Shear Strength of Carbon Fiber/Epoxy Hinges Using the V-Notch Rail Shear Test

A Senior Project

Presented to

The Faculty of the Materials Engineering Department

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Bachelor of Science, Materials Engineering

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Abstract

The mechanical properties of carbon fiber reinforced polymer (CFRP) hinges produced by Common Fibers (Kent, Washington) are a new technology with uncharacterized mechanical properties. Currently, Common Fiber's hinges are utilized in wallets, but in order to expand the application of the hinges to structural components, complete characterization of the mechanical properties of the hinges is necessary. To address this problem, hinges developed by Common Fibers were tested utilizing the V-Notch rail shear test, ASTM D7078, to determine the shear strength of the hinges. Two layups, $[+45/-45/0]_s$ and $[0/+45/-45/0]_s$ were produced by Common Fibers for the experiment. Hinged and unhinged laminates of both layups were tested using the V-Notch rail shear test for maximum load producing load-extension curves. The results of the hinged and unhinged laminates were compared to characterize the shear behavior of the composite hinges. Comparison of hinged and unhinged composites revealed that the production of the hinge results in a reduction in shear strength from an average of 12.260 kN to as low as 1.568 kN. The load-extension curves display a pre-loading phase where the fibers in the hinge region undergo a period of relaxed extension until they are engaged in supporting the applied load. Observations of specimens after testing revealed splintering delamination as the failure mode along the interface between hinged and unhinged material parallel to the 45^0 oriented fibers.

Keywords: Materials Engineering, Composite Hinges, V-Notch Rail Shear Test, Shear Strength

1. Background

1.1 Fiber Reinforced Composite Materials

Composite materials are composed of multiple components that in combination produce a monolithic material with unique properties not demonstrated by the constituent materials. Fiber Reinforced Composites (FRPs) are a subset of the greater composite material family and are composed of two constituents; a fiber and a matrix. Each constituent serves a different purpose in the composite material. In the composite, the fiber supports the load while the matrix ensures the fibers are held together as well as protects the fibers from the environment. Fibers can be composed of carbon, glass, polymers, ceramics, and natural materials while matrix materials are typically some form of polymer. Fibers can be unidirectional, multidirectional or woven fabrics. There are various manufacturing techniques, however, FRPs are usually produced in the form of laminates which are composed of multiple thin sheets of composite material. The laminates can be manufactured with many different types of layups which vary the orientation of the fibers in each lamina.

1.1.1 Carbon Fibers

Out of all of the engineering fibers, Carbon fibers are the most commonly used. Carbon fibers were first developed by Thomas Edison as he was developing filaments for the lightbulb, but were more intensely investigated over a period of decades in the mid-20th century by various developers [1]. Carbon fibers are produced from pyrolysis of a polymer precursor. Cellulose was the original precursor when carbon fibers were first being developed, however, modern carbon fibers are produced from polyacrylonitrile (PAN) and petroleum pitch with PAN being the most common [1]. The processing methods to produce carbon fibers from PAN follows three basic steps: stabilization, carbonization, and graphitization. During stabilization, the precursor fiber is placed under stress at an elevated temperature between 200^{0}C and 300^{0}C where the precursor undergoes chemical changes and the density is increased. The polymer structure of PAN contains carbon atoms triple-bonded to nitrogen. Stabilization opens this triple bond up forming a ladder molecular structure. After stabilization, the fiber is placed in a nitrogen rich environment at temperatures between 1000^{0}C and 1700^{0}C under zero stress to undergo carbonization increasing the carbon content to above 90%. The final stage is graphitization where the carbon fibers are subjected to an inert environment at temperatures of 2000^{0}C to 3000^{0}C. This final step produces the hexagonal carbon chain structure which controls the mechanical properties of the carbon fibers under stress. The elastic modulus is dependent on the orientation of this hexagonal carbon sheet structure in relation to the fiber axis. The more aligned the hexagonal carbon chain structure is with the fiber axis, the greater the elastic modulus of the carbon fibers. Theoretically, carbon fibers can achieve elastic moduli of 1,060 GPa [1].

Carbon fiber's low weight, high strength, and high modulus makes them suitable for sporting goods applications. Shafts for golf clubs, which were once made from steel and other alloys, were greatly improved with the utilization of carbon fibers. Using carbon fiber meant golf club manufacturers could place more weight in the head of the golf club. This change in design meant golfers could achieve greater swing speeds and thus greater distances. Soon golf club manufacturers were expanding the use of carbon fibers into the golf club heads themselves. Companies such as Callaway have produced driver heads made of composite materials further reducing the weight of the club (Figure 1) [2].

Figure 1– Callaway's XR Pro driver features a carbon fiber composite crown that reduces the overall weight of the club.

Carbon fibers are also utilized in applications such as chemical protective clothing, electromagnetic shields, and woven fire retardant fabrics [1]. Carbon fibers are expensive though. While low moduli carbon fibers can be purchased at $20/kg, high moduli carbon fibers, the ones needed for many advanced structural applications, can cost $3,000/kg [1]. In terms of composites, the full mechanical advantages of carbon fibers cannot be exploited in FRPs. However, the addition of the matrix, or resin, adds characteristics to the composite material that prove to be advantageous for many applications.

1.1.2 Epoxy Resin

The matrix material that has received the most commercial success is epoxy resins. Epoxy resins are a large and diverse group of thermosetting polymers that have obtained wide usage due to the variety of properties these resins can display. The manipulation of these characteristics comes from modifying the processing method and introducing different additives to the resin which alter the molecular structure of the epoxy resin. The basic production method for producing epoxy resins involves a precursor, often epichlorohydrin, containing base molecules of double-bonded carbon atoms [3]. The epoxy resins can then be altered to display different properties by varying the additives. Curatives and modifiers are chemical additions to the base epoxy resin that serve to alter the properties of the cured resin [3]. Which curatives and modifiers the manufacturer choses is largely dependent on the desired properties of the application. The ability to produce various properties allows epoxies to be utilized in many different applications making excellent adhesives, electrical insulators, surface coatings, and matrix materials for composite applications.

Epoxy resins offer many advantages to being utilized in composite applications. Epoxies lack volatiles and experience low shrinkage during curing, they have excellent chemical and solvent resistance, and they display excellent adhesion to the fibers in the composite [4]. The primary indicator of suitable use for epoxy resins in structural applications is the glass transition temperature (T_g) [3]. The glass transition temperature indicates the point at which the molecular chains in the epoxy resin will be able to slide past each other. A higher glass transition temperature indicates an epoxy resin that will have superior performance for structural applications because the polymer chains cannot move relative to one another. The glass transition temperature is dependent on the final molecular structure formed from curing the resin and is largely related to the degree of crosslinking apparent at the molecular level. Since higher degrees of crosslinking are obtained at higher curing temperatures, epoxy resins cured at higher temperatures will have a higher T_g and display greater performance in structural applications. Another important feature of epoxy resins is the ability to be partially cured, which is essential when developing prepreg composite sheets. The curing process can be manually adjusted by lowering the temperature which halts the formation of crosslinks between the polymer chains in the epoxy. When this is done, the epoxy resin is said to be partially cured, or in the B-stage, because the polymer chains are not fully crosslinked. Prepreg materials rely on this property. Prepreg composites are sheets of fibers and partially cured resin that are manufactured to produce a composite panel. A common manufacturing technique for prepreg composites involves cutting the prepreg sheets into smaller sections and then stacking them in the desired lamina sequence. Once the composite stacking sequence is completed, it is placed under high temperature and pressure to fully cure the epoxy resin and produce a final composite panel.

With all of their distinct advantages epoxy resins have disadvantages such as high cost and long curing time. A mechanical disadvantage of epoxy resins is low strain to failure and poor fracture toughness. However, this can be improved by adding carboxyl-terminated butadiene acrylonitrile (CTBN) to the resin [4]. The addition of CTBN to the epoxy resin forms a second phase within the matrix that acts as an impendence to micro cracking that can occur when the resin is placed under stress.

1.2 Folding Composites

Recent developments in composite technology have been aimed at producing composite components capable of acting as hinged structures. A typical hinge structure consists of two distinct structural members that are connected by some means, such as a fixture, that allows the components to flex or extend. The benefit of utilizing composite technology is aimed at eliminating the need for extra processes or components required to produce a hinge. Instead, the composite material, in its own monolithic state, needs to act as a hinge. Given the structural advantages of composite materials, and the reduction in weight they provide, being able to produce a composite hinge has many advantages in structural applications. However, the properties of composite materials means there are challenges in producing a hinged monolithic composite structure.

One of the issues with producing a hinged composite material is that FRPs are lightweight stiff structures that are difficult to flex. Looking at the minimum folding radii of composite laminates, both woven and non-woven, experiments showed that composites failed when put into bending deflection when the in-plane strains exceeded the ultimate strains of the composite material [5]. Considering a flat, balanced symmetric plate of a composite laminate material, when large radius of curvature in bending is imposed onto the structure, the in-plane stiffness of the material prevents stretching. The inhibition of stretching in the material causes the section of material being forced into bending to form a cylindrical shaped structure (Figure 2) [5].

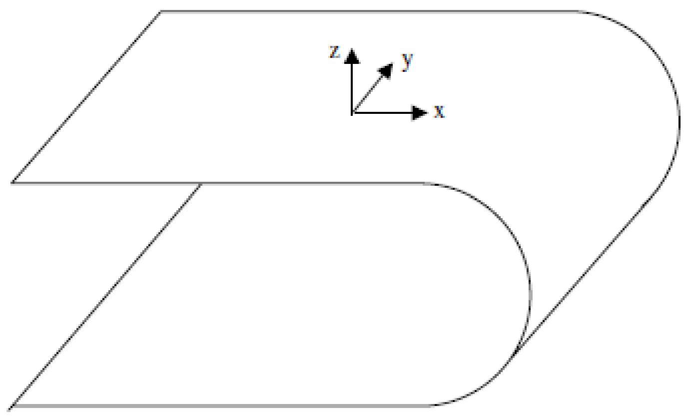


Figure 2 - Folding of a thin plate. The stiffness of the material is too great and has a minimum radius of curvature which produces the cylindrical shape at the bending region of the material.

This produces a problem when it comes to the development of a hinge. First, the stiffness of the composite prevents the material from being a fully flexible hinge and thus has limitations in its application as a structural hinge. Since by bending the composite places the material under load, the amount of load the 'composite hinge' will be able to support is reduced because of the internal strain energy present because of the initial bending of the material. The results of these experiments means that modifications must be made to the composite material to allow greater movement in the bending without producing large amounts of internal strain.

In order to reduce the internal strain produced in the composite upon bending deformation, the composite materials must be modified or changed in order to reduce the stiffness and allow for more flexibility. The fibers in a composite material are the constituent responsible for supporting the load whereas the matrix, or resin, is there to protect and maintain the part geometry of the composite materials. If the hinge is to be utilized in a structural application, the fibers must remain since they are integral to the strength of the composite material. However, the matrix can be altered to produce more flexibility in the composite. Hyper elastic matrix materials, such as a silicone matrix, have been shown to allow composite materials to have greater flexibility which is key to producing a hinged composite material. The approach is a variant to the technology used in tape-springs on solar arrays and utilizes an extremely soft elastic matrix. This soft elastic matrix is orders of magnitudes softer than the standard epoxy and allows the composite to achieve greater bending curvatures [6]. An interesting mechanical feature is noticed with the use of this matrix. Since the composite material is allowed to bend at even greater curvatures, the fibers on the compression side of the laminate experience elastic micro buckling (Figure 3) [6]. The fibers on the compression side reach a critical buckling load shifting the neutral axis of the laminate towards the tension side and reduces the maximum tensile and maximum compressive strains (Figure 3).

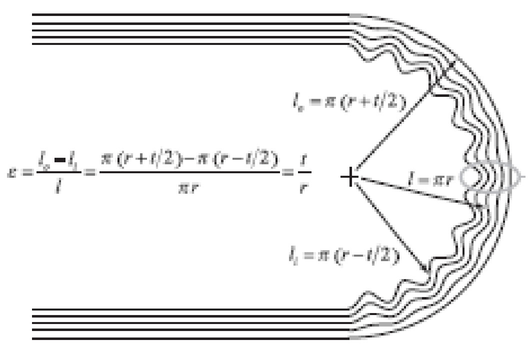


Figure 3 – Geometrical depiction of fiber deformation as a result of a load producing bending. The fibers on the compression side are experiencing elastic micro buckling and are deformed into a sinusoidal shape.

This mechanical phenomena displayed in composite materials allows the fibers to remain elastic for higher curvatures reducing the internal strain produced as a result of the bending of the composite.

1.3 Producing an Integral Composite Hinge

The previous techniques for producing a composite hinge required additional materials and multiple processes for manufacture. Common Fibers has developed and patented an integral hinge in CFRP panels which is manufactured through one additional process. Their process involves utilizing CO_2 laser ablation technology to produce the integral hinge in a composite panel [7]. Once the panel is manufactured, the CO_2 laser is focused on a region of the panel and travels across the entire length of the panel (Figure 4) [8]. The process removes the resin material at this site. The result is a section of the composite material that is composed of mostly fibers and thus a section with complete flexibility is produced.

Figure 4 - Image of the CO_2 laser ablation process Common Fibers uses to manufacture their composite hinge technology.

Prior testing performed by Common Fibers demonstrated that the production of these hinges resulted in a reduction in strength, however, the elastic modulus remained unchanged. These hinges are currently only used in everyday applications such as wallets (Figure 5), but has potential to be utilized in structural applications if more characterization of their mechanical properties can be obtained [8].

Figure 5 - Common Fibers wallet displaying the patented CF-Lex hinge technology.

1.4 Plate Theory of Laminates

In isotropic materials, such as steel, the mechanical properties of the material do not depend on direction. For example, the elastic modulus is the same in the x, y, and z directions of reference. However, FRPs are not isotropic. Since FRPs are composed of constituent materials, fibers and a matrix, composite materials are denoted as orthotropic materials meaning they exhibit elastic properties in two or three perpendicular planes to each other. For example, the elastic modulus of a FRP in the direction of the fibers is different than in the direction perpendicular to the fibers. Additionally, composite materials are typically manufactured as laminates, or multiple laminas (layers), of composite material with differently oriented fibers. Because of the complicated nature of the composite laminate, plate theory can be used to describe the mechanical behavior of the laminate.

In laminated plate theory, four assumptions are made in laminated plate theory beforehand and are listed below [4].

1. The width of the plate is much greater than the thickness. (w>>t)
2. There exists perfect interlaminar bonding.
3. The strain distribution through the thickness of the plate is linear.
4. The composite is macroscopically homogeneous and linear elastic.

Furthermore, the laminated plate is described as having a mid-plane which will act as a reference to describe the behavior of the rest of the composite. Reference points will be located at the edges of each of the lamina and can be seen depicted in Figure 6 [9].

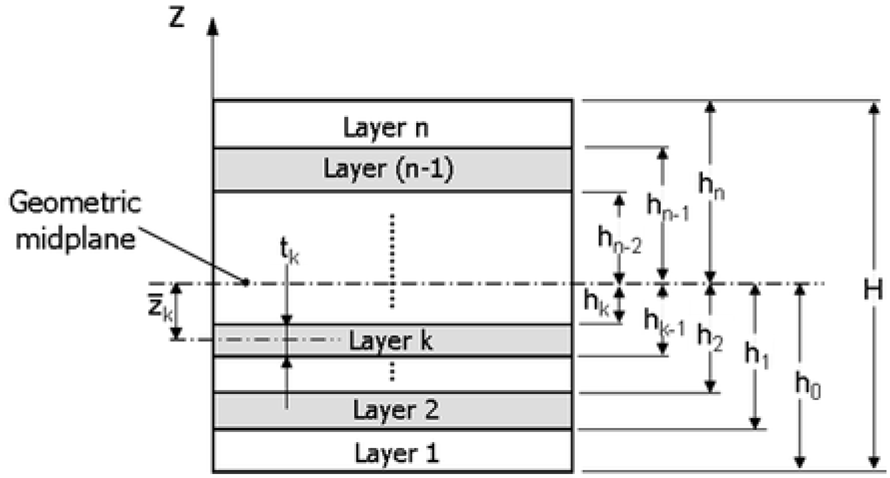


Figure 6 - Diagram of a composite laminate showing reference distances between each lamina edge and the mid-plane of the laminate plate.

From plate theory, skipping over the derivation stemming from the governing differential equation for plates, a relationship between the applied loads and moments and the strains can be derived (Eq. 1) [9].

(Eq. 1)
$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = [A] \begin{Bmatrix} \epsilon_x^o \\ \epsilon_y^o \\ \gamma_{xy}^o \end{Bmatrix} + [B] \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix}$$

(Eq. 2)
$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = [B] \begin{Bmatrix} \epsilon_x^o \\ \epsilon_y^o \\ \gamma_{xy}^o \end{Bmatrix} + [D] \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix}$$

The terms in Equations 1 and 2 are listed below.

1. *N = Forces*
2. *M = Moments*
3. ϵ°, γ° = *Strains at the midplane of the laminate*
4. *k = Curvature at the midplane of the laminate*
5. *[A] = Extensional Stiffness of the laminate*
6. *[B] = Coupling stiffness matrix of the laminate*
7. *[D] = Bending stiffness matrix of the laminate*

The important observation from Equations 1 and 2 is the coupling stiffness matrix of the laminate [B]. In Equation 1, [B] is multiplied with the curvature implying that normal forces will produce curvature in the laminated plate. In Equation 2, [B] is multiplied with the normal strains implying that moments will produce normal strains in the laminate plate. There are no other materials known that exhibit this coupling and this has important implications in the design of the laminate. In order to eliminate this coupling, [B] must equal zero. This can be achieved by designing the laminate to be symmetrical [9]. Therefore, with this design consideration in mind, the design of a laminated plate should be symmetrical in design to eliminate the unwanted coupling. If this is done, and the forces reduced to only shear stress, Equations 1 and 2 reduce to Equation 3.

(Eq. 3)
$$\begin{Bmatrix} 0 \\ 0 \\ N_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_x^o \\ \epsilon_y^o \\ \gamma_{xy}^o \end{Bmatrix}$$

Another important observation in composite laminate mechanics is that there is a distribution of the applied stresses throughout the laminate. Figure 7 displays the stress distribution with the y-axis representing the distance from the midplane of a laminate cross-section while he x-axis represents stress. Figure 7 demonstrates that as you move away from the midplane, the stress value gets larger. The outer laminas, those furthest from the midplane of the laminate, experience the larger portion of the stress distribution.

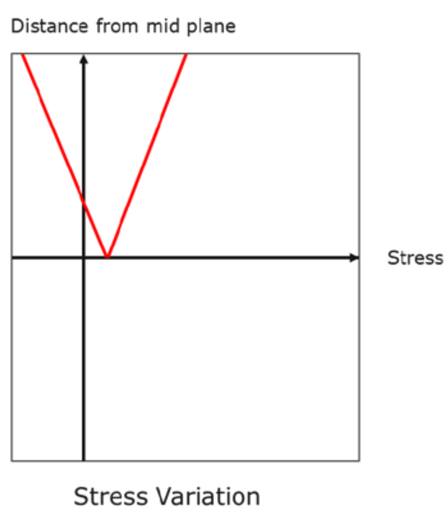


Figure 7 - Graph of the stress distribution experienced in a composite laminate.

1.5 Applications of Folding Composites

Composite materials are slowly making their way into multiple industries. Characteristically lightweight and stiff, composites provide an advantage over other material systems such as metals by reducing the overall weight of the structure while maintaining structural integrity for optimal performance. Composite manufacturing techniques typically are only capable of producing a monolithic composite structure. This means that any hinged design will still require additional hardware, such as bolts and fixtures, to connect the composite structures at hinged locations. Producing a monolithic composite hinge would eliminate the need for extra components reducing both manufacturing time and weight of the overall structure. The ability to produce these monolithic composite hinges capable of performing in structural applications will assist many industries.

Foldable skis are currently being developed to allow backcountry skiers to have a portable ski that is easy to transport by being able to fold down to a size that can fit into a backpack. Figure 8 displays the current design for foldable skis produced by the company MTN [10].

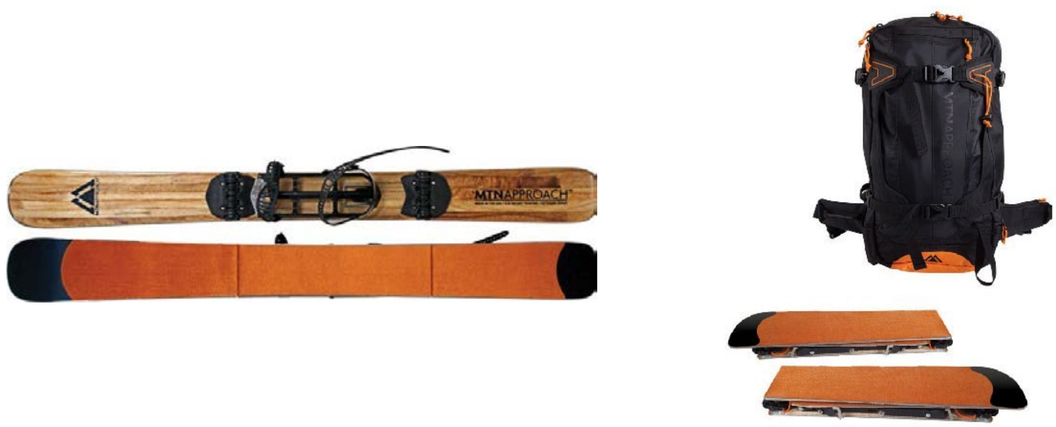
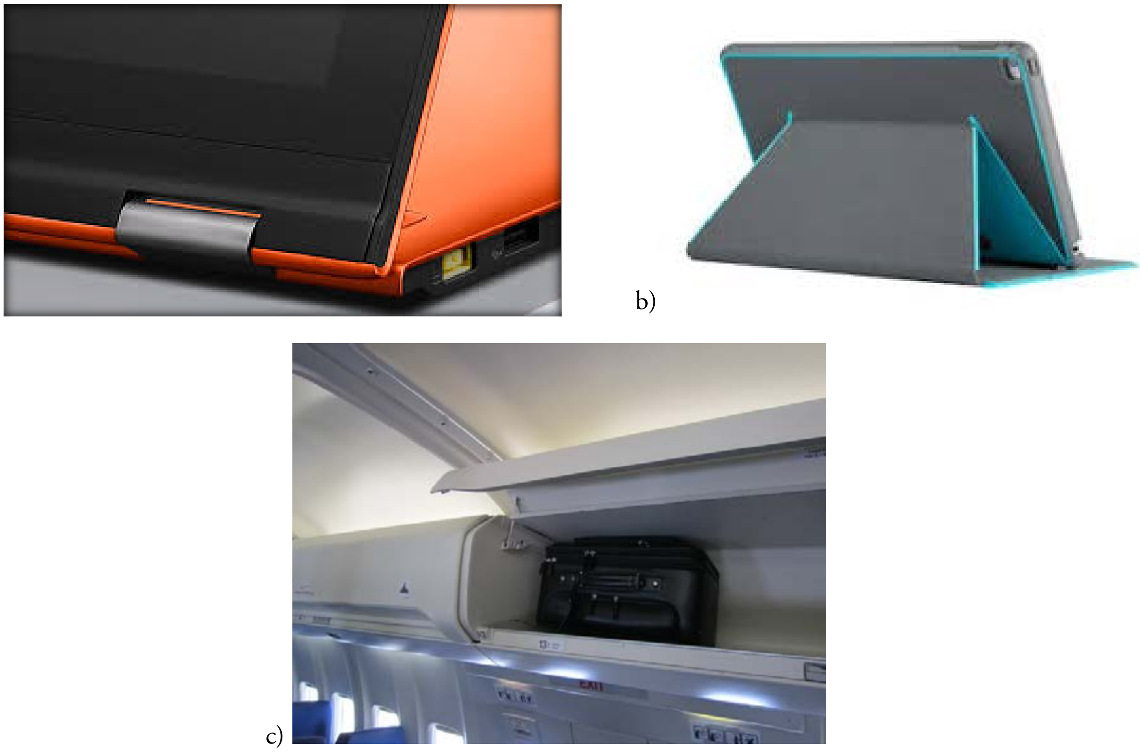


Figure 8 - MTN's design for foldable skis which fold at two locations allowing for compact travel size which can fit into a backpack for easy transport.

The foldable ski design replaces the traditional split boards typically used by backcountry skiers with the introduction of the hinged system. However, since split boards were designed to become snow shoes for the trek upward on a mountain, the foldable ski is meant to be stored on the ascent. This means the skier will have to transport the weight of the skis on their backs as they travel up the mountain. This puts a premium on reducing the overall weight of the ski to provide a functional design for the consumer. Composite materials have an advantage of reducing the weight of the skis while providing the necessary strength properties to function as a ski. Furthermore, in order to maximize the advantage of using composite materials to reduce the weight, Common Fiber's hinge technology would be utilized to eliminate the need for extra hardware to form the hinge.

Hinged composites have the potential to infiltrate many other industries beyond the sporting goods industries as well. Currently, Common Fiber's hinge technology is only being utilized in non-structural applications such as wallets. However, greater characterization of the mechanical properties of Common Fiber's hinges will provide a better understanding of what technologies can benefit from being manufactured with this material. The designer does not have to think of complicated technologies to find suitable applications for these CFRP hinges. Hinged devices exist all around in everyday life from personal computers, electronic device protectors, doors and many more. Laptop computers rely on a hinge to be able to fold in a more compact and portable device (Figure 9a) [11]. Manufacturing the body out of composite material and implementing the hinge technology will provide the benefit having a lightweight personal computer to the user. Additionally, the impact toughness of the composite will better protect the fragile, internal electronic components in the case of accidents. These benefits extend to the electronic device cases such as the iPad case pictured in Figure 9b [12]. Furthermore, aircraft interiors can also benefit from the hinged composite technology. For instance, the overhead compartment doors (Figure 9c) and the folding trays on the back of the seats could be manufactured with Common Fiber's composite hinge technology [13].



a) b) c)

Figure 9a, b, c – Images of various hinged devices that could potentially benefit from the application of Common Fiber's hinged composite technology.

2. Methods and Procedures

2.1 The V-Notch Rail Shear Method

The decision to characterize the shear strength of Common Fibers' composite hinge was determined by observations of loading conditions hinges undergo. For example, when considering a door hinge, the load of the door is inducing shear forces on the hinge. The V-notch rail shear method, specified by ASTM D7078, is used to test the shear mechanical properties of composite materials [14]. The test involves the use of a fixture designed to offset the load from the central axis of the testing sample (Figure 10). The offsetting of the load allows for shear forces to be applied to the specimen using an Instron mechanical testing system. The specimens are water-jet cut with a 'V-notch' to concentrate the shear forces to a specific region (Figure 11). The concentration of forces at a specific region of the composite allows the specimen to fail in the same location allowing for consistent results.

Figure 10 - Image of the ASTM D7078 fixture with specimen loaded ready to be tested.

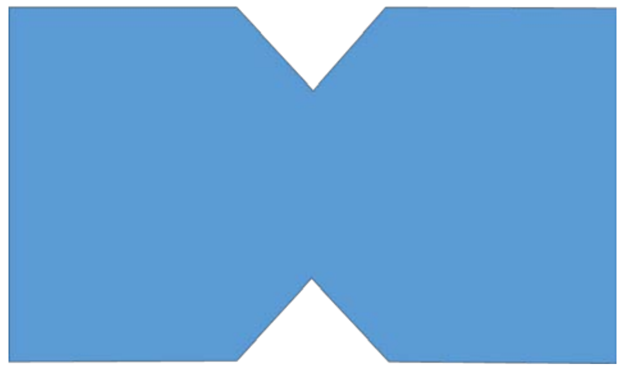


Figure 11 - Shape of the test specimen displaying the 'V-notch' used to concentrate stresses to a particular region.

As seen in Figure 10, the fixture has three screws which tighten to apply a clamping surface onto the composite sample. Each bolt was tightened to 35 ft-lbs as specified by ASTM Standard D7078 ensuring that enough force is applied onto the sample to prevent slipping [14]. The fixture is then loaded into an Instron mechanical testing system into the crossheads using the appropriate adapters. The Instron displaces the fixture producing an applied load on the composite sample inducing shear forces at the 'V-notched' region (Figure 12). The Instron interface then records load (kN) and displacement (mm) while producing load-extension curves.

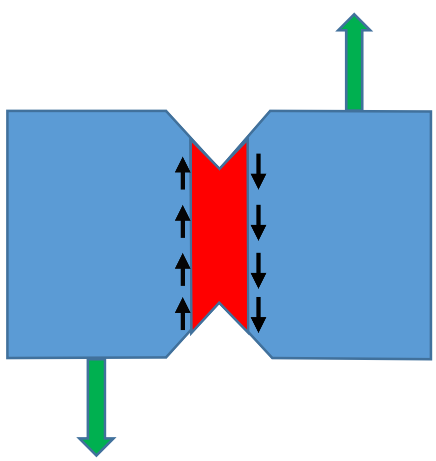


Figure 12 - Diagram of specimen (blue) with hinge (red) and applied loads and reaction shear forces displayed at the hinge.

The Instron mechanical testing system was set up to have a crosshead rate of 2 mm/min as specified by ASTM D7078 [14]. The V-notch rail shear testing fixture was purchased from Wyoming Testing Fixtures.

2.2 Procedure

2.2.1 Composite Layup design

The composites designed for the experiment included layups of $[+45/-45/0]_s$ and $[0/+45/-45/0]_s$. Since shear strength is the focus of the experiment, both designs of the composites included alternating layers of $+45^0$ and -45^0 orientations of laminas providing maximum resistance to shear forces. Furthermore, both designs also included middle layers of 0^0 oriented fibers to provide resistance in the tensile mode as well. However, the second layup has an additional layer of 0^0 oriented laminas on the outside of the laminate. The hinging process performed by Common Fibers introduces a high heat input to the surface of the composite that may have an adverse effect on the outer layer of fibers. With that concern, the outer layer of 0^0 oriented fibers acts a sacrificial layer protecting the 45^0 oriented fibers that provide the necessary shear strength. The laminate designs were sent to Common Fibers who contracted with a third-party company that manufactured the laminates. Once manufactured, Common Fibers waterjet cut the samples into the appropriate dimensions as specified by ASTM D7078. Common Fibers used their CO_2 laser to hinge half of the specimens at 'V-Notch' indicated by the red region of Figure 12.

2.2.2 Testing and Experimental Plan

The experiment was designed to characterize the shear properties of composite hinges. Shear testing on a flexible, live-integral composite hinge has never been done before. The V-notch Rail shear was designed for traditional and stiff composite materials. In order to characterize the shear properties of the hinges, traditional, or unhinged, composites served as a baseline to compare to Common Fibers' hinged composite. ASTM D7078 specifies that five specimens are needed to have a complete test and obtain significant results. With that in mind, five specimens of each laminate, both hinged and unhinged, were tested to obtain data that could be analyzed to characterize the shear properties. The thickness of each sample was recorded and observed for any defects or irregularities in condition (i.e, surface flaws). The fixture was loaded into the Instron mechanical testing system. Then a composite sample was then loaded into the fixture following the ASTM standard. Each test was run until failure obtaining data for maximum load and load-extension curves. After each test, observations of the sample were recorded noting failure mode and pictures of each sample were taken to document appearance of a failed, hinged and unhinged, composite for comparison.

2.2.2.1 Experimental Plan Revision

After a complete round of testing, which included testing both hinged and unhinged composites of both laminates, a new variable was introduced into the observational data. It was observed that the composite samples could be loaded into the fixture with different fiber orientations. Using the outer layer of fibers as a reference, it was noted that for the $[+45/-45/0]_s$ laminate, the sample could be set into the fixture at a $+45^0$ or a -45^0 orientation (Figure 13 and 14). This observation and variable was noted in a second round of testing for these laminates.

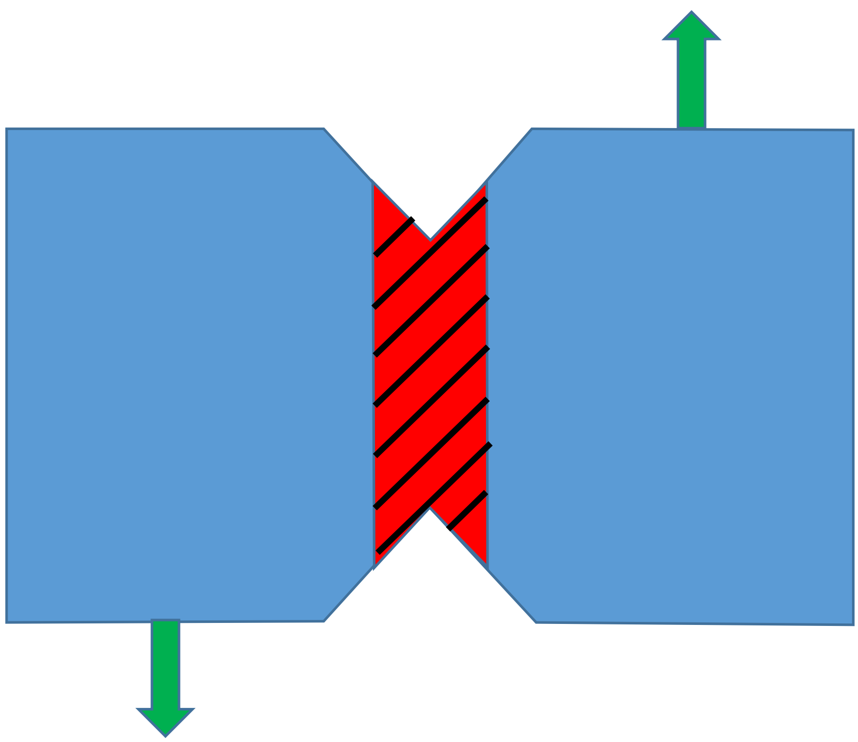


Figure 13 - Diagram of setup condition 1 with the fibers of the outer lamina oriented at $+45^0$.

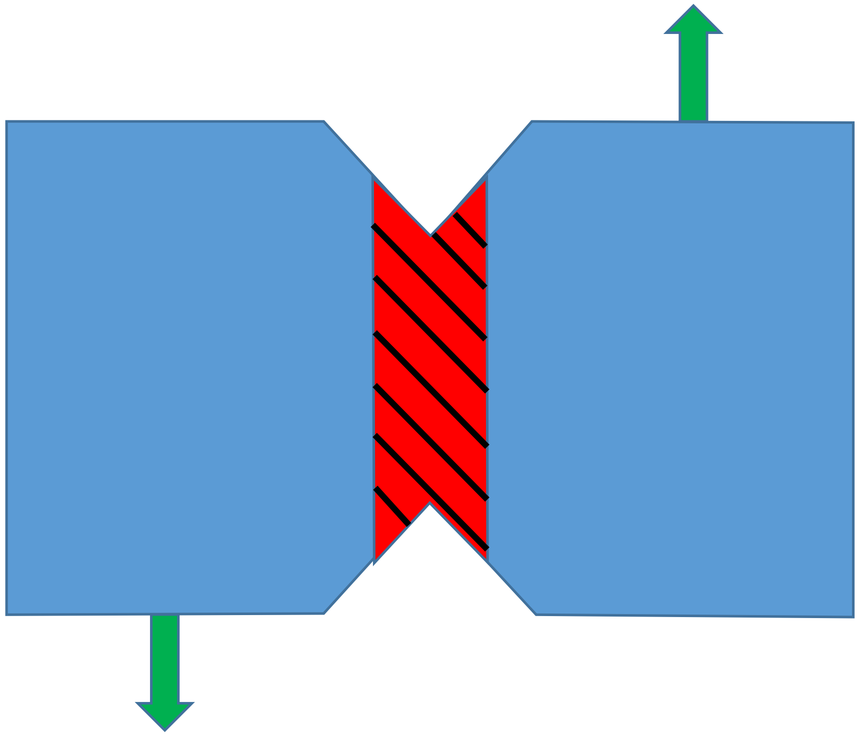


Figure 14 - Diagram of setup condition 2 with the fibers of the outer lamina oriented at -45^0.

3. Results

3.1 Traditional Unhinged Composites

To begin to characterize the shear mechanical properties of the composite hinges, traditional composite properties needed to be measured to provide a baseline for comparison. The unhinged laminates were tested using the V-Notch rail shear method obtaining load-extension curves and maximum load achieved. Per ASTM D7078, 5 samples of each layup would be tested to provide enough data for characterization. Table I displays the results of maximum load from the unhinged composites. The average load-extension curves for both laminates, $[+45/-45/0]_s$ and $[0/+45/-45/0]_s$, displayed similar behavior (Figure 15).

Table I: Maximum Loads from Unhinged Composites

Sample	Maximum Load (kN) $[+45/-45/0]_s$	Maximum Load (kN) $[0/+45/-45/0]_s$
1	12.033	12.237
2	12.751	11.398
3	11.687	10.727
4	12.518	11.437
5	12.311	11.396
Average	12.260	11.396

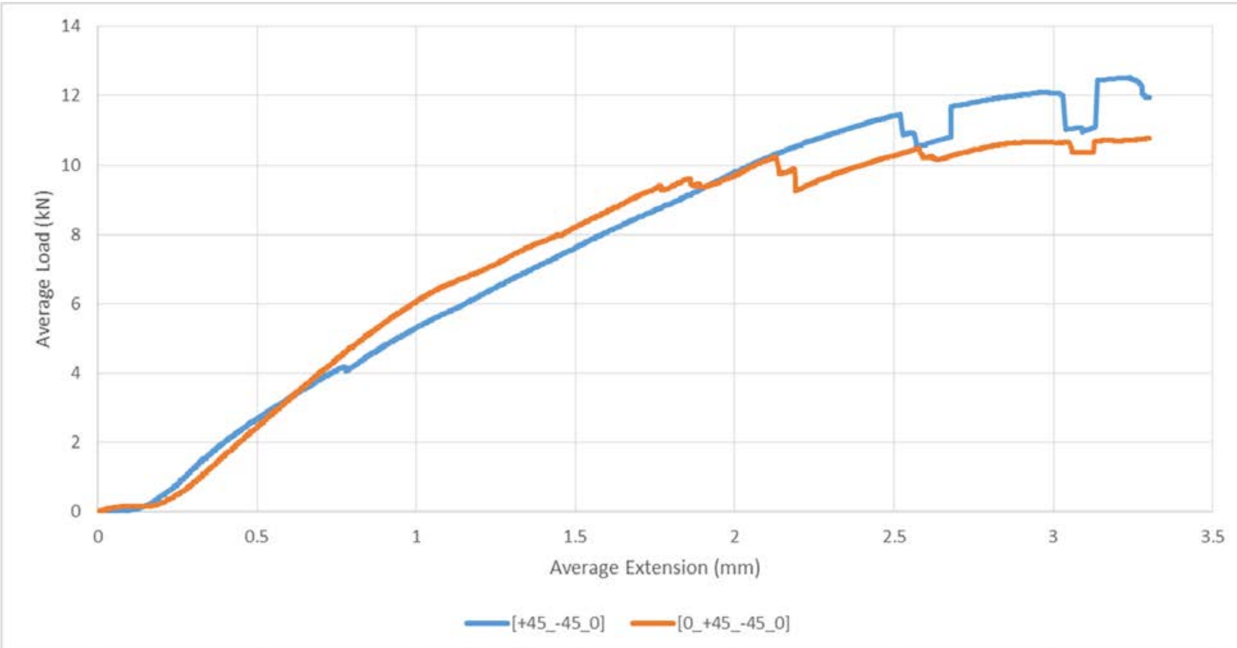


Figure 15 - Average load-extension curves for both the $[+45/-45/0]_s$ and $[0/+45/-45/0]_s$ laminates displaying similar behavior.

The average maximum load for the $[+45/-45/0]_s$ laminate was measured to be 12.260 kN. The average maximum load for the $[0/+45/-45/0]_s$ laminate was measured to be 11.396 kN. As can be seen in Figure 15, combined with the numerical data previously listed, both composite laminates exhibit similar data with little variance.

3.2 Hinged Composite: First Observations

As specified by ASTM D7078, five samples of both hinged composite layups were tested to obtain a significant amount of data for characterization. The consistency of the traditional composites was not observed in the initial tests of the hinges. The load-extension curves for the $[+45/-45/0]_s$ laminate displayed extreme amounts of variability from sample to sample (Figure 16). As seen in the load-extension curves, each sample, with the exception of samples 2 and 5, exhibited unique mechanical behavior and shear properties. The maximum load of sample 1 reaches almost 5 kN while the lowest recorded maximum load is 1.709 kN. Similarly, the load-extension curves for the $[0/+45/-45/0]_s$ hinged laminate also displayed inconsistencies in the data as well (Figure 17). Table II lists the maximum loads measured from each sample of composite hinges.

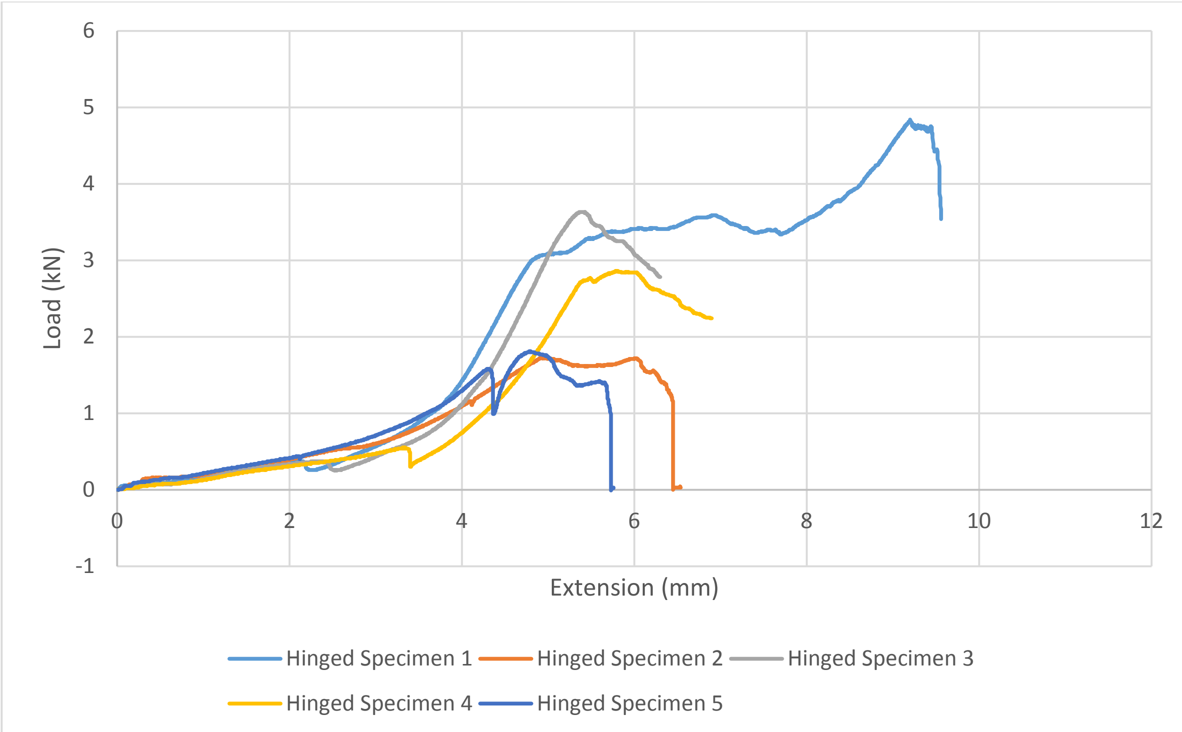


Figure 16 - Load-extension curves for the hinged $[+45/-45/0]_s$ laminate.

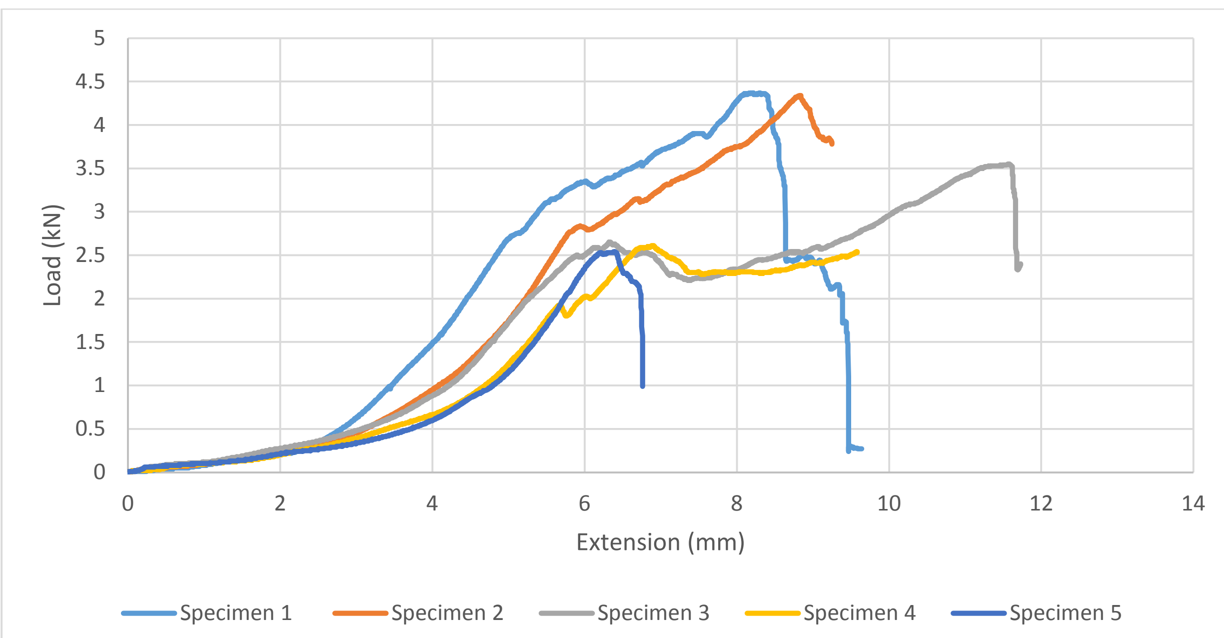


Figure 17 - Load-extension curves for the $[0/+45/-45/0]_s$ hinged laminates.

Table II: Maximum Loads Measured for Hinged Composites

Sample	Maximum Load (kN) $[+45/-45/0]_s$	Maximum Load (kN) $[0/+45/-45/0]_s$
1	4.836	4.372
2	1.727	4.343
3	3.634	3.550
4	2.858	2.613
5	1.807	2.537

Given the variability in the data for both hinged laminate designs, characterization of the shear mechanical behavior is difficult. However, it was discovered that the manufacturing process was inconsistent for the production of each hinge. The variability in manufacturing was eliminated and more samples were produced for testing.

3.3 Hinged Composite: Variable Heat Input Removed

The variability in processing was eliminated in the manufacturing of the hinge and new samples of the $[+45/-45/0]_s$ hinged laminates were produced for testing in the V-Notch Rail shear method. Although this was believed to be the root cause for the variability seen in Figures 16 and 17, the data obtained from testing these hinges produced with consistent heat input displayed similar variability. Referring to Figure 18, the load-extension curves display similar behavior up until the 4mm extension point. Past that extension mark, the curves diverge revealing inconsistencies throughout the testing. Again, the inconsistencies in the results prevent conclusions from being drawn.

Table III: Maximum Loads for Hinged Composites Produced with Same Heat Input

Sample	Maximum Load (kN) $[+45/-45/0]_s$
1	5.320
2	4.903
3	3.396
4	4.883
5	3.029

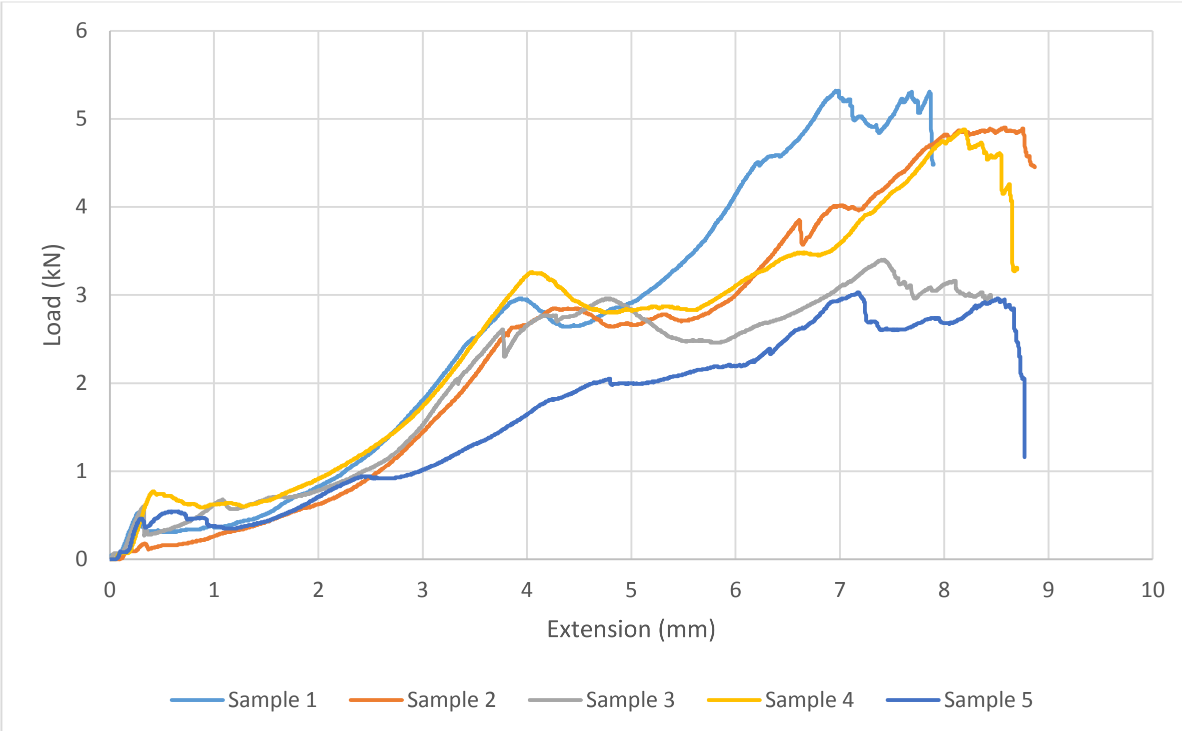


Figure 18 - Load-extension curve for a [+45/-45/0]$_s$ laminate produced using consistent heat inputs from the CO_2 laser for each sample.

3.4 Hinged Composites: Varying Fiber Orientation

Hinged samples produced with the varying heat inputs were revisited for testing, however, a new observation was noted during this set of tests. During the set up for each test, it was noted that there are different orientations of the fibers based on how each sample is loaded into the fixture. Using the outer layer as a reference, the sample can be loaded into the fixture with a +45^0 fiber orientation or a -45^0 fiber orientation (Figures 13 and 14). When this observation was noted, the results from the V-Notch rail shear test on the [+45/-45/0]$_s$ hinged laminate began to display consistent results. Figure 19 displays the load-extension curves for the samples tested noting fiber orientation.

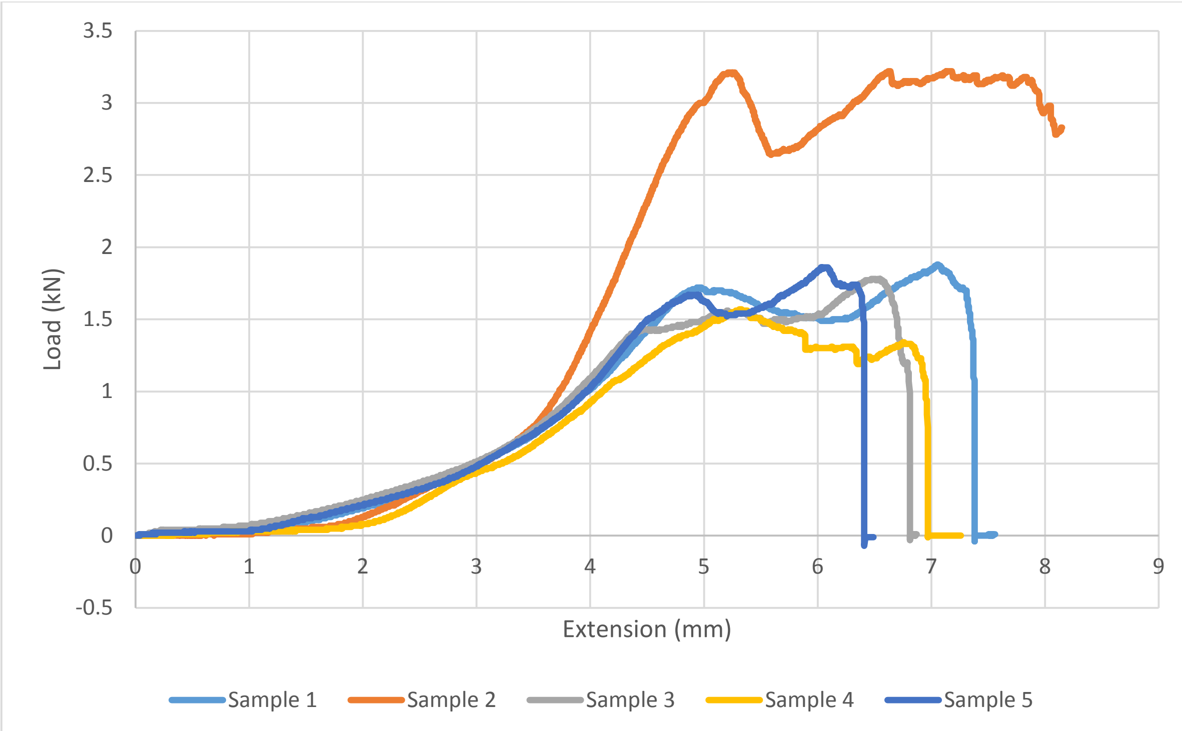


Figure 19 - Load-extension curves for $[+45/-45/0]_s$ hinged laminates produced with variable heat input. The samples (1, 3, 4, and 5) display consistent results due to consitent set up with the fiber orientation of the surface lamina set at -45^0.

Referrring to Figure 19, samples 1, 3, 4, and 5 all exhibit similar shear mechanical behavior and were loaded into the fixture with the surface laminas oriented at -45^0 to the horizontal plane. Sample 2, however, was oriented at $+45^0$ to the horizontal plane.

3.5 Visual Observations

3.5.1 Ablation Process

Visual inspection of the $[0/+45/-45/0]_s$ hinged laminate on arrival displayed evidence that the assumption that the outer layer of fibers would act as a sacrificial layer protecting the inner +/- 45^0 laminas is correct. Figure 20 displays an image taken of one of these hinged samples in the as received condition. Observations of the hinged region show that the horizontal fibers that should appear in the hinge are not present. Instead, looking at this image reveals the inner laminas of 45^0 oriented fibers giving credence to Common Fibers' claim.

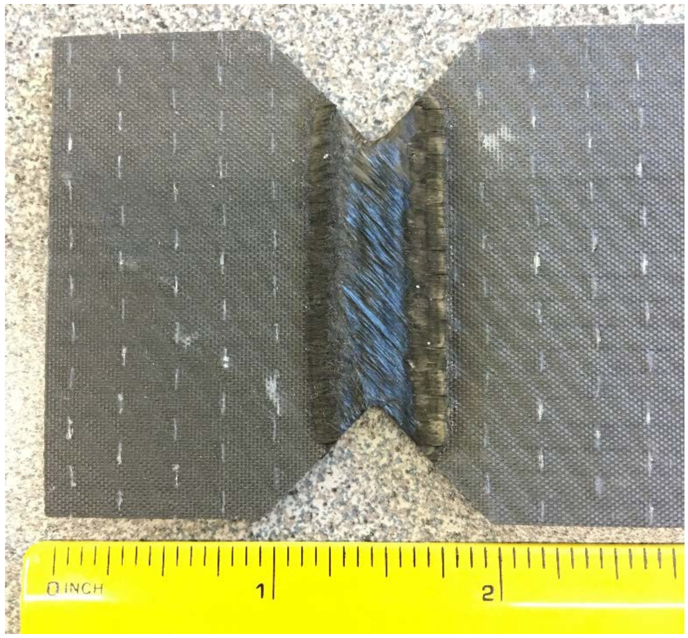


Figure 20 - Image of the hinged region of a $[0/+45/-45/0]_s$ laminate after laser ablation displaying the absence of the outer 0^0 fibers revealing the inner layers of 45^0 oriented fibers.

3.5.2 Failure Mode: Splintering Delamination

Hinged composites, similar to the traditional unhinged composites, demonstrated evidence of delamination as the failure mode during the shear tests. However, for the hinged composites, the delamination presented itself in a splintering fashion along the hinge-composite interface (Figure 21). Looking at Figure 21, splinters of the unhinged region of the composite material are begin to peel, or delaminate from the inner layers of composite material. However, instead of the lamina remaining intact and delaminating as one piece, the outer lamina splinters producing multiple sections of delaminating composite material. This behavior unique to hinged composites presented itself in all hinged samples as a common failure mode among the hinges from the shear test.

Figure 21 - Image of a $[+45/-45/0]_s$ hinged laminate post V-Notch shear testing. The image displays the failure mode of splintering delamination along the hinge-composite interface.

4. Discussion

The results from the hinged composite V-Notch rail shear tests, although varied, all display a reduction in ability to support a load. While the $[+45/-45/0]_s$ unhinged composite was able to support an average load of 12.260 kN and the $[0/+45/-45/0]_s$ unhinged composite was able to support an average load of 11.396 kN, the hinged composites, regardless of laminate layup design, were only able to achieve a maximum load of at most 5.36 kN. Carbon fiber, by itself, is a flexible material just like any other fiber. It is only with a resin, such as epoxy, that carbon fibers can be used to produce a stiff composite panel. Since the hinged region in Common Fibers' composite hinge is assumed to be dry, exposed carbon fibers with the resin being ablated from the CO_2 laser, the production of a hinge increases the flexibility of the hinge. This is evidenced in Figures 16, 17, 18, and 19 displaying the shear extension as being greater than the 2-3 mm extension of the traditional unhinged composite material (Figure 15). Since this hinge is no longer technically speaking a composite material, the increased properties, such as strength, achieved by combining carbon fibers with an epoxy resin are lost. This results in a weaker material displayed by the maximum strength results of the composite hinges.

The variability of the load-extension curves and the maximum load achieved by the hinges appears to be caused by two reasons. Initial testing of the composite hinges immediately demonstrated the variability in shear mechanical strength of Common Fibers' hinges. Investigation into the manufacturing process revealed that the production method used to produce the hinge had variations in it. Figure 21 displays the production set up used to manufacture the hinge. As the position of the CO_2 laser moves up and to the left on the table, the heat input generated by the laser increases. With the evidence of Figure 20 displaying the effect the CO_2 laser can have on both the resin and the fibers of the hinge, it can be concluded that the variations in the heat input from the laser can have varying effects on the material properties of the carbon fibers and the composite hinge.

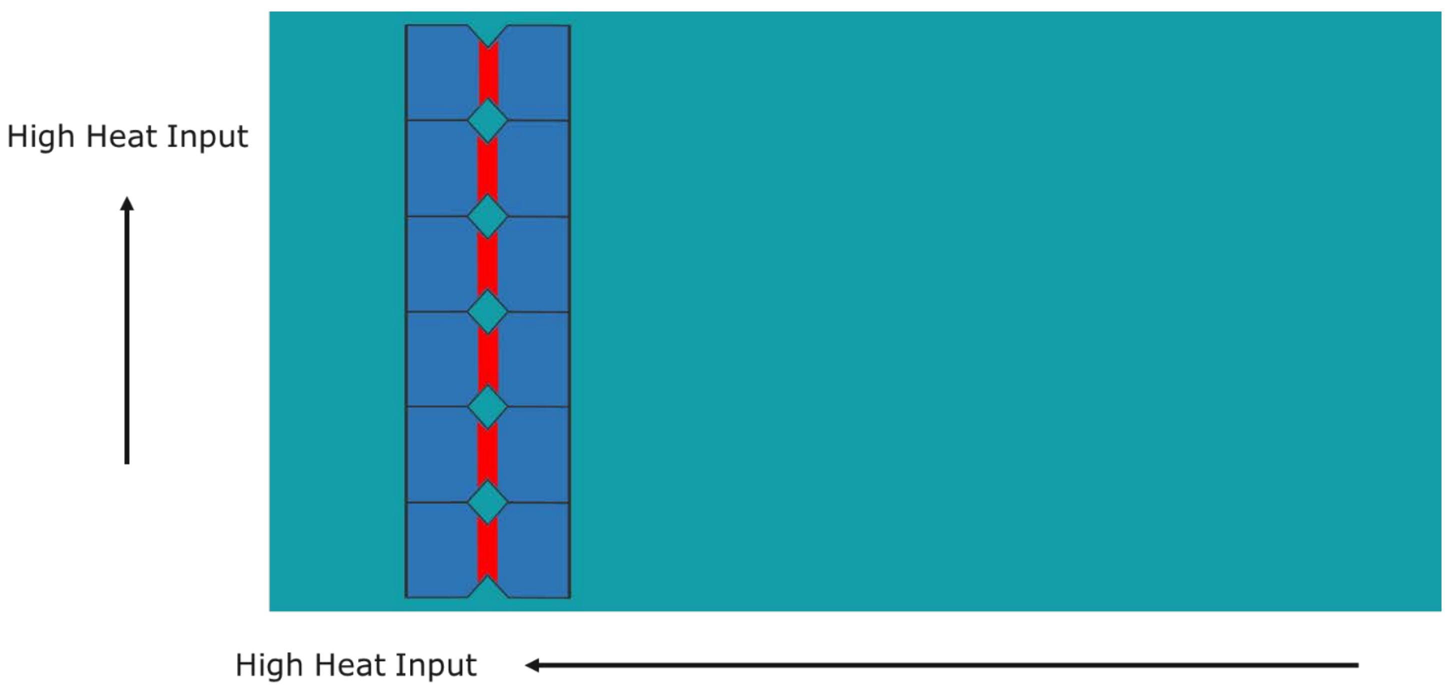


Figure 22 - Diagram of the hinging process displaying that the hinges were manufactured using varying heat inputs.

On the other hand, further results demonstrated the possibility of a second cause of the variability displayed in the shear strength of the composite hinges. Figures 13 and 14 exhibit the two set up positions for the composite samples using the fiber orientation of the outer lamina of $+45^0$ or -45^0 as a reference. When this variable was noted, the results of the V-Notch Rail shear method began to display consistency among the samples set up in the fixture with similar fiber orientations. Figure 18 displays four samples with similar load-extension curves that were all set up into the fixture with the outer lamina fiber oriented at -45^0. The -45^0 oriented samples achieved lower maximum loads that the sample which was set up in the $+45^0$ orientation. The reason we can use the outer layer of laminas to explain this behavior is due to the stress distribution of the load throughout the composite laminate. As is seen with Figure 7, the outer layers of the laminate experience the greatest stresses in the stress distribution of the composite laminate. Therefore we can neglect the inner laminas of fiber orientations in the analysis. Using the outer layer of fibers as a reference, when the composite hinges are set up in the $+45^0$ orientation, the shear load is transferred to the fibers along the longitudinal axis of the fiber (Figure 23). Since the fibers in this orientation are supporting the applied shear load along their longitudinal axis, the composite hinge will be able to support a greater load as was seen in Figure 19.

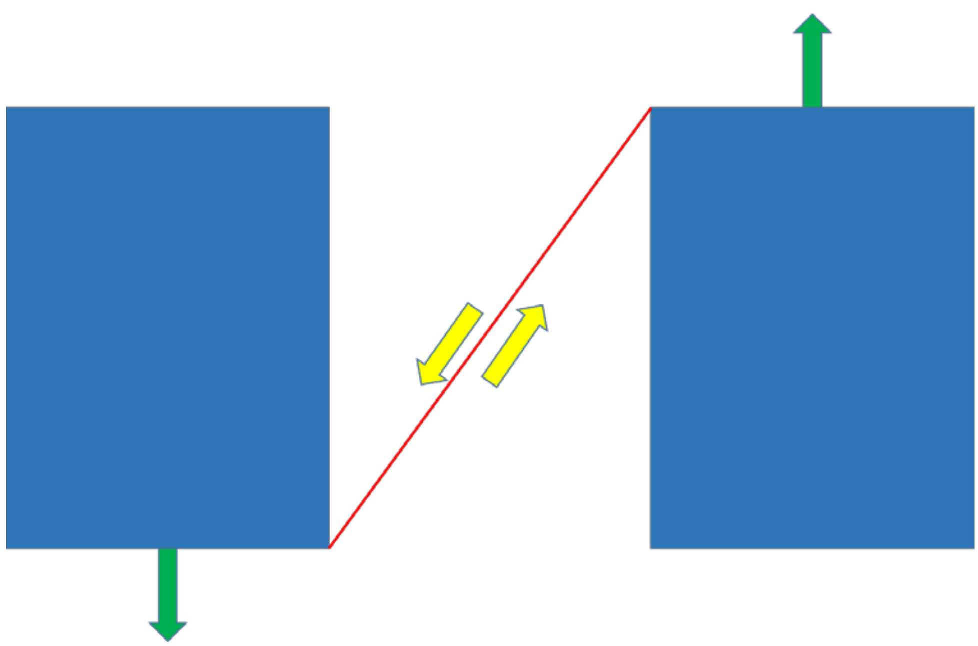


Figure 23 - Diagram demonstrating how the applied load is transferred to the fibers loaded at a $+45^0$ orientation. Since the load is transferred along the longitudinal axis, the composite hinge is able to support a greater load.

On the other hand, when the outer laminas are oriented at the -45^0 orientation, the load is transferred perpendicular to the longitudinal axis of the fibers. Since this is the case, as the hinge begins to displace, the fibers deform into a S-shape rather than supporting the applied load (Figure 24). This explains why the four samples, which were set up in this -45^0 orientation, achieved less maximum loads than the outlying sample oriented at a +45^0 orientation.

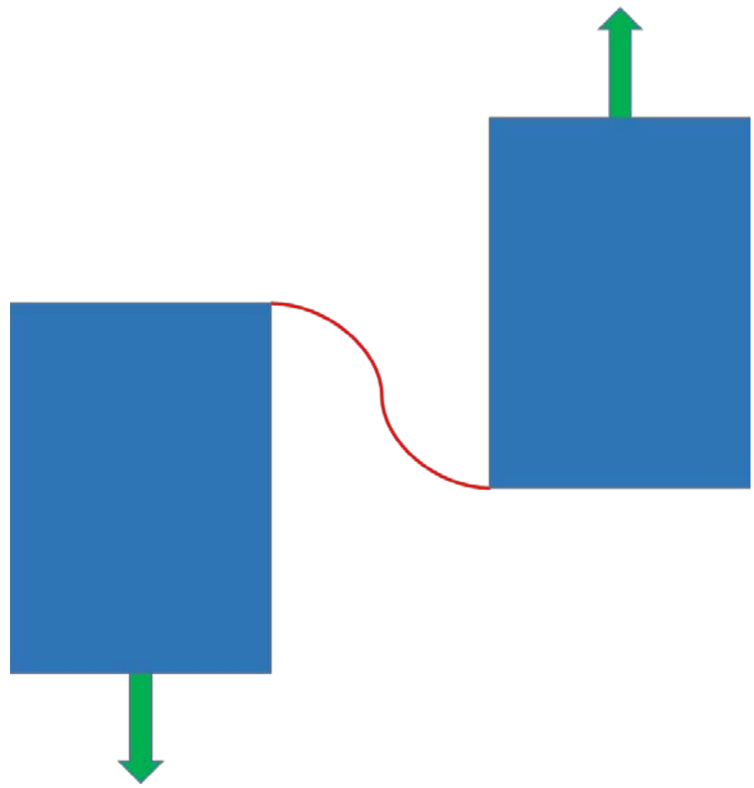


Figure 24 - Diagram of a hinged composite loaded with the outer lamina oriented at -45^0 during testing. The diagram displays an example of a fiber in the outer lamina forming an S-shape which explains why samples loaded in this orientation achieved smaller loads.

With these results connected to the observations of the fiber orientation of the outer lamina, hinged composites appear to demonstrate a sensitivity to fiber orientation not experienced in traditional composite materials. More testing is recommended to further verify the conclusions from these observations.

5. Conclusions

1. Although the results displayed large amounts of variation, the composite hinges shear strength was less than that of a traditional unhinged composite. While hinged composites achieved maximum

loads on average of 12.260 kN and 11.396 kN for $[+45/-45/0]_s$ and $[0/+45/-45/0]_s$ laminates respectively, hinged composites, regardless of the layup, achieved maximum loads of 5.320 kN.

2. The variability in results seen in testing the shear properties of the hinged composite can be traced back to the variations in heat input used to manufacture the hinges. Not only does this provide an explanation to the variability in the results, but it also demonstrates that there is an effect on the conditions of the materials located in the hinged region.

3. Variability of the results can further be tied to variations in the fiber orientation with respect to the loading axis. Taken into account the connections displayed between maximum load and fiber orientation, there is evidence that hinged composites produced by Common Fibers experience a sensitivity to the fiber orientation.

6. References

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