbles to be removed. However, it was more of the fixture that was used for holding the samples, rather than the actual sample size. In other words, there needs to be a way to fit a fixture in the evacuation chamber, or use a different evacuation chamber. There also needs to be a more complete study on how resin amount affects the peak load values as this be the most accurate measure of the true bond strength.

5. Conclusions and Recommendations

1. In the future, it is recommended that the vacuum bag setup be improved to allow for a more appealing surface finish. In addition, removing bubbles in the fiber bundle pull-out samples, particularly Flex-It 10 and Econ 80, could provide more consistent bond strength results. Lastly, testing more resin options could allow for the best combination of properties that could be useful for Common Fibers.

2. It was concluded that vacuum bagging produced better and more consistent results than resin transfer molding (RTM). These qualities include total fiber encapsulation, edge fiber containment, flexibility, and surface appearance and feel. It was concluded that the fiber bundle
pull-out test is a legitimate method for determining the bond strength between carbon fiber and the selected flexible resins. Overall, Econ 80 had the highest mean peak load of 113N and Encapso K had the lowest mean load of 12.6N.
References


