Mechanical Testing of Multi-Construction Composite Tubes for use in Fly Fishing Rods

A Senior Project

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By

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Abstract

A testing protocol was established for measuring the flexure properties of thin-walled tubes constructed of a composite mixture of glass and carbon fibers and epoxy resin for use in Fly Fishing rods. Standard three point bend tests were conducted in accordance with ASTM standard D7329-13 with a span length of six inches. All samples were of the sample length and diameter, allowing direct comparison of the maximum loads reached before failure, which are directly indicative of the Modulus of Rupture (MOR). Two constructions were tested both containing the same unidirectional fiber but with different support structure. These tubes were tested identically for both as delivered samples and for the samples having undergone ultraviolet, humidity, and elevated temperature exposure. Construction 1 reached higher maximum stresses than Construction 2 and displayed similar amounts of flexure. When coated and exposed, the strength of Construction 1 and 2 both increased when compared to uncoated and unexposed samples. In Construction 1, maximum loads achieved in samples painted, clear coated and exposed averaged loads at failure of 45.33lb, solely clear coated and exposed samples averaged 42.9lb at failure, uncoated and exposed averaged 38.1lb, and uncoated and unexposed averaged 40.9lb. In Construction 2, the differences were less pronounced. Painted, clear coated, and exposed averaged 39.6lb at failure, clear coated and exposed averaged 38.0lb, uncoated and exposed averaged 36.2lb, and uncoated, unexposed averaged 36.6lb. To ensure population differences, statistical evaluation was done at a 95% confidence interval.

Keywords: Composite, Carbon Fiber, Epoxy, flexure testing, Fly Fishing, Bend test, ultraviolet, exposure, irradiation, polymer degradation, Materials Engineering

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Introduction

Fly Fishing History

Fly fishing today has advanced significantly over the last 100 years, but the basic premise remains the same: trick a fish into biting a hook that looks like an insect. Fly fishing has moved past a method of sustenance and into a recreational pursuit and a cultural pillar. The first reference to this style of fishing comes from the Roman author Claudius □lian in his document called *Various History*, written around 200AD[1]. In the text, he describes a Macedonian method of fishing using feather and wool wrapped around a hook. The direct passage is translated as:

> *"..they have planned a snare for the fish, and get the better of them by their fisherman's craft. . . . They fasten red wool. . . round a hook, and fit on to the wool two feathers which grow under a cock's wattles, and which in color are like wax. Their rod is six feet long, and their line is the same length. Then they throw their snare, and the fish, attracted and maddened by the color, comes straight at it, thinking from the pretty sight to gain a dainty mouthful; when, however, it opens its jaws, it is caught by the hook, and enjoys a bitter repast, a captive."*[2]

It is thought that many nomads practiced this method of fishing but no historical record can be found[1]. Although many Germanic texts bear mention of fishing with a "feathered hook", the first western publication focusing on fly fishing was *Treatyse of Fishing with and Angle*. Published in 1496 and attributed to Dame Juliana Berners, the book contains a wealth of information[1]. It contains methods of tying different types of flies, rod and line construction, and lists many of the British fish species. Figure 1 below shows a painting titled *Angling* by a 17th century painter, illustrating what short fly rods looked like[3]. The Japanese also have a method of traditional fishing called "Tenkara" which was recorded being practiced in the small mountain streams of Japan since the 17th century, but is thought to have been practiced for millennia[3]. Bamboo rods were commonplace in Japan beginning in the 17th century but archeological evidence shows that bamboo rods were likely used as early as the 9th century BCE[4]. Tenkara rods are still used as a novelty today, as they are made with a short line attached directly to the rod with no reel, limiting the effective reach of the line. In the 19th century after the British had made several voyages to the east, they brought bamboo back with them, where it soon found use in rods.

Figure 1: Painting by Wencelaus Hollar depicting angling on an English stream. Painted between 1607 and 1677[3].

The rods of Britain around this time were made with flexible wood, often hazel, with braided horse hair fixed line. The rods for salmon fishing were long, around 15 to 18 feet, while all other fish were caught on rods between 10 and 14 feet[1]. In the 18th century, the advancement of metalworking allowed for the first free lines on reels, typically made of bronze. These failed frequently due to their soft nature and their high stress situations. American metalworkers earned their place in the fly fishing world by developing the first reliable, durable reels. It was not until the 19th century that bamboo and split cane rods began to be commonly used, and Figure 2 contains an example of a split-cane style rod[5]. Silk processing and metalworking advanced to the point where reels and lines began to resemble those we use today. The Dry Fly technique, which remains the style of choice today, was developed in Scotland in the 1850s and popularized the use of shorter rods for trout. Once the

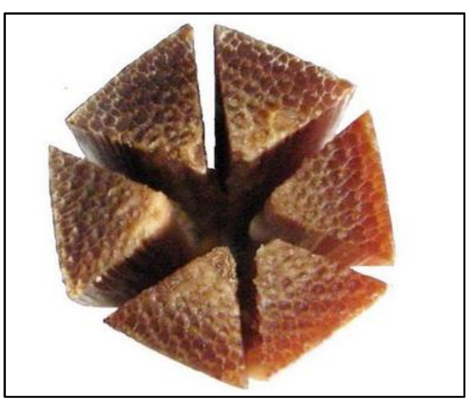


Figure 2: An example of a split cane rod before adhesive glue is applied[5].

20th century began, standardization began to take place across the industry. Rods began to be measured in length and their weight, which corresponded to stiffness, and the mounting points for reels and other devices were also standardized. Split cane rods, made of hexagonal milled bamboo strips glued together, were the standard and performed better than any other rod type that came before. The development of floating lines removed the need for long heavy rods so the 18 foot salmon rods basically became obsolete overnight[1]. In the 1950s, the development of fiberglass rods brought the cost of a rod down, as they were more easily produced than split-cane rods and achieved the same performance. The carbon-fiber rods of today were first produced in 1976 and brought the weight of rods down to the point that the weight of the fly line became much more important than the rod weight[6].

Rods Today

The available styles of rods today are as numerous as they are different. Bamboo rods are still available, but are more of a novelty and have a small niche market. Most quality rods are made with carbon fiber or fiberglass, or a mixture of several options. Rods are built with a type of fishing in mind, so a rod designed for creek run trout weighing no more than two pounds is going to be significantly different than a saltwater rod meant for chasing 100+ pound Tarpon. The system used to classify the differences is called a weighting system with each rod getting a "weight". Table 1 lists the various physical measurables of the Sage Salt series, and you can see that the higher weight rods typically are heavier, due to more material needed to combat bigger fish[7]. This weight has nothing to do with the actual mass of the rod; it is instead to be paired with a fly line of equal weight. The heavier weight lines are stronger and for larger fish, and as such higher rod weights are meant for bigger fish. The small 2 pound trout from earlier would be well fished on a 2 or 3 weight rod. The Tarpon, which can grow up to nearly 300 pounds and typically breach the water

Table I: Physical properties of Sage Salt series rods

MODEL	LINE	LENGTH	TUBE SIZE	WEIGHT	MSRP
590-4	5	9'0"	30"	3⅔	$850
690-4	6	9'0"	30"	3⅘	$850
790-4	7	9'0"	30"	4	$850
890-4	8	9'0"	30"	4	$850
990-4	9	9'0"	30"	4⅛	$850
1090-4	10	9'0"	30"	4⅓	$850
1190-4	11	9'0"	30"	4⅘	$850
1191-4	11	9'0"	30"	4⅞	$850
1290-4	12	9'0"	30"	4⅞	$850
1291-4	12	9'0"	30"	5	$850
1386-4	13	8'6"	28½"	$5^{4/9}$	$850
1686-4	16	8'6"	28½"	6⅜	$850

during fights, are often caught on rods with a weight above 11, from 12 all the way up to 16.

Fly Fishing as a Cultural Identity

Dating back to the 15th century, fly fishing was regarded as a sport of gentleman, akin to hunting[1]. Once the Americas were established, fly fishing made its way from the Pennsylvania streams to the vastness of the west. The fly industry was growing at a rapid rate as wealthy individuals journeyed west on vacations, inspired by magazine images commissioned by the industry. Up until the 1940s, the Steelhead and other salmon species of the Pacific Northwest and the wild trout of the Sierra Nevada mountain range were considered the ultimate fly fishing species and scenery. Several men who owned fly fishing shops and put out catalogues decided to sell Montana and the Rockies, whose wild trout remained mostly untouched in slow winding rivers winding through vast grassy plains. Today, Montana, Colorado and Wyoming are renowned for their fishing.

Culturally, the fly fishing community has always been a small niche in the broad scope of fishing. It takes hours of practice, it can be lonely, the fish are rarely of record size, and the long hours away can be a barrier to the full experience. It has however taken on an aura typically reserved for religions. Earnest Hemmingway was a lifelong fisherman and his famous *Big Two-Hearted River* helped awaken the public to the mystique of fly fishing. With passages such as the following, the public became enamored with the idea of tossing lines:

> *"There was a long tug. Nick struck and the rod came alive and dangerous, bent double, the line tightening, coming out of water, tightening, all in a heavy, dangerous, steady pull."*
> *"With the core of the reel showing, his heart feeling stopped with the excitement, leaning back against the current that mounted icily his thighs, Nick thumbed the reel hard with his left hand … As he put on pressure the line tightened into sudden hardness and beyond the logs a huge trout went high out of water. As he jumped, Nick lowered the tip of the rod. But he felt, as he dropped the tip to ease the strain, the moment when the strain was too great; the hardness too tight. Of course, the leader had broken. There was no mistaking the feeling when all spring left the line and it became dry and hard. Then it went slack.*
> *His mouth dry, his heart down, Nick reeled in. He had never seen so big a trout. There was a heaviness, a power not to be held, and then the bulk of him, as he jumped. He looked as broad as a salmon.*
> *Nick's hand was shaky. He reeled in slowly. The thrill had been too much. He felt, vaguely, a little sick, as though it would be better to sit down.* "[8]

As of recently, the novel and subsequent 1992 movie *A River Runs Through It* starring Brad Pitt, is a depiction of 20th century of life in Montana that thrust fly fishing into the public consciousness. It was nominated for three Academy Awards, winning the award for Best Cinematography and grossing over $43 million in theaters[9]. The movie had a dramatic impact on the fly fishing industry; nationwide the industry grew by 60% the year following the film, and another 60% the year after that[10]. The 1970s explosion in the industry was brought about as a byproduct of increased leisure time, better rod technology, and a renewed interest in the outdoors. Figure 3 is from a publication put out by airstream called *The Airstream Story* that demonstrates the perception of fly fishing and its participants at the time[11]. Then in the 90s, A *River Runs Through It* established fly fishing as an "American" activity and gave it an aura and a certain mystique, an almost religious pursuit. It also fed the sweeping "faux-cowboy" culture growing in pop culture[12].

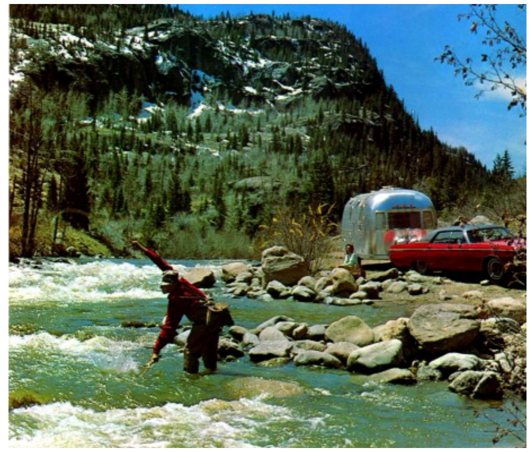


Figure 3: Image from a 1970s Airstream pamphlet, depicts the lifestyle associated with fly fishing[11].

Understanding Composites

Timeline

Composite materials are by definition: two materials dissimilar in composition and behavior that when combined, have properties different from the individual components. In this case, humans have been using natural composites for as long as humanity has been around. Wood and cork are two examples of composites that nature produces, while straw-reinforced mud is identified as the first man-made composite[13]. In the 12th century, Mongols developed archery bows consisting of a bamboo spine, laminated with cattle horn, with cattle tendon added for spring, wrapped in silk and soaked in pine sap. These bows were renowned for their compact size and amazing strength and have been recorded to reach 80% of the strength of a modern composite bow[13].

In the late 1800s, the first synthetic resins were developed, which included Bakelite, celluloid, and melamine[14]. 1936 marked the first patent issued for a polyester resin, and in 1938, the first glass fiber was produced by Owens Corning employee Russell Games Slayter and was quickly adapted for use as insulation. 1938 also marked the development of epoxy resins, which would become more utilized later. World War II in the 1940s brought the use of composite glass systems from the lab into full scale production as glass fiber reinforced polymers (GFRP) found uses in radar domes, boat hulls, and soon after, automobiles. The 1953 Corvette was made with a completely composite body and found widespread success. The 60s saw a widespread adoption of GFRP in the marine industry, as a majority percentage of consumer boats rolled off production lines with fiberglass hulls. 1961 was when the first patent was issued for carbon fibers, but mass production and market adoption would not take place for several years after and is still being adopted in mass markets today[14].

Basics

By analyzing composites at their most basic elements, they can be more fully understood. A glass fiber reinforced polymer (GFRP) or carbon fiber reinforced polymer (CFRP) is structurally fairly simple. Glass fibers are extruded or spun to various sizes from a liquid melt. Typically additives are added to the SiO_2 to improve workability, although these do have an impact on the final properties. Carbon fibers (CF) are made from one of two precursors, Polyacrylonitrile or pitch-based. They are stabilized, then carbonized at high temperatures, and then graphitized at even higher temperatures under an applied stress. These fibers can be made up to thousands of yards long and are typically less thick than a human hair. The fibers are aligned in one direction or woven in two, and mixed with resin to make a single, essentially 2-D lamina. These lamina are then stacked together to make a 3-D laminate, which is then shaped in a mold and cured to harden the resin. The fibers of a composite can be packed with varying density to alter the properties. The strength of glass fibers comes directly from the atomic bond strength of the Si and O atoms. With carbon fibers, ideally sheets of carbon with a graphite structure are stacked parallel to the fiber length, meaning the strength lies in the strength of covalent carbon bonds.

Epoxy is the most common matrix element used in conjunction with carbon fibers because of the combination of processing ease, cost, and performance. Epoxy is a thermosetting polymer, a type that when cured at certain temperatures, forms cross-linkages of new bonds, chemically and mechanically altering the epoxy as a whole. These cross links are referred to as primary bonds. When epoxy is held at an elevated temperature, it forms these primary bonds throughout its whole, so instead of only individual long monomer chains being bonded, these chains are now bonded to each other. This makes the structure much stronger and also solidifies into the shape of its mold. When fabricating a 3-D structure out of 2-D sheets of CFRP or GFRP, this crosslinking is what bonds the layers together. Debonding of layers is a common mode of failure in composites and thus is an area of heavy research and testing.

Production

Elaborate structures can be made out of composites with enough planning and expertise. Figure 4 is a car wheel made from many pieces of laminate, but collectively form one complete system[15]. The wheel's maker, Swedish hyper-car company Koenigsegg, is a pioneer in the use of CFRP and other advanced materials in the auto industry. To produce any structure, as mentioned before, layers are stacked on top of one another and the adhesives applied to the sheets help initial bonding. Typically this is done directly in a mold with a release film between the part and mold, as Figure 5 shows. The release film ensures that the part can be removed after curing. Figure 5 is also from Koenigsegg, and the part being produced is a turbocharger pipe, essentially a thin-walled pressure vessel. Once the part is laid up in the desired thickness, it will be vacuum bagged and placed into pressurized oven called an autoclave. It is run through a curing cycle dependent on the epoxy and amount of cure desired and then removed and ready for use. In the case of the Aircore wheel, it is perfectly balanced, down to the gram, even factoring in the tire nozzle. The weight savings over a forged aluminum wheel is over 40%, making performance in every area, power, efficiency, handling, all better[15].

Figure 4: The Koenigsegg "Aircore" wheel. A hollow CFRP structure weighing a total of 13lbs[15].

Figure 5: The Aircore wheel being made by hand layup in an aluminum mold[14].

Mechanics

When trying to understand the forces that act on a system and how the system responds, it is helpful to look at it from a mechanics standpoint. In most structural systems, metals are the main constituent, and when studying composite systems, there is a major difference from metals. Metallic bonds are the same in every direction within the material. This means that regardless of which direction you measure, assuming the shape is uniform, the properties will remain the same. These materials are defined as being "isotropic", while having properties dependent on directions is called "anisotropic" or orthotropic. Composites behave orthotropically because of the fiber's directionality. In some uses, fibers are organized in a weave to minimize 2-axis anisotropy, but in this case, we will focus on unidirectional laminates, where the fibers all run in the same direction, as this is the primary load-bearing structure in our testing.

Hooke's law is a commonly taught subject in most entry level physics classes that deals with the fundamentals of spring behavior. It can also be applied to mechanics, treating atomic bonds like springs, requiring a certain amount of energy (stress) to strain and then break. In isotropic materials, the relationship between stress and strain is direct and easily found with some matrix algebra, as Poisson's ratio (υ) is the same in all directions. Poisson's ratio is the amount of elastic deformation a material undergoes in the direction perpendicular to the strain. For example, when you strain a metal in its longitudinal axis, it will get thinner in the other two perpendicular axes. In isotropic materials, the stress and strain are related using matrix algebra, which can be found in any introductory mechanics of materials text. When you work through the proofs, you get strain (ε) matrix as a product of the matrix of elastic constants, called the compliance matrix, and the stress (σ) matrix. The compliance matrix is made of three elastic constants, E, the elastic modulus, G, the shear modulus, and ν, Poisson's ratio. In isotropic behavior, only two of the elastic constants are independent, meaning the third is constrained. This allows a relationship between the three to be developed, which is later used in calculations.

Figure 6[16] is an axial breakdown of a representation of a fiber reinforced matrix. The visual illustrates why the properties are different by direction. If the sample is loaded in the fiber direction, 1, the fibers carry the majority of the load, while only epoxy is carrying the load if one is applied in the 2 or 3 directions. E represents the elastic modulus of the material, while G (not pictured) represents the shear modulus.

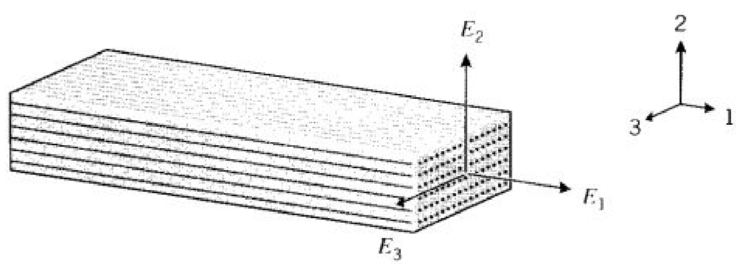


Figure 6: A representation of an orthotropic material, with fibers running in the 1 direction.

So while E_1 is not equal to E_2, E_2 is equal to E_3 due to the similarity in fiber orientation in the 2 and 3 directions, both are perpendicular. So within the plane normal to the fiber direction, CF-Epoxy matrices can be considered isotropic, $E_2 = E_3$. Because the elastic constants are all different than isotropic materials, the same reduction and relation cannot be applied. All the linear constants, E, G, and υ become specific to a plane and direction, for example, E_{11} is the elastic modulus in the plane normal to the 1-axis in the direction of the 1-axis. In total, there are 7 total elastic constants, five of which are independent. These are: E_{11}, E_{22}, G_{12}, G_{22}, ν_{12}, ν_{23}, and ν_{21} where $G_{22}=G_{23}=G_{32}=G_{33}$, $\nu_{22}= \nu_{33}$, and $E_{22}=E_{33}$ because of the plane of isotropy mentioned previously. What this equates to in words is that for stiffness, it is equal in the 2- and 3-directions, and different in the 1-direction. Figure 7 is an illustration of a single unit in the material. Shear and normal stresses are shown to help the reader get a visual of what is happening inside a system under stress. The σ stand for normal stresses in the direction of the subscript, white the τ are shear stresses action in the plane of the first subscript, and the direction of the second.

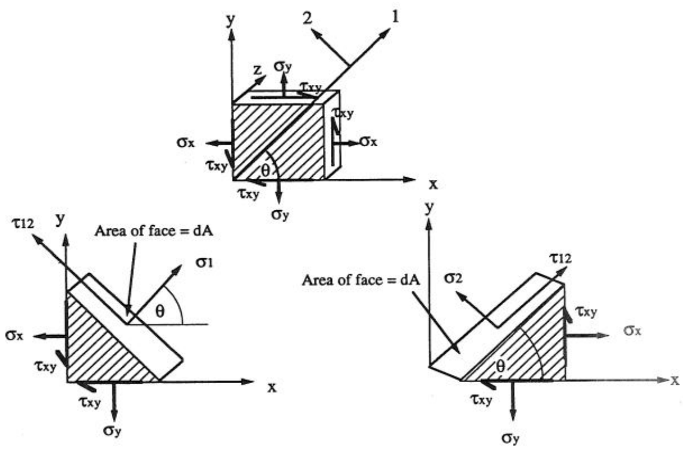


Figure 7: A 45° lamina split apart to visualize stress and shear[16] .

Note that all of these are dealing only when the fibers are aligned along the principal axis, the 1-axis. This is typically called a "zero degree orientation" in the manufacturing field of composites. To do calculations on fibers not aligned with the principal axis, for example, a laminate loaded at a 45° angle to the fiber direction, you need to transform the vector field. To do this, a transformation matrix is used, which acts as a multiplier on all vectors, effectively "rotating" them to line up with the principle axis and simplify the math. The transformation matrix is denoted $[T]_\sigma$ to transform the stresses, and $[T]_\varepsilon$ to transform the strains to the principal axis. Once these equations and formulas are applied, they allow calculation of stress via known strains for any thin, unidirectional orthotropic lamina and vice versa for known stresses and unknown strains.

Testing Composites

There are many tests that have been developed for composite systems of many different shapes. One of the most commonly used tests to find properties is the three-point bend test, illustrated in Figure 8[17]. In this test, a sample is placed on a fixture, resting on two points and spanning a certain distance. A third point of contact is made on top of the sample equidistant from both other contact points, and slowly depressed into the sample until fracture. In beam

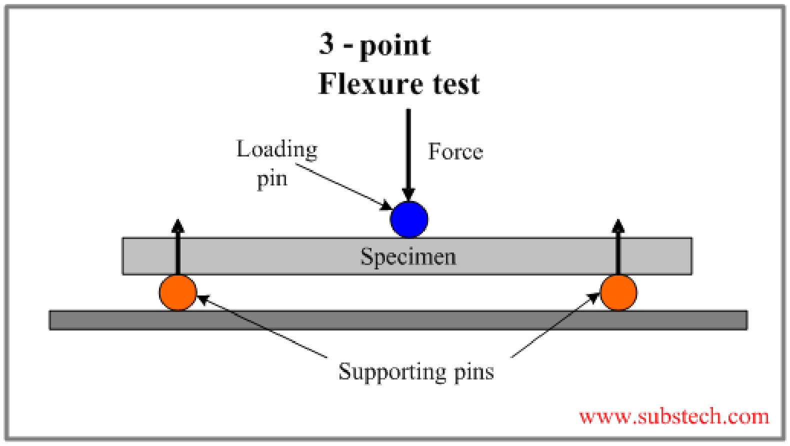


Figure 8: Representation of three point flexure testing[17].

testing, this failure mode will most likely be delamination between the layers, a failure of the epoxy, or the failure of the fibers themselves in tension or compression. This test is typically done on beams but not limited to them and can provide a variety of data. The testing specifications are outlined in ASTM D 2344[18] for short beam and ASTM D 790[19] for long beam, which also contain information on calculations that give the Interlaminar Shear Stress (ILSS) at failure, the maximum flexural stress, flexural strength, Flexural offset yield strength, stress at given strain, and Modulus of Rupture[18,19]. These are key properties in composite engineering and are well established in merit.

Degradation and Exposure Resistance

CFRP systems do not corrode in the typical sense, but they can degrade in certain environments. Water absorption can be one of them; UV degradation is another. During prolonged exposure to water, there can be two mechanisms by which the system degrades, both involving the epoxy matrix, as the carbon fibers are immune to any effects. When water is absorbed into the epoxy by diffusion, the structure itself expands, which can cause cracks which weaken the overall strength. It can also weaken the Fiber-Matrix (F/M) interface and lead to lower debonding stresses[20]. The other problem that arises with absorbed water is that hydrolysis can occur with the cross-linkages in the epoxy that give it its strength. The water molecules break the epoxy bonds and form hydrogen bonds at the sites, dissolving the crosslink network over time[21].

UV degradation is another significant factor that can deteriorate the epoxy matrix while having little to no effect on the carbon fibers. UV radiation that reaches Earth's surface typically falls in a similar range to the dissociation energies found in some polymeric covalent bonds[22]. This can have a two pronged effect of "scissoring" the polymer into shorter chains, and further curing of the epoxy, forming more cross-links and embrittling the material. It has been shown that extended exposure to UV light can bring about significant decreases in properties such as ILSS, flexural strength, and flexural stiffness. When in environments where moisture is present, microcracks formed from excess curing due to UV light can act as capillaries, allowing more water to enter than normal and furthering the damage done. Water can also enhance the effects of scissoring and UV-based crosslinking[21].

Sage Fly Fishing Company

Company History

Founded in 1980 by Don Green on Bainbridge Island, Washington, with six employees and 1500sq ft of shop and warehouse space, the company grew steadily to its size of 175 employees today. The first major series of rods, released in 1982 were called the RP rods, which stood for reserve power. The belief that Don had was that an angler should never run out of casting power. These rods quickly became famous throughout the fly fishing community. By 1986, the Sage lineup consisted of the world's first saltwater specific rods (RPLX models), the lightweight setup (LL), and two-handed Spey rods. Sage worked closely with professional fly shops to help sell their products and further establish their name in the industry. By the early 90s, Sage was being sold in roughly 450 dealers nationwide, and in over 30 countries overseas[23].

Company Today

The company is still located on Bainbridge Island and has expanded to a 30,000sq ft. The market for rods cycles yearly but Sage claims they do roughly 38,000 units per year in rods alone, at the top of the price point outside of custom rod designers. Figure 9 shows a rod of four piece construction from handle to the fine tip[23].

Sage is a worldwide leader in fly rod design and technology and has the credentials to prove it. Every year, the International Game Fish Association publishes a list of fish caught that year that are of world record size. Over the last few years, no other rod manufacturer has caught more record fish than Sage, 40 in 2013, 75 in 2012[24]. The current lineup of rods incorporate what Sage calls "Konnetic" technology, which helps stabilize the rods in flight to improve casting accuracy. The alignment of the fibers and the density of the shaft walls are higher than rods made by other companies and lead to a more responsive unit[20]. The attitude behind Sage is that more technology is better, and as such, they are frequently on the cutting edge of material development and application.

Figure 9: A four piece Sage rod showing thickness at the tip and various points in the shaft[23].

There are an estimated 3.83 million fly anglers in the US ranging from the dedicated to the casual[25]. Any information that can be provided from this project that can help design a better product is better not only for Sage but for everyone looking to buy a rod. If Sage is able to use more quantitative data when designing, there will likely be more consistency and a more property-based design. To be able to design a rod that combines the feel of a rod and with data to quantify it would make performance much more consistent across rods of the same model, as well as help establish defined niches of performance.

Project Scope

The current challenge is to develop a testing protocol and examine the results of three point bend tests for composite cylindrical tubes, as well as a protocol to test degradation caused by UV, elevated temperature, and humidity exposure. The data collected will be used in designing planning of future rods and better understanding current rods. Available literature concerning composite testing is readily available, but little has been published regarding the mechanics of small scale composite tubes. To address this problem for Sage, the proposed project will collect a statistically significant amount of data on various constructions of tubes and provide them the data to help in future rod construction and coating selection.

Experimental Procedure

Safety

All lab safety protocols were followed in order to minimize risk of injury or equipment damage. A polycarbonate shield was placed in front of the machine to prevent any shards from flying. All proper testing attire was worn, close-toed shoes, long pants, and safety goggles. During sample preparation, a diamond blade tile saw was used to cut samples to length, and proper instruction on the machine was undergone before use.

Sample and Testing Information

Tubes were sourced from Sage, where they are produced in-house by a process that combines machine and manual labor. The final rod blanks that were received were dimensioned 36" long, with an outer diameter of 0.3" and were composed of two different constructions. These will be designated Construction 1 and Construction 2 for the remainder of this document and are identical in testing populations 1 and 2. Figure 10 illustrates how the manufacturing process can alter the properties to a large degree. The imbalance in the wall leads to a "hard" and "soft" axis in the blanks. To find the weakest part, samples were loaded with the "soft" axis in tension on the bottom of the three point test rig. Population 1 consisted of 21 samples of construction 1 and 24 in construction 2, further outline in Table II. All bend testing was conducted on an Instron tensile machine model 5584. To obtain flexure data for thin walled tubes, the testing method used is detailed in ASTM standard D7264 as no test methods for thin-walled composite tubes are available. The support span length is 6 inches with an overhang of 10%, giving a sample length of 6.6 inches with a crosshead rate was set to .05in/min. Samples were cut to length from the 36" blank using a tile saw with a diamond blade. Test parameters were uniform across construction and coating, to ensure that results

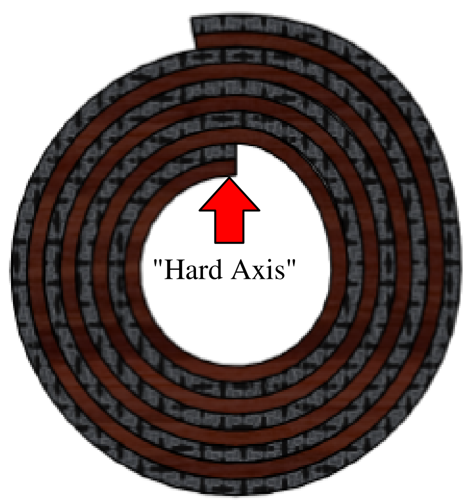
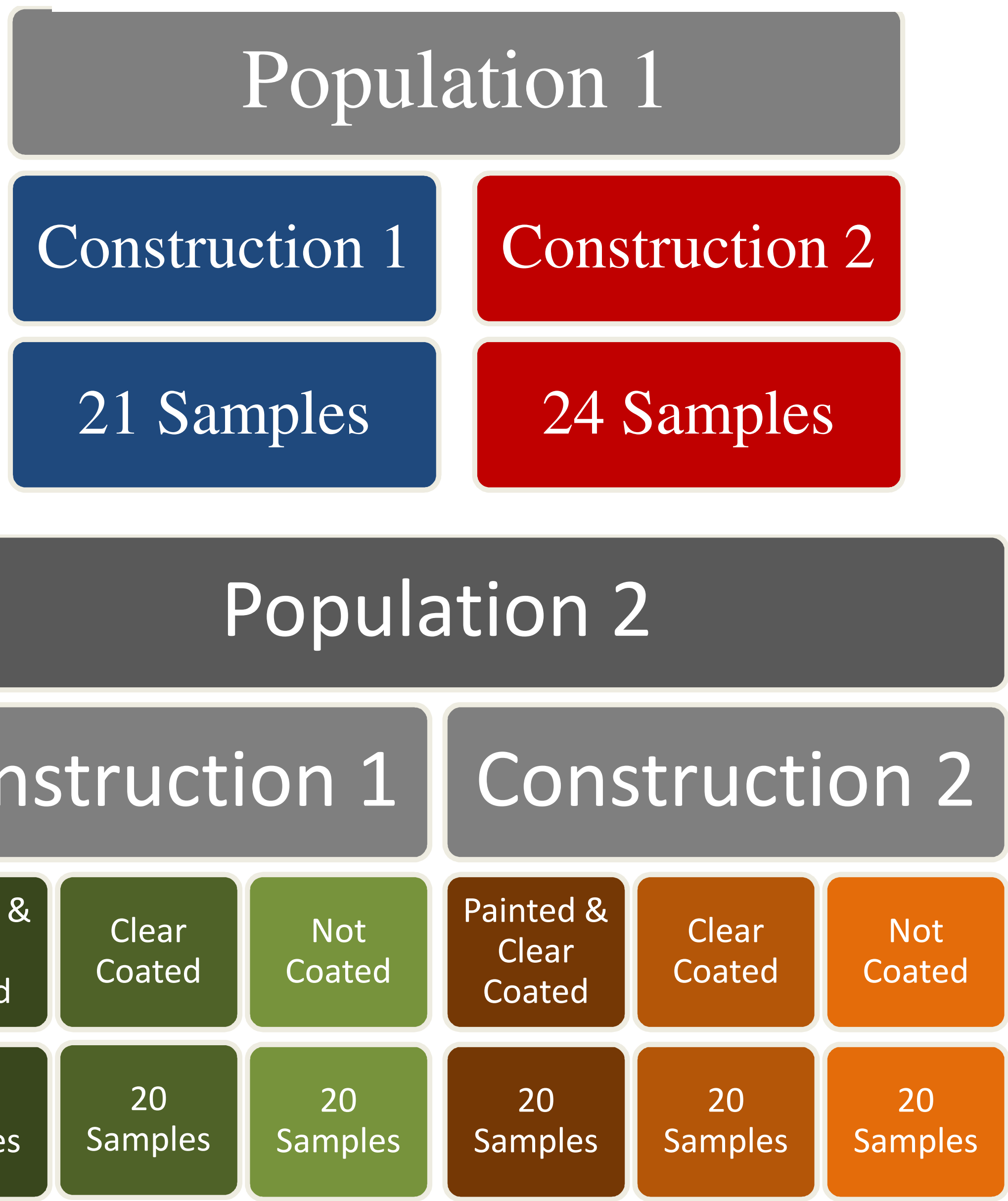


Figure 10: Cross sectional view of the construction type leading to the imbalanced wall. Top is the "hard axis with more material, while bottom is soft.

could be directly comparable.

Table II: Visual Breakdown of Samples



The second sample set had no difference in construction, only in exterior coating applied. The tests to be done on the second set, Population 2, were primarily to evaluate the difference between the performances of rod blanks post exposure (UV, temp, humidity), based on the coating applied. Three different coating conditions were tested, painted and clear coated, clear coat only, and non-coated. Each construction had a total of 60 samples, 20 of each coating condition. They were placed in a QUV accelerated weathering machine, soft axis facing toward the light, for 28 days and tested per ASTM standard D4320-13[26]. The samples were exposed to Suggested Cycle A: 8 hours of UV-A light, elevated humidity, and 60°C temperature, and four hours of only elevated humidity and 50°C temperature, cycled twice daily. The wavelength of light emitted from the lamps was limited to only 340nm, limiting the effective "true" exposure of the machine to the irradiance shown in Figure 11. The so called "true" exposure the samples underwent had an irradiance of .89 W/(m^2 x nm) and over 28 days amounts to roughly 164 days. This was found by looking at the typical irradiance per m^2 of natural UV light over one year and

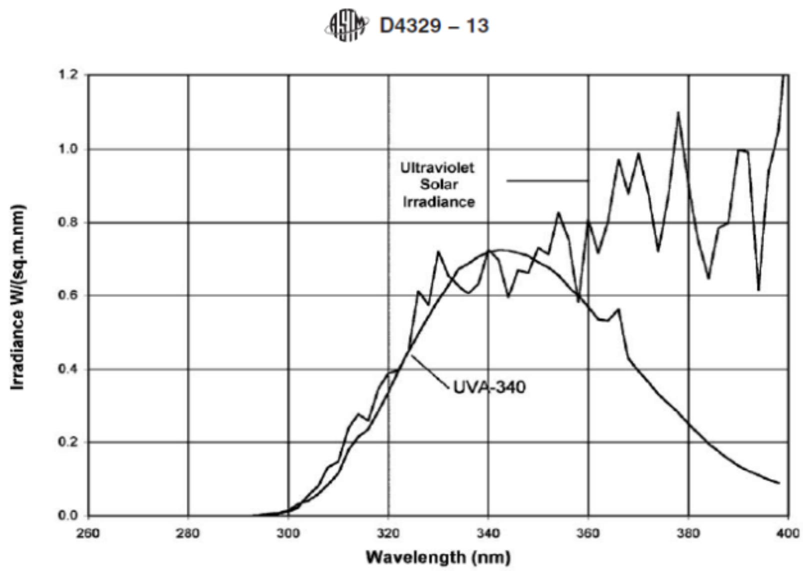


Figure 11:Irradiance received in natural UV light versus as tested 340nm wavelength light25.

establishing a ratio. Under UV-A 340nm wavelength, as stated in the ASTM standard, 1000 hours of exposure equate to 1 year of tropical latitude. As such, 448 hours run in our test equate to 163.52 days.

During initial testing, it was discovered that the roller pins on the fixture were creating too large of a stress concentration due to the limited flexure, and the samples were cracking at lower loads than expected. Essentially a hardness test was being conducted on the samples, measuring the ability of the rod to resist indentation. Figure 12 is an image of the fixture's support pins, which are 17-4PH stainless steel, and have a diameter of .25"[27]. To mitigate the indenting, carbon steel tubes of .75" diameter were cut into half-cylinders and attached to the pins. This significantly reduced the indentations, and resulting early failures. Testing was stopped once the load being carried fell below 25lb or once a large failure

Figure 12: Wyoming Test Fixtures flexure testing setup[27].

was observed, typically taking between two to three minutes. From these tests, the data was collected from the slope of the loading period, the maximum load achieved, and extension reached before failure.

Results

Population 1

Containing only untreated and uncoated samples, the data was easily visualized. Figure 13 shows

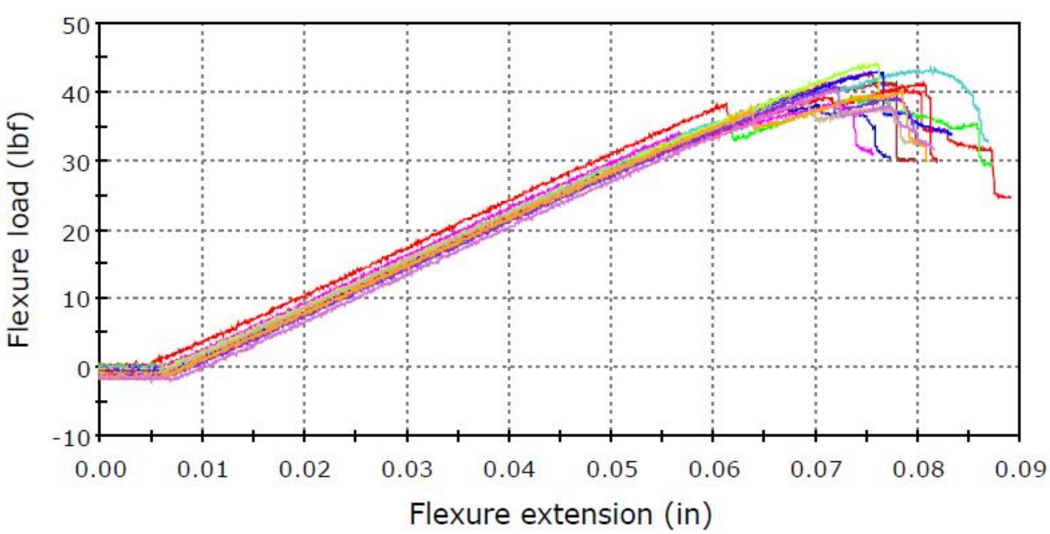


Figure 13: Plot of the load supported as a function of flexure extension for construction 1.

the data collection for samples 9-20 of construction 1. The stiffness can be seen to be uniform among the samples and there is limited scatter at the points of failure. There is also a rapid unloading of the samples, which was typically accompanied by a loud popping or cracking sound. The sharp drops in load imply a total and complete failure. Figure 14 is the same test run on construction 2. The scale of the graphs is slightly different, but the difference in failure can be seen. The unloading is much more gradual in construction 2 than is visible in construction 1. Samples of construction two also show slightly lower max loads reached than construction 1.

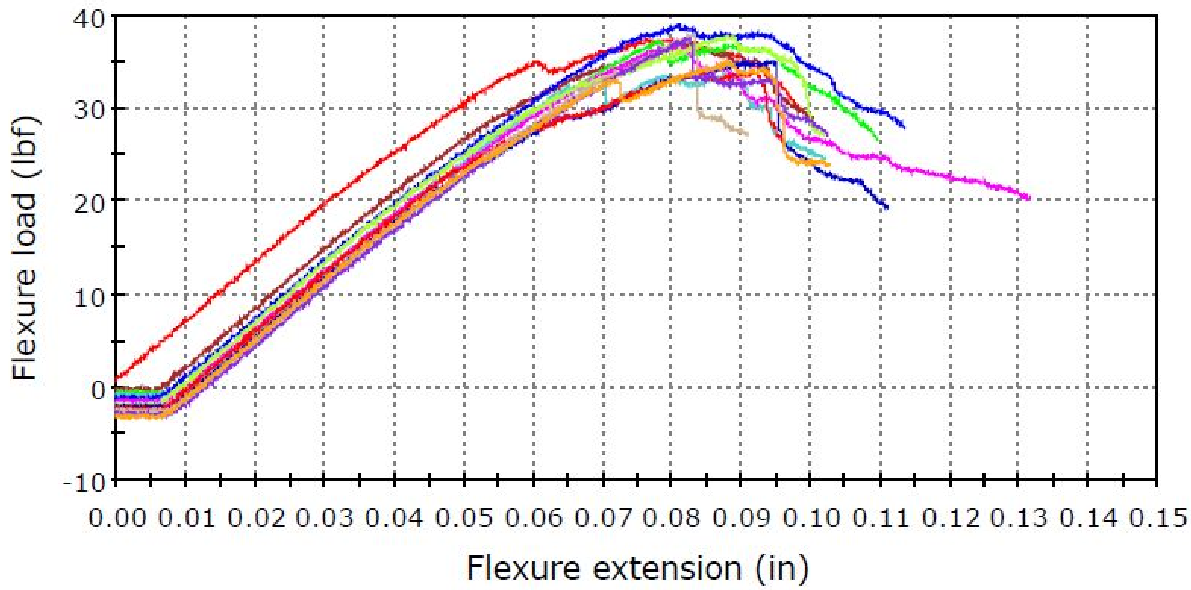


Figure 14: Load as a function of flexure extension in construction 2; gradual unloading visible.

Figure 15 shows the complete collected data from the 45 total trials (21 Construction 1, 24 Construction 2). The lighter spots are the actual max loads reached for each sample, while the darker marks are the averages of the two construction sets. Table III below shows the average values for multiple parts of the loading process.

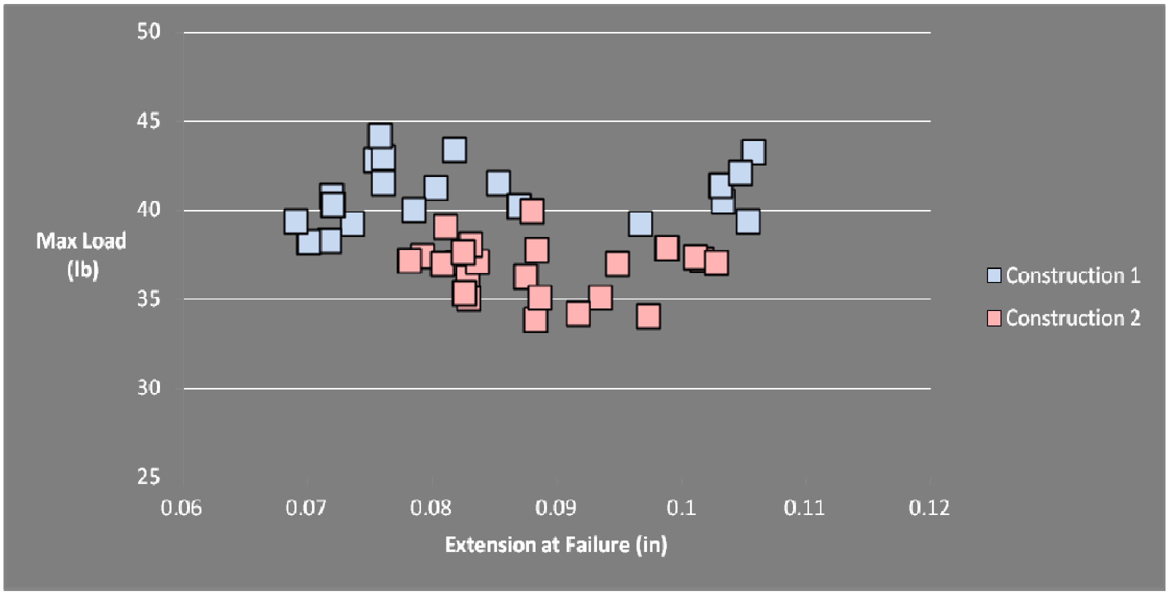


Figure 15:Plot of the testing data from population 1; illustrates slight difference in strength between constructions.

The difference between the two groups is clearly visible, as both the groupings and averages agree with the visuals. Table III includes the average values for the maximum load reached, as well as the standard deviations, which give a good representation of the scatter present. The data showed limited scatter, with standard deviations of 1.7lb for Construction 1 and 1.5lb for Construction 2, which amounts to less than 5% of the values reached.

Table III: Summary of Population 1 Tests

Sample	Flexure extension in	Flexure strain %	Flexure load lbf
Construction 1	0.08 σ=.013314	0.42 σ=.06658	40.93 σ=1.716798
Construction 2	0.09 σ=.007	0.44 σ=.038	36.64 σ=1.544

Population 2 - Exposed Samples

Construction 1

In Population 2, the samples have been delivered with one of three possible coatings, painted and clear coated, only clear coated, or uncoated. Testing was conducted following UV exposure and there is significantly more scatter in the data than in the unexposed samples. Figure 16 is the plot of testing for painted and clear coated samples, figure 17 is the plot for clear coated, and figure 18 is the plot for uncoated.

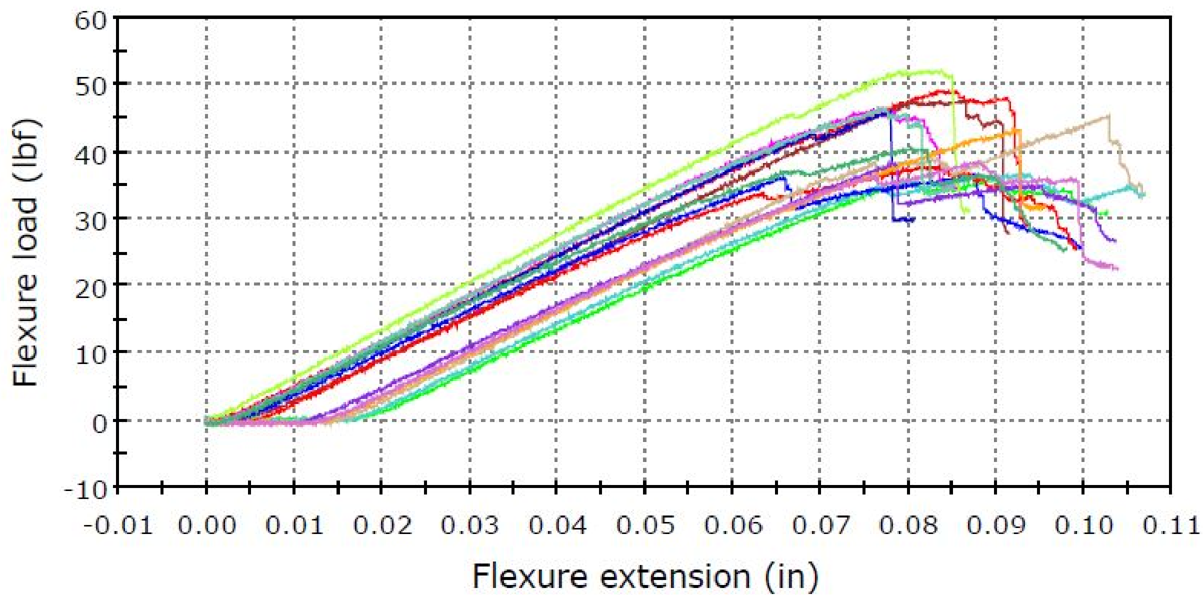


Figure 16: Plot of data collected from painted and clear coated samples after UV, humidity, and elevated temperature exposure.

In the painted and clear coated data (figure 16) the loads reached are much higher than seen before in population 1. This is likely caused by the two extra heat treatments that the blanks underwent in the painting process.

The clear coated samples also show higher maximum loads reached than the unexposed samples in population 1 of the same construction. The clear coat has one additional heating process to dry the clear coat and this is likely the cause of the increased strength.

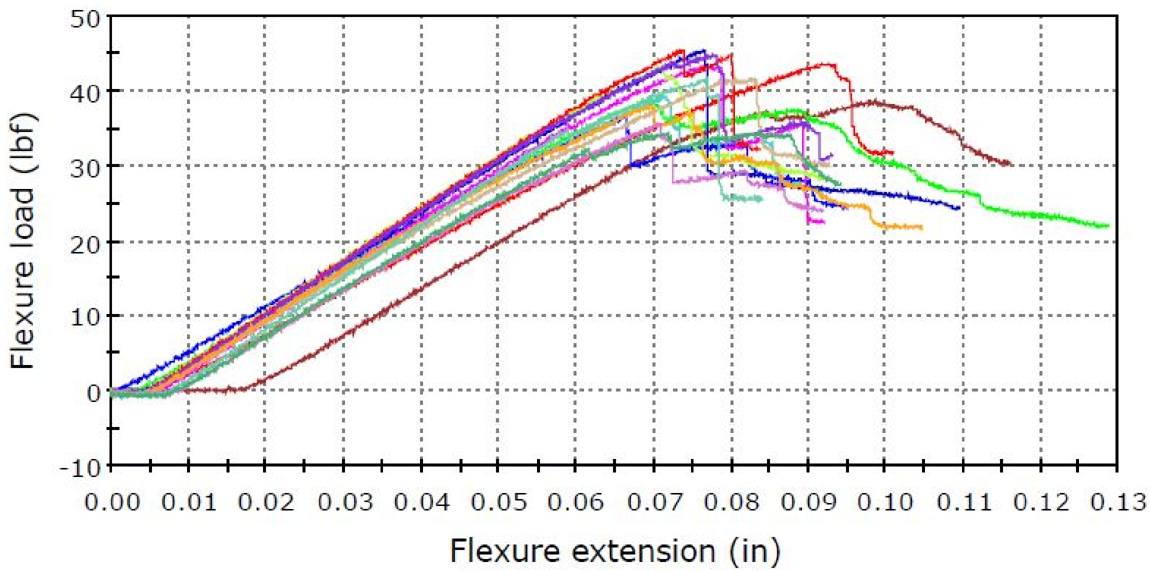


Figure 18:Data collected from testing of exposed samples with clear coat applied.

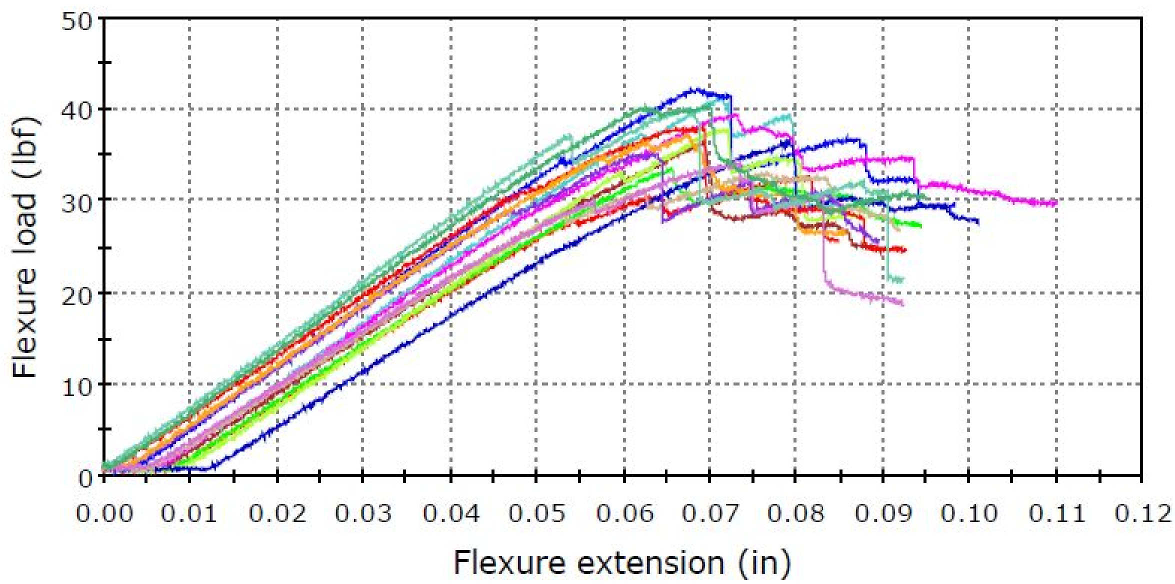


Figure 17: Data collected from tests of exposed samples with no coating.

The data is clear that the uncoated samples do not increase in strength with exposure, as was initially expected. The uncoated samples have no extra heating processes for paint or clear coat curing, and as such the epoxy is weaker.

Construction 2

Construction 2 showed less strength than Construction 1 in population 1, which held true for the exposed samples of population 2. Figure 19 is the plot of the painted and clear coated tests, Figure 20 is of the clear coated tests, and Figure 21 is of the uncoated tests.

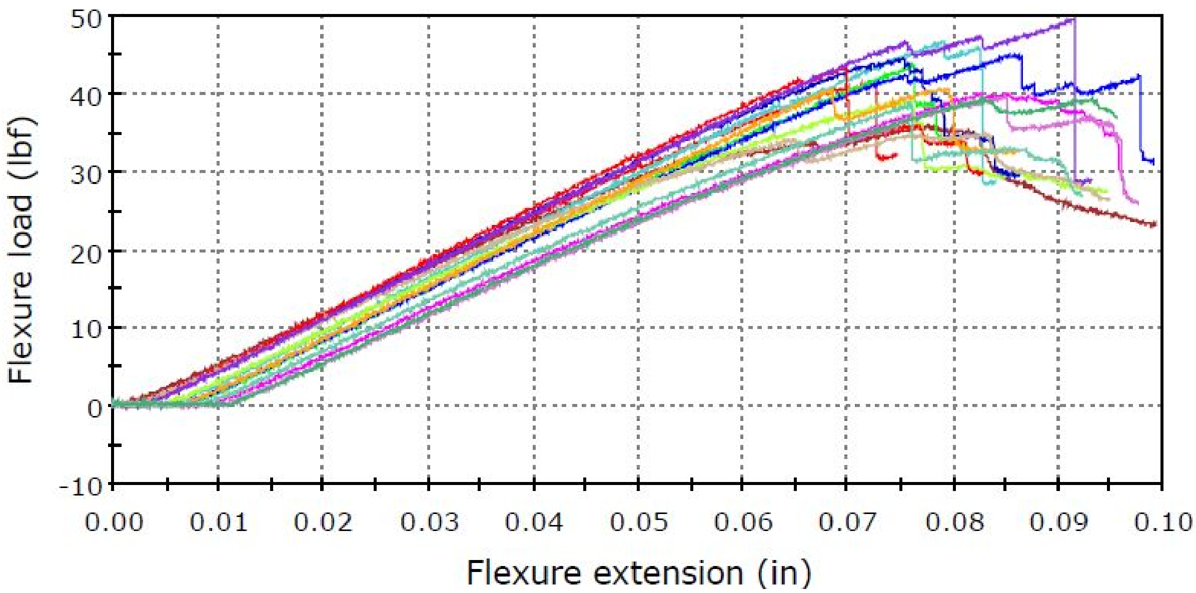


Figure 19:Plot of data collected from tests of painted and clear coated samples of construction 2.

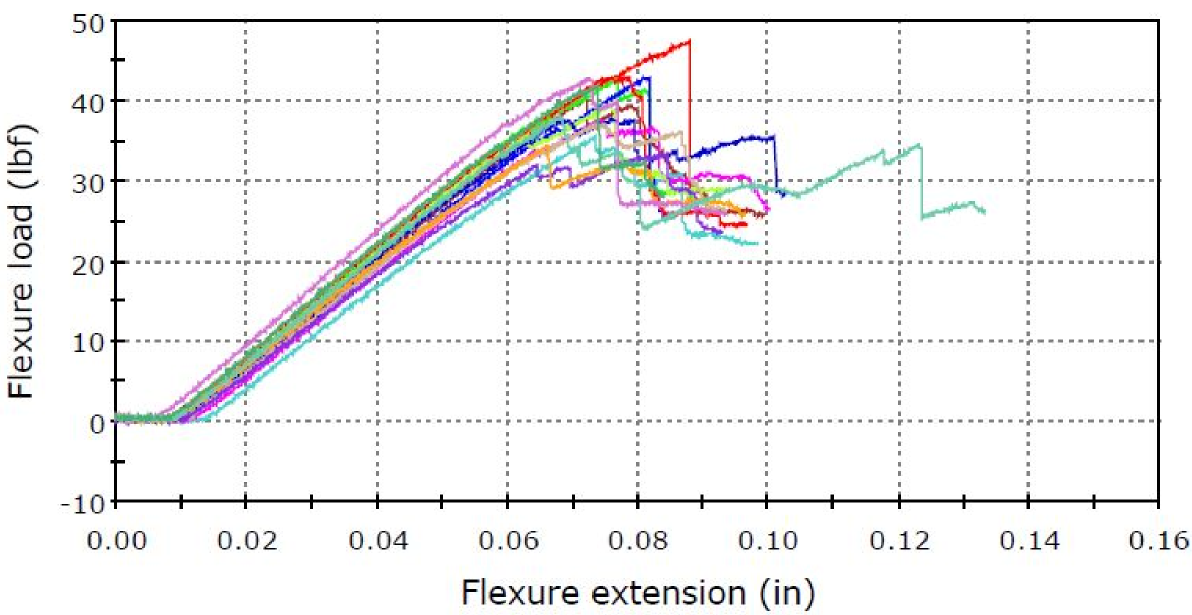


Figure 20: Plot of the data collected from tests on clear coated samples of construction 2.

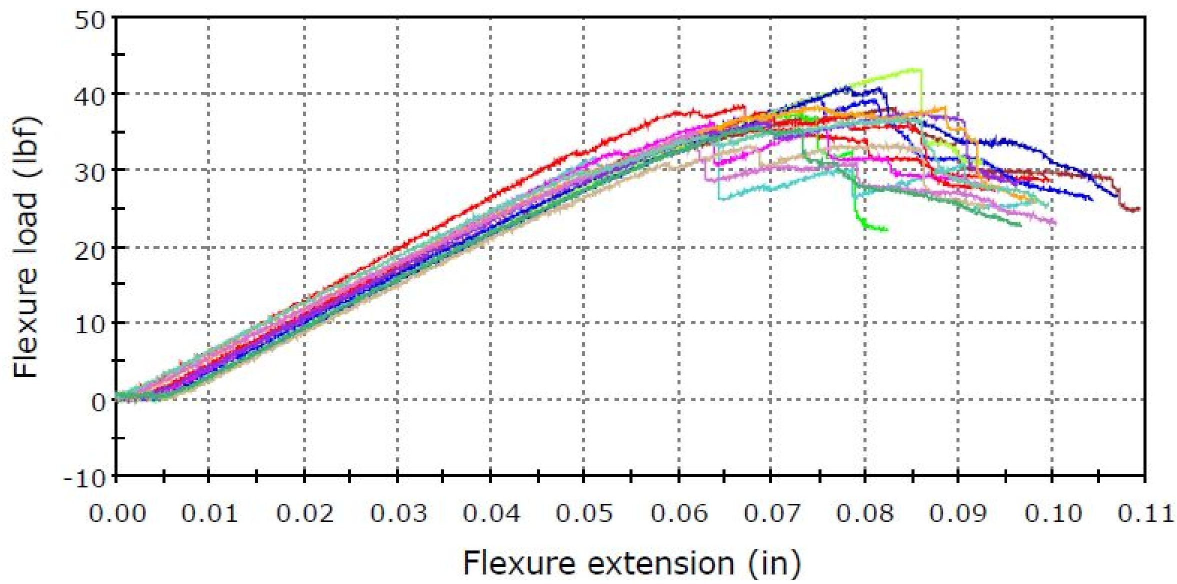


Figure 21: Data collected from the uncoated samples of construction 2.

The maximum loads reached by each group are different than the initial samples of construction 1. The failure method of rapid unloading also appears in the clear coated and painted and clear coated samples. This is likely due to epoxy embrittlement, or overcuring caused by the coating cures. When the maximum loads reached of each data series are averaged out, trends do begin to appear, as shown in Table IV.

Table IV: Average values for the series of Population 2

Sample	Flexure extension	Flexure strain %	Flexure load lbf
S14-99 Painted and Clear Coated	0.083 σ=0.007	0.415 σ=0.036	45.331 σ=3.29
S14-99 Clear Coated	0.08 σ=0.0062	0.39 σ=0.031	42.94 σ=2.65
S14-99 No Coating	0.07 σ=0.01	0.37 σ=0.048	38.19 σ=3.01
S14-100 Painted and Clear Coated	0.08 σ=0.007	0.41 σ=0.037	39.61 σ=2.90
S14-100 Clear Coated	0.08 σ=0.007	0.38 σ=0.035	38.00 σ=2.59
S14-100 No Coating	0.07 σ=0.005	0.37 σ=0.03	36.20 σ=3.11

Figure 22 is a graph of the compilation of the average values for Constructions 1 and 2. Construction 1 again shows higher levels of strength than Construction 2, regardless of coating condition. The painted and clear coated samples sustained higher loads than the clear coated, which reached higher loads than those with no coating. The standard deviations visible in Table II are much larger than their predecessors in Population 1. The 1.7lb and 1.5lb standard deviations are roughly half as large as the average standard deviation in the exposed samples.

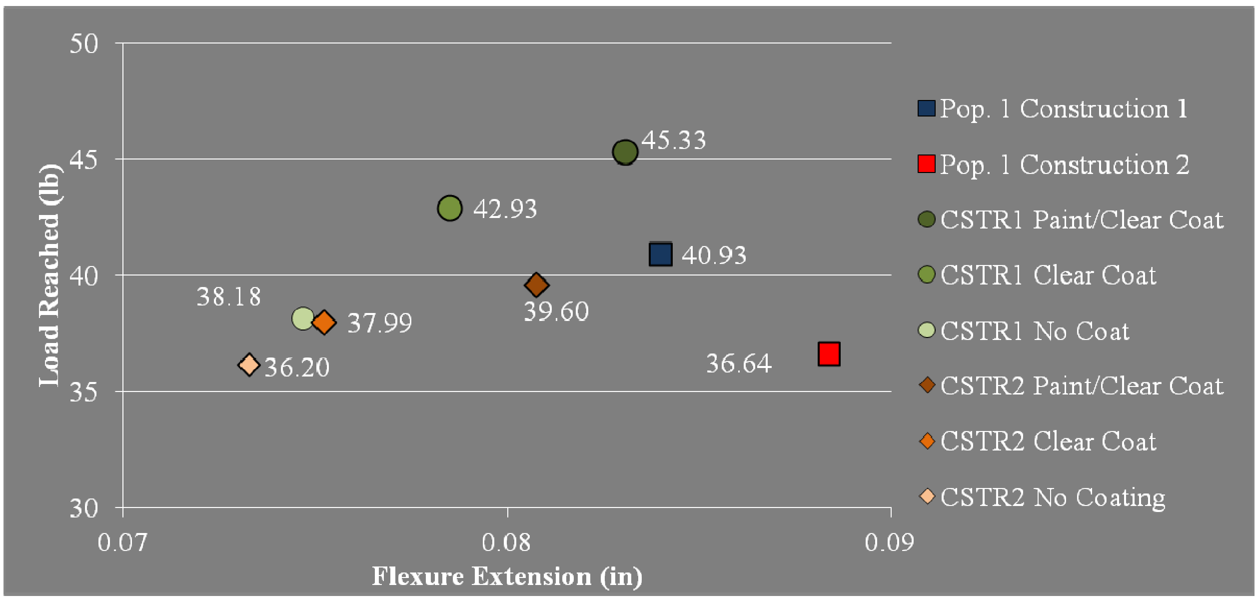


Figure 22: Summary of all series tested across populations 1 and 2; red and blue are from population 1, while the green and orange are population 2. The trend shows more coating offers better performance regardless of exposure.

Discussion

Population 1

It was predicted going into testing that the samples of Construction 1 would have higher strengths than those of Construction 2 by Sage, the rod blank producers. This was validated by our testing by the clear visible difference between the samples, as well as the statistical analysis performed. A combination of ANOVA and t-tests determined that the two sample groups were significantly different with a confidence interval of 95% and a p-value of <0.0001. Due to proprietary reasons, the nature of this difference cannot be disclosed in too much detail, other than the core layers contain a key difference, despite being made of the same fiber and matrix components.

The fracture location also show differences between constructions as Figure 23 and Figure 24 show. Figure 23 is of a failure surface of a Construction 1 sample and the crack is bright white. This is a mostly circumferential failure with some smaller cracks jutting into the longitudinal direction. This failure is likely caused by the deformation of the rod in the circumferential direction, as opposed to a failure in tension due to flexure. The circular cross section is becoming more like an oval, and this causes a compressive stress in the top of the sample. All samples failed on the top point of contact with the fixture, so the strength of the unidirectional carbon fibers are not the determining strength of the rod in this test; it is however the support structures underneath that help to prevent hoop deformation. Figure 24 shows not only long dark cracks in the long orientation, but also chipping of the epoxy. The dark cracks are delamination occurring in the composite. The epoxy crosslinking that holds the material plies together had broken and the layers are no longer attached. The chipping of epoxy is likely a section of fiber broke in that location and took the surrounding epoxy with it.

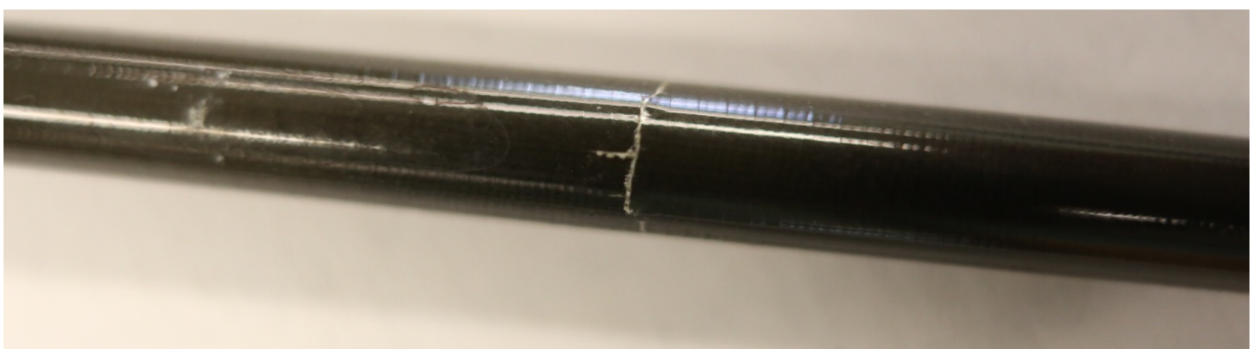


Figure 23: Failure location of construction 1. Circumferential crack wraps around the tube in bright white color. Minimal delamination seen.

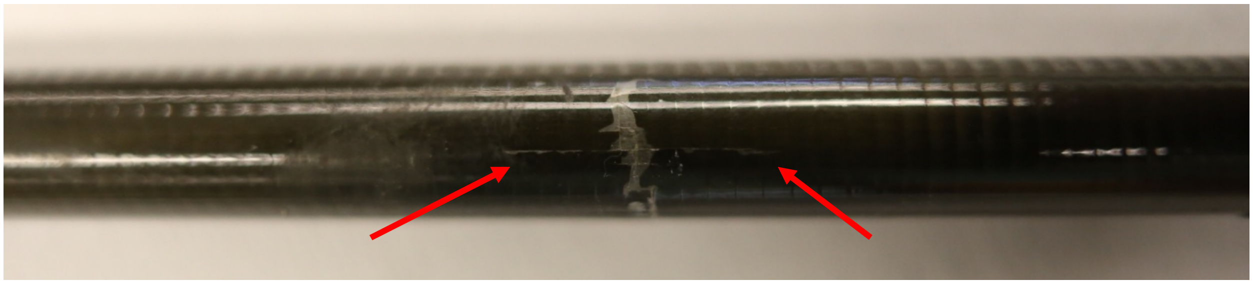


Figure 24: Failure location of construction 2. Visible chipping of epoxy can also be seen, with long longitudinal delamination marked by the arrows.

Population 2 - Exposed Samples

When the samples were put into the QUV exposure machine, a slight drop in performance was expected when compared to the original untreated samples. This was opposite the case as the data shows. The best performing samples were those that received paint and a clear coat layer. The samples with only a clear coat performed second best, and the uncoated performed worst. This trend matched with predictions as it was expected that the coatings would protect the epoxy matrix and prevent the epoxy from degrading. In Construction 1, the three series of various coatings were determined to be completely statistically significant. ANOVA tests showed an appreciable difference with a confidence interval of 95% that the addition of paint adds protection. Painted and clear coated samples could be predicted to behave differently than samples with just a clear coat. Through t-tests, the samples (Paint and clear coat and just clear coat) that received any coating were significantly different statistically than the uncoated samples in construction 1, meaning that the coatings were shown to have an effect on final behavior. In Construction 2, the results were less pronounced, and ANOVA testing revealed that no significant difference could be found between any of the three series of samples with 95% confidence. There may be a difference, but the sample size was too small and the scatter too large to identify it with certainty.

What is most surprising is that the samples that underwent the UV, humidity, and elevated temperature exposure performed better post-exposure than the samples in population 1 that never had UV exposure. What we learned from Sage post testing and initial analysis was that the paint and clear coats go through a baking cycle at an elevated temperature to cure the paint. This is the most likely scenario as to why the painted and clear coated (two additional bake cycles) performed the best, the clear coated (one additional bake cycle) had the next best performance, and why the uncoated samples (no additional bake cycles) performed similarly to those samples of Population 1. The best analysis to do under this assumption is the comparison of both uncoated series of both constructions.

Conclusions

It can be said that construction 1 is stronger than construction 2 with a statistical degree of certainty. The difference in construction leads to a greater ability to carry a load without much drop off in flexure ability. The additions of coatings add performance because of the paint curing processes that they undergo. To say whether or not the coatings effectively protect against UV exposure would be unreliable. More tests must be run under identical sample preparations before testing to make certain.

Recommendations

1. Compare only samples manufactured at the same time, and only those undergoing identical production processes (curing, baking, etc.)
2. Extend exposure times into several months
3. Design of a more ideal testing fixture for cylindrical samples

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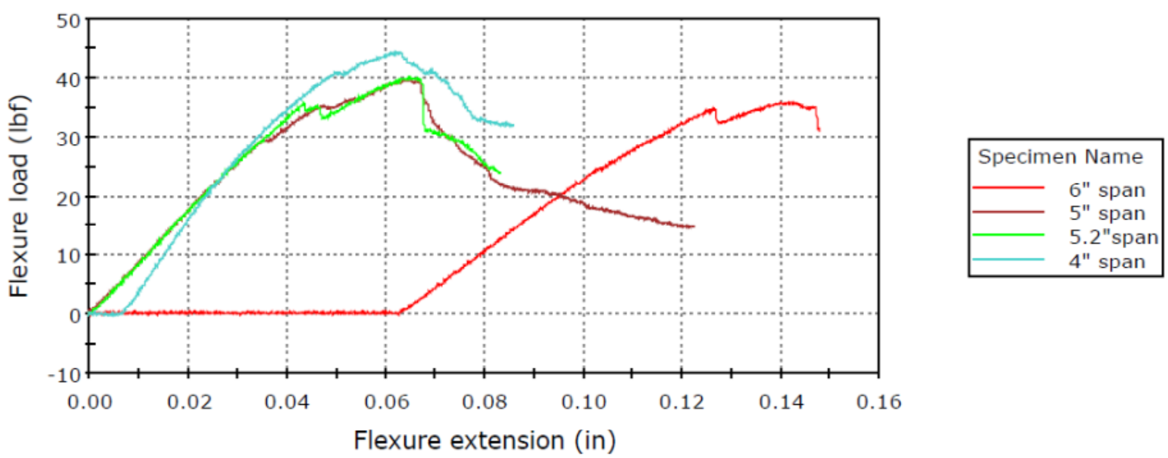
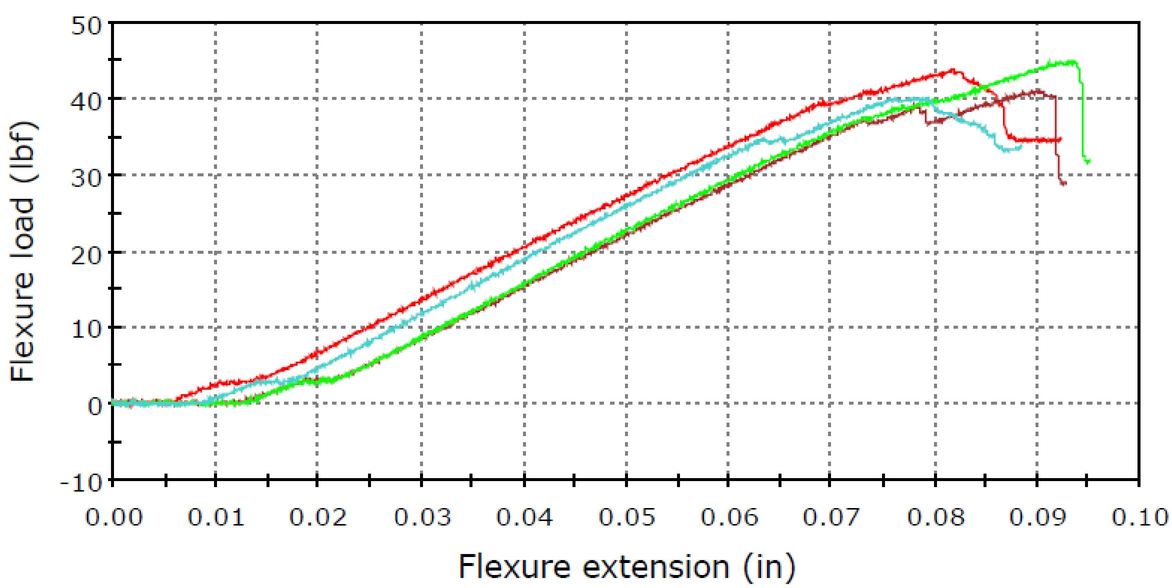
Appendix: Remaining Tests

Construction 1 Tests

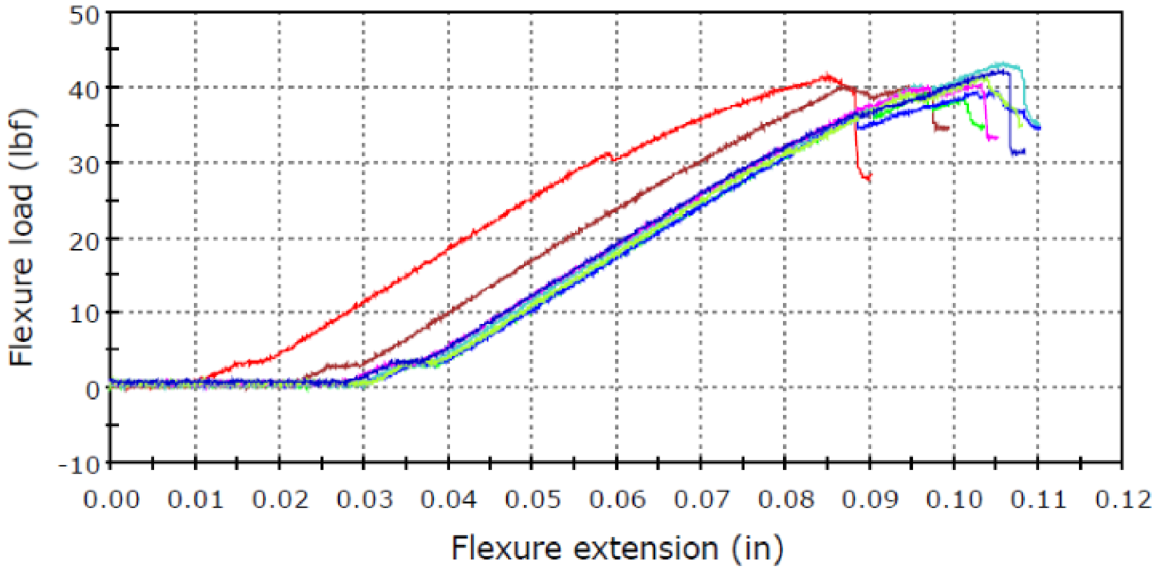
Practice Tests



Delocalization of Stress

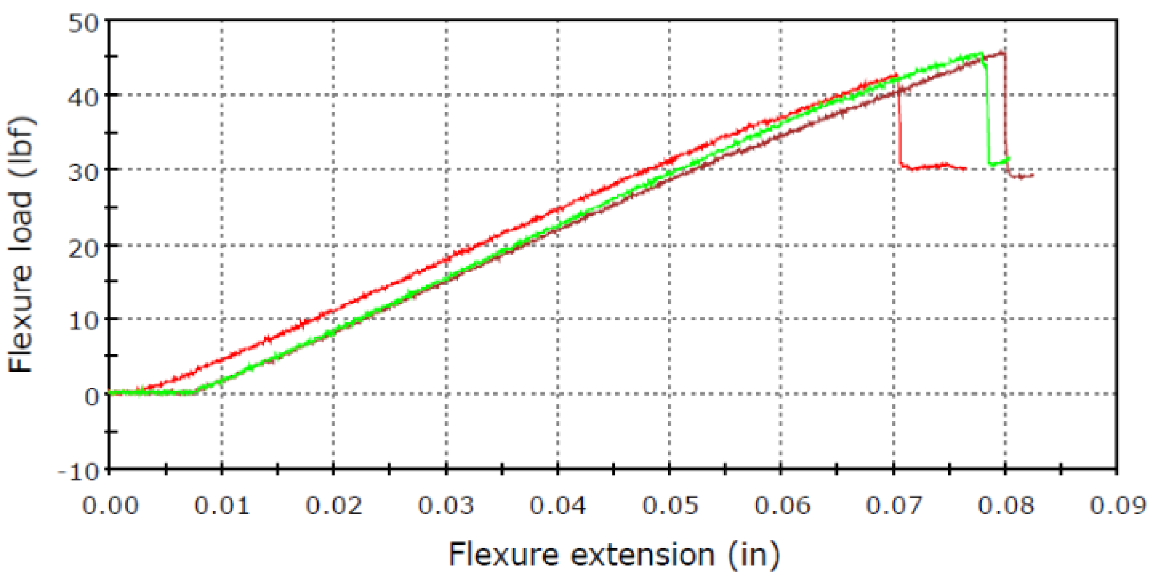


Population 1

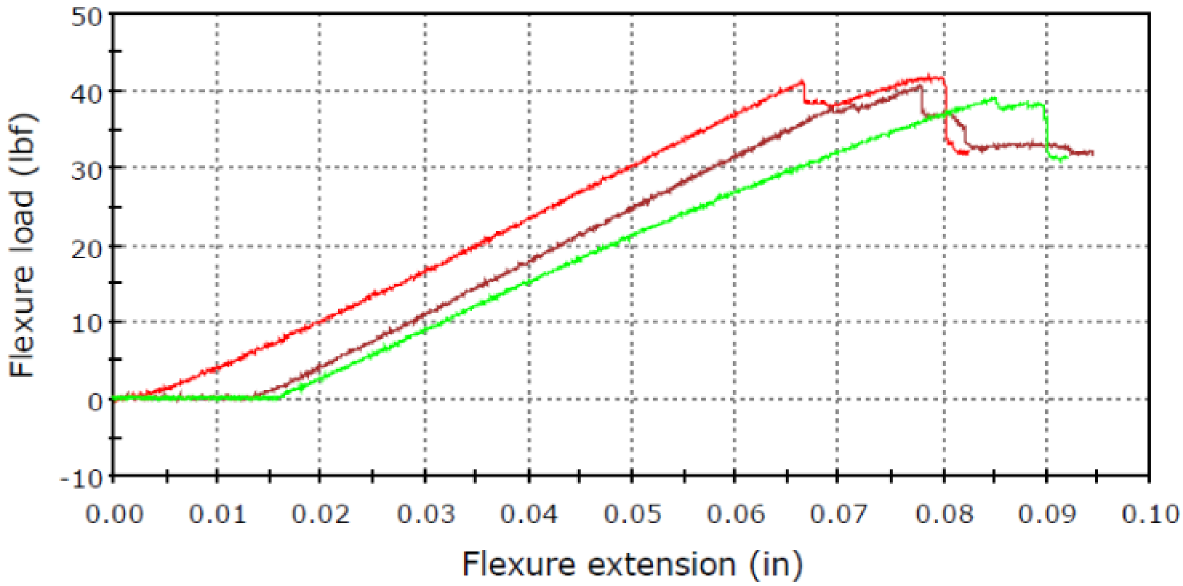


Population 2

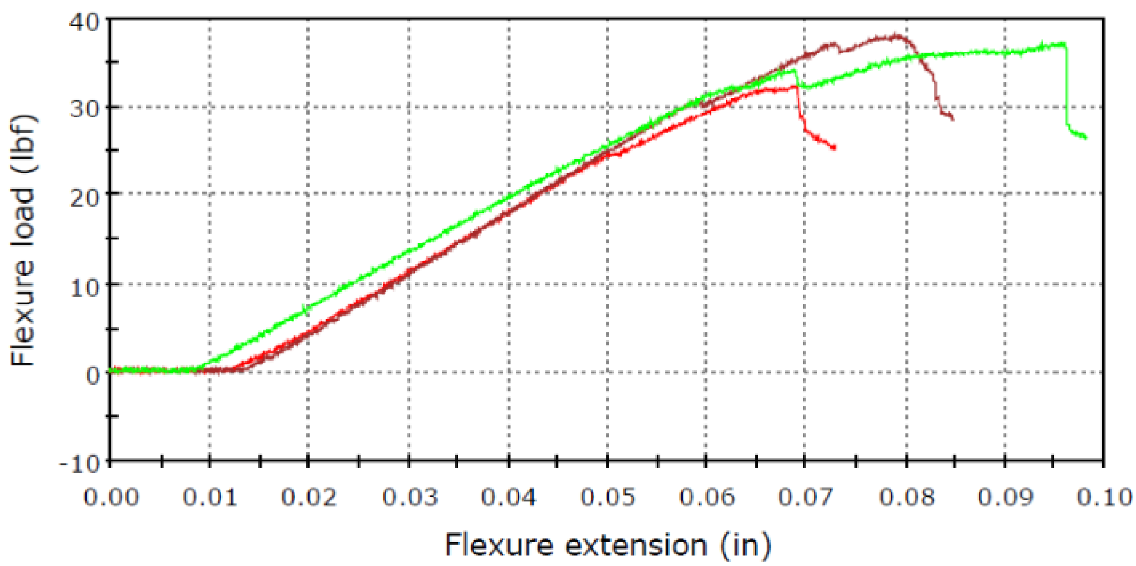
Painted and Clear Coated



Clear Coated

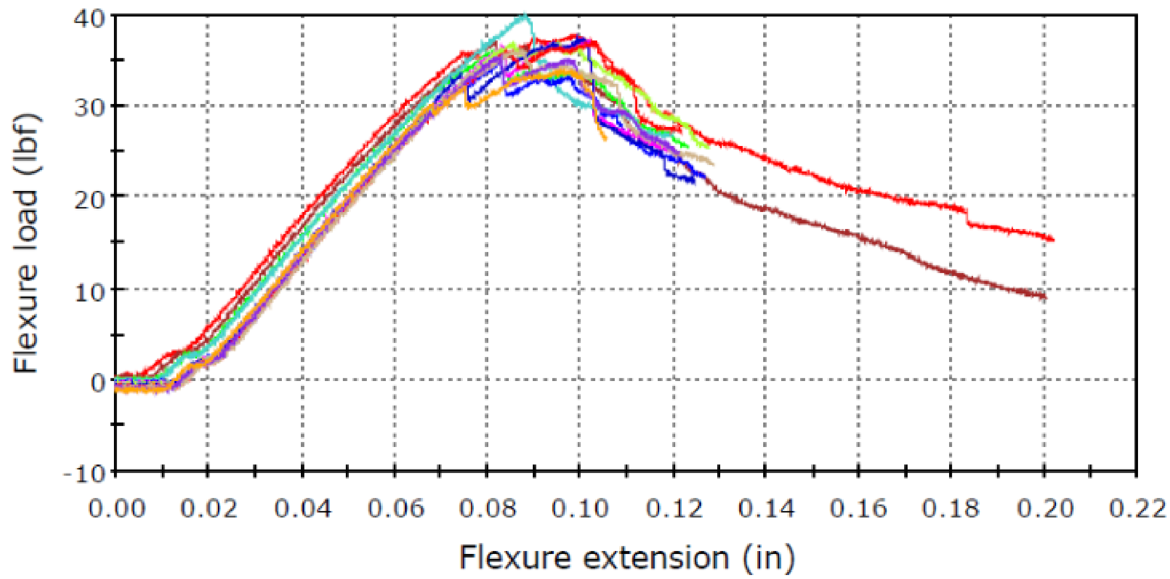


Uncoated

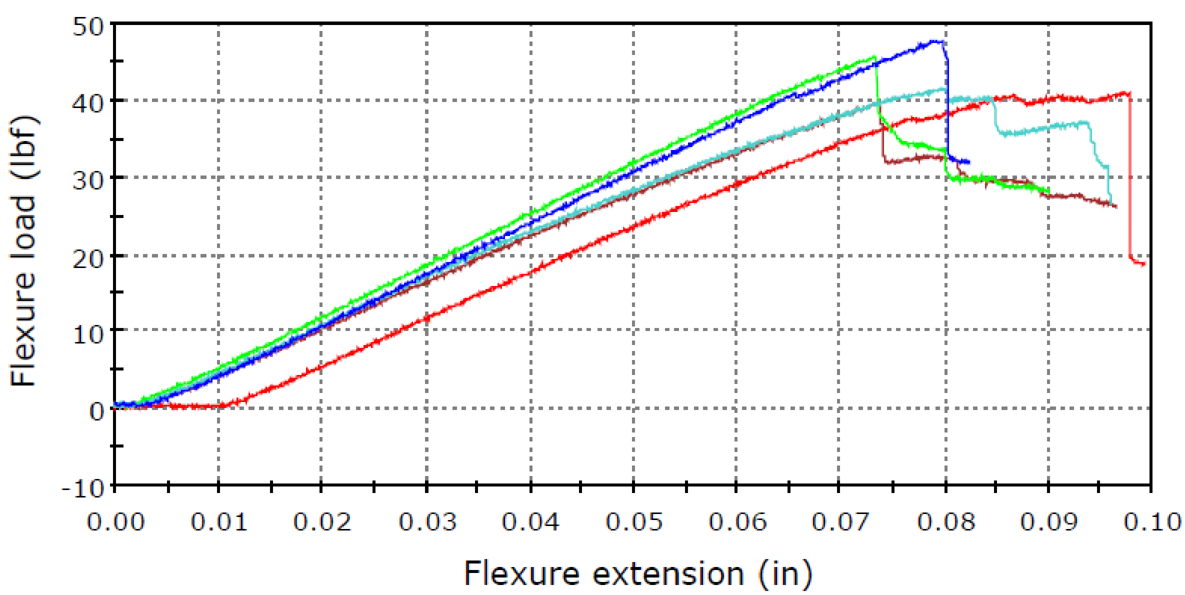


Construction 2

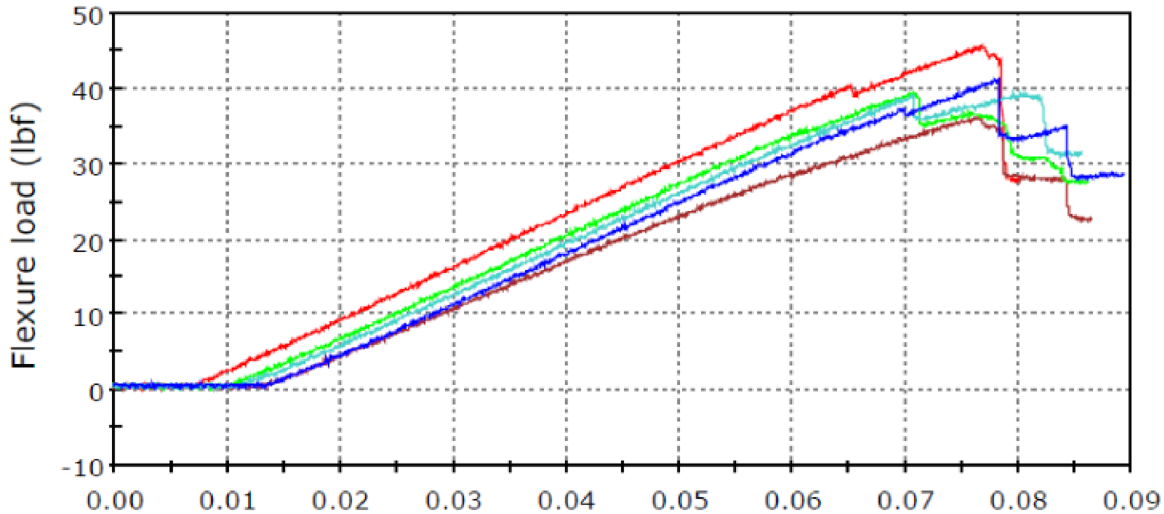
Population 1



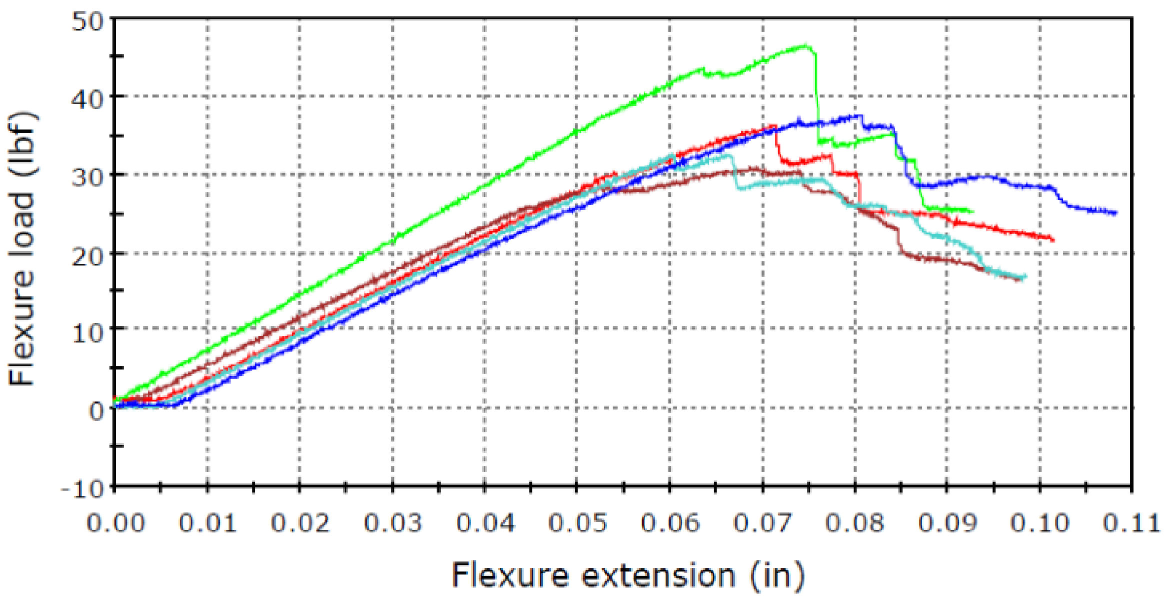
Painted and Clear Coated



Clear Coated



Uncoated



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