Carbon Fibre

CARBON FIBRE IS BECOMING COMMON PLACE IN MODERN MOUNTAIN BIKES. RAOUL LUESCHER **TAKES AN IN-DEPTH LOOK AT THIS EXOTIC MATERIAL, HOW IT IS MADE AND ITS STRENGTHS AND WEAKNESSES.**

Not that long ago, carbon fibre was considered a fragile material only suited to weight obsessed cross country racers. These days, carbon fibre is popping up everywhere—from long travel trail bikes to downhill rigs. Some still feel that the use of carbon is a fad and believe that it should remain on the road while others see it as the future. In either case, there is no denying that it is a major part of the modern day MTB market. So what is it, how is it used on mountain bikes and what are its limitations?

Carbon composites as we know them are a blend of carbon fibres with a polymer matrix. The fibre provides very the high tensile strength and most importantly stiffness, the polymer matrix holds the fibres rigid so each fibre can transfer load to the next fibre.

With composite materials an engineer can design specific mechanical properties to handle a particular problem. Want a bike that is torsionally stiff for good power transfer but vertically compliant for comfort? Carbon composite can do it, and do it at a very low weight.

About the Fibre

There are many different types of carbon fibre as well as other fibres such as aramid, ceramics and of course glass fibres. Basically, and without too much engineering jargon, the most common grades of carbon used in cycling are known as T300, AS4 and T700. Some companies are also using 'high modulus' fibres of various grades such as T800, MJ 50 and others.

What is Modulus?

Modulus refers to the stiffness value of a material—it has nothing to do with strength. This is important because the two terms are often used incorrectly; stiffness is the rate of deflection, strength is the load that can be resisted. High modulus fibres have a higher stiffness than standard modulus fibre, in fact they can be more than twice as stiff. Bike frames generally are limited by stiffness, so using high modulus fibre means that less material is needed to meet the design requirements, thus a lighter bike is the result. However high modulus fibre has less elongation and lower strength, so using less of it makes the frame or component less damage tolerant than standard modulus. High modulus fibre is also very expensive; these factors can limit its use in mountain biking. Sometimes blends of different fibres are used at various locations on a frame. This starts to get complex so the designer really has to know what is going on with each layer and how it interacts with other plies within the frame for this to be successful.

Fabric Types

There is a lot of talk about 'unidirectional' and 'multidirectional' fibre, so here is a very basic explanation. Wherever you see the carbon 'weave' you are looking at a multidirectional fabric. This is made by weaving bundles of carbon filaments called 'tows'. These tows are commonly made up of 3,000, 6,000 or 12,000 individual carbon fibres—these are referred to as 3k, 6k 12k etc. There are many different styles of weave that give different properties and looks. Unidirectional has the fibres running in one direction only and doesn't have the same woven look.

Some advantages of woven fabrics are that it is easier to place in complex shapes, it is more damage resistant and it also looks good. Disadvantages include slightly lower mechanical properties, it is more expensive and it is slightly heavier. Often a woven outer layer is used with unidirectional material underneath. This blends the better protection and look of a woven fabric with the lighter weight, greater strength and lower price of unidirectional carbon.

Fibre Direction

Why do people talk about the direction of the fibre, what does this mean? Individual filaments are only strong along their length. This means a unidirectional material is only strong in one direction, woven bi-directional material is strong in two directions.

This is where the design engineering comes into it. By placing layers at different angles, an engineer can dial in the properties required. This is the reason that carbon frames can be stiff when you stand on the pedals and comfortable at the same time. This is the major difference between composites and metals. Metals have the same strength and stiffness in all directions, the only things metal tube makers can change is wall thickness and the diameter/shape of the tube.

So the direction that fibre is placed in a structure is very important to the final outcome and must be controlled during manufacture. Unidirectional material gives the designer very good control over what each layer of fibre is doing and they can optimise the part if they know how the loads are applied. We will talk more about this a bit later.

About the Resin

It can get just as confusing with the resin or 'matrix' as it is known. The matrix resin is used to encapsulate the fibres and bond each fibre to the others around it. This allows each fibre to transfer load to the next and thus create a rigid product. Remember it is the fibre that has the high tensile strength and stiffness; the resin is weak compared to the fibre.

What are the resin choices?

In most cases, epoxy resins are used for bike parts—it is similar to the 'Araldite' glue that you may use around the house. As with all the different types of fibres there is a broad choice of epoxy resins. Some resins are 'toughened' which means they have additives to limit crack growth. Resin selection is dependant on the environment that you want it to perform in; compared to aircraft, mountain bikes have got it pretty easy with far less variation in temperature and other environmental factors.

What is 'Prepreg?'

These carbon fibres come supplied with resin pre-impregnated. This fabric with resin has to be stored in a freezer until ready to use. It is cured at an elevated temperature usually from 80 C to around 180 C and does not require resin mixing prior to use. The advantages are many, especially with handling and quality.

What is Carbon Nano Technology?

Some marketing material talks about Carbon Nano Tubes—this also refers to the resin blend. Carbon nano tubes are currently the strongest and stiffest material known to man. They are very small carbon tubes about 1/50,000th the diameter of a hair that can be added to the resin to reinforce it and hence improve its properties—like adding gravel to cement to make it tougher. Some of the data on this looks good in terms of improving toughness and strength. Carbon nano tubes are very expensive, however only small amounts are required.

Manufacturing Techniques

An assortment of techniques can be used to form the fibre and resin into the desired shape. These methods may be used to create frame components (tubes & lugs), complete frames or other bike parts such as cranks or handlebars.

Bladder Moulding

Bladder moulding is very common on cycling products. One piece or 'monocoque' frames are made this way, as are most of the lugs and tubes used in a bonded frame. Most hollow tubular parts are bladder moulded as well as rims, handlebars, even some cranks. Bladder moulding is where the fibre is pressed against a mould by a plastic or rubber bag inflated to high pressure inside the hollow carbon section. Prepreg material is generally used due to its ease of handling.

Tape Laying

Tape laying is a computer controlled method for making tubes. Layers of fibre tape are continuously wrapped around a mandrel by a robot and then cured. This method is not that common in cycling, however it is one of the best ways to make a round tube. Some tubes used in tube and lug type frames are made in this manner.

Compression Moulding

Used extensively in the automotive industry. This method involves placing fibre, usually a random orientation prepreg mat, into a closed mould then simultaneously heating and pressing it. It is used for small parts such as suspension pivots, cranks, where loads are not defined.

So as you can see there are lots of choices for composite engineers to select the fibres, resin and the process from.

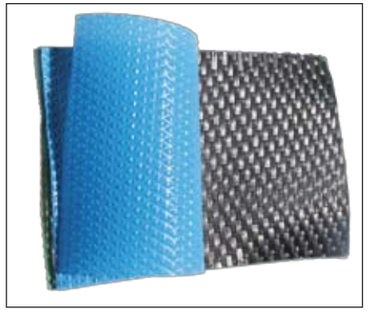
Frame Construction

Much of the jargon refers to the frame construction techniques. There are a few different ways to make a bike frame. It can be made in one piece, often termed monocoque, or it can be made in smaller pieces that are assembled to form a whole. Other common methods include using tubes and lugs that are secondary bonded in a jig, or the tube to tube method which is also made in a jig.

Although one piece frames can have a performance advantage when made properly, history has shown that quality control problems can be encountered in a production line environment. Setup costs are also restrictive due to the number of costly moulds required to get a good range of frame sizes.

Therefore, most modern carbon bikes are secondary bonded. The parts are made and cured separately, and then the individual parts are assembled with adhesive to create the full frame. This has many advantages in a production line environment. It is much easier to control the manufacturing process of a single tube or component than a complete bike. This provides a higher level of quality control when compared with one piece frames. If a problem is found in one section, it can be discarded and a new one made, so only a relatively inexpensive part of the frame gets scrapped. A problem in a monocoque may result in the whole frame being scrapped, which can be expensive. This leads to quality advantages with the secondary bonded method. The disadvantage of a bike made this way is that assembly needs to be done carefully and bonding can have its own problems. It also requires more finishing work which is labour intensive.

The 'tube to tube' method, sometimes referred to as 'carbon welding', is similar in that the frame is also made from a collection of smaller pre-cured parts. The tubes are placed in a jig and bonded, then more carbon is wrapped around the joint to provide strength. This method requires careful finishing around the joints to ensure the integrity is not compromised. It is a very labour intensive process that is commonly used in Asia, or for very low volume custom work. It is possible to make very good frames with this method.



This is 'prepreg' carbon fibre—it comes pre-impregnated with the resin and is cured at an elevated temperature.
Photo • Raoul Luescher

The fibre itself provides the stiffness and strength but it is nothing without the resin.
Photo • Phil Latz

Air bladders such as this are used inside a mould to form the carbon fibre. *Photo • Phil Latz*

Other methods combine the lugs and the wrapping methods, where tubes and lugs are bonded and then a layer of carbon is placed over the joint to reinforce it and create a seamless look. This overcomes some of the potential bonding problems, but also requires more finishing work.

The Big Picture

So what makes a good composite bike you ask? There are many factors that all must be met to produce a good carbon bike.

Firstly the design must be created by people who are experienced with using composite materials. By this I mean engineers who know how these materials behave under load. Composites got a bad reputation in the seventies because people basically replaced aluminium or steel with carbon composite without understanding its behaviour. A well designed frame will be stiff, strong, light and have a long fatigue life.

Secondly, selecting the most appropriate manufacturing method for the design is paramount. There are many different ways to make composite structures, each method suited to certain types of components. This must be considered during the design stage.

Thirdly, the materials used must be appropriate for the task. This means selecting the right fibre type and form; i.e. woven, braid or unidirectional. The right resin system for the manufacturing process is also important along with its environmental properties. Does it get soft in the boot of your car on a hot day?

Last but by no means least is the quality control aspect of the process. Does each frame meet the intended quality standards so it delivers the performance that the designer intended? This is very important with composites; the aerospace industry spends a lot of money inspecting products to ensure that they deliver a consistent standard of performance. With metals you know the properties of the tubing before it is welded because it is certified by the tube manufacturer. This is generally not the case with composites; the builder has to have their own quality control facility to ensure that a safe product goes out the door.

What about the shape?

Structurally the conventional double diamond shaped frame is very efficient; it had to be because the materials used in the early days weren't nearly as good as today's offerings. A well designed straight round tube is still very hard to beat and most fancy tube shapes are based around marketing. However, it does get interesting with modern dual suspension rigs as you need to fit pivots and a shock into the frame design—composites can offer great flexibility in this regard. Other ideas such as using designed in flex to create a pivotless suspension system are entirely possible, utilising the properties available with composites—check the Cannondale Scalpel reviewed in this issue.

What about the ride?

Why is it that some carbon frames are very stiff and a bit unforgiving when others can ride really smooth yet still deliver the power to the trail? The answer lies within the points that I have already covered. It is possible to dramatically change the ride by changing the grade of carbon, the number of layers (called plies) and the orientation of the plies. It comes down to the level of design engineering and selection of materials. Getting the balance just right for a particular riding style can be tricky, to make it so its suits everyone is just about impossible.

Back in the days of custom metal frames, the frame builder would select particular tubes based on your weight, height and riding style. With production metal bikes this ceased to happen. Now the majority of carbon bikes are made on mass in a controlled production facility to keep close tabs on the quality level and reduce the manufacturing cost. So, even though composites can be customised to a very high level, they seldom are because it is just too expensive. Bike companies tend to target a particular set of ride qualities and engineer the frame accordingly.

What about carbon for recreational use?

Trail riders are now able to enjoy some of the performance advantages previously only available to XC racers. Everyone likes riding a lighter bike, as long as it can handle the type of riding asked of it. Some of the new long travel carbon fibre dual suspension bikes are half a kilo lighter than their metal predecessors. A lighter bike makes riding more enjoyable and that is what it's all about for most people. Reputable manufacturers rely on engineers who test their bike designs on machines that simulate years of hard use within a short time and use this information to refine their designs. The production line is also refined to ensure consistent quality control and minimise any warranty issues. A carbon fibre trail bike made using this design process will provide years of trouble free riding.

Composite materials are also great for components such as bars and seat posts as these are relatively easy parts to make at consistently high quality level. Other parts such as wheels are coming into the market with the two opposite ends of the spectrum being covered. Very light rims for XC racing are becoming available and at the other end there is the virtually bombproof TAG full composite wheel designed for aggressive downhill riding.

This is good example of carbon construction—nice even distribution of the fibre and resin with a consistent wall thickness.
Photo • Raoul Luescher

An example of why consistency is vital in the manufacturing process. A glitch has occurred with the internal bladder, leading to an uneven wall thickness. This can produce weak spots where the material is too thin.
Photo • Raoul Luescher

What should I look for in a carbon bike?

It is very difficult to tell the quality of a composite bike by just looking at it. It is even harder when the fibre is covered with fillers and paint. So how do you know what your hard earned cash is buying?
Things to look for include:

- Does the frame have a good reputation for quality?
- Does the fibre look evenly placed with no wrinkles or distorted weave?
- Are the corners well rounded to help distribute stress?

Look inside the tubes where possible.

- Does the thickness look even? Are there wrinkles? Is there extra adhesive?
- Does the exterior have lots of filler covering up problems?

Quality, quality, quality!

Quality control in composite manufacture is difficult and expensive. In aerospace it often takes longer to perform the quality checks than to make the part. Every step of the process is controlled to achieve consistent results. At the end of the line, ultrasonic scans and X-ray images are commonly used to check for compliance. These extra steps would make carbon bikes way too expensive, so manufacturers rely on process control combined with designing in a factor of safety. This means they control the steps of manufacture as closely as possible and they design quality into the part, which minimizes the things that can go wrong. Having a large 'safety margin' in a design gives you some leeway; if things aren't perfect the part will still meet the minimum strength requirements. Have you noticed how the weight of carbon frames is coming down each year? This is because the size of the safety margin decreases as the manufacturing process and quality control gets better—there is a limit however.

What happens when I crash?

Firstly, let me say that a well engineered composite part can take an enormous amount of punishment and survive; you just have to look at Formula 1 cars to see that. The main pod that the driver sits in is designed to hold together whilst the rest of the car breaks up to absorb energy.

It is possible to break a carbon frame just as it is possible to break anything if the design loads are exceeded. The difference with carbon is that it does not bend, it either can take the load or it cannot. This can sound scary, however in reality the strength is very high and there is usually some warning in the way of delamination and cracking due to the interaction of different ply angles. It really does come down to the design; if it is designed and manufactured well, it is no more likely to fail catastrophically than a metal part.

What if I find cracks in my frame?

It is good practice to regularly check your bike for damage and cracks regardless of what it is made of. Cracks in the paint on lugged bikes around the join can be quite common—this is caused by the paint flexing at the joint. Although usually not a problem it is best to get it looked at.

Pronounced gouging caused by dropping the chain or excessive chain suck is far more serious. This may cause breakage in the fibre or even delamination which can significantly weaken the frame. This is a limitation with carbon; it doesn't handle scrapes very well. This type of damage is best avoided by having guards to protect the carbon in these areas. A frame that is engineered with mountain bike use in mind should have extra plies of carbon or kevlar in vulnerable locations such as the drive side chain stay and the rock damage prone down tube. The most common problem is usually impact damage caused by dropping the bike against a hard object. This can cause local delamination at the impact site—similar to a dent on a metal tube.

All these types of damage need to be assessed by an expert to really know if the structural integrity of the frame has been compromised. There are numerous methods for evaluating the extent of the damage but it requires a lot of experience to assess the damage accurately. So if you do find something that you are not sure about, take it to your shop and ask them to get it looked at by someone with experience. For something like a handlebar it is best to just replace it.

Can carbon fibre be repaired?

Each damaged carbon part needs to be evaluated on a case by case basis, the same as with any other material. Carbon repair methods are well established in the aerospace industry and have proved to be very effective. In many cases a carbon repair on a metal frame may be preferable as it avoids any heat damage. With good knowledge of these methods, it is even possible to do field repairs with very little special equipment and no mains power. I have repaired many frames that have suffered damage – usually caused by exuberant baggage handlers – the night before a major race with no issues whatsoever. However you need to get a specialist to look at the damage, I have seen people try to fix holes in their frame with a home fibreglass repair kit; this is definitely not recommended. Take it to someone who knows what they are doing.

Mountain bikes usually see plenty of knocks and bumps that will mar the outer finish of the carbon. Where the marks are in the top coat with no damage to the underlying fibre, the surface can be resealed with some clear lacquer. Resealing the carbon will protect the fibres from further damage from oil, aggressive degreasers, UV light and moisture related damage.

A Carbon Fibre Future

Composite materials have made major inroads into the mountain bike market and carbon fibre usage is increasing across all areas of off-road use including BMX. All of this suggests that the off-road market will follow the road market and embrace the performance advantages of composites.

It seems that every day some new carbon fibre part is let loose on the market. Some products are clever in their application of composites, other's it seems are carbon for the trendy look without an engineering advantage. Be warned that composites do have limitations—aerospace engineers do not set out to design an entire aircraft from carbon, they use the best available material for the job, be it steel, aluminium, titanium, composites or whatever. Reliable performance is far more important than fashion. Look for products from reputable manufacturers, preferably with a solid history using composites, companies with a quality test program. Think about this next time you find yourself drooling over some funky looking carbon fibre bike part.

Ultrasonic scan equipment such as this is commonly used in the aerospace industry to check for manufacturing faults—bike parts do not undergo the same costly testing. They rely on a consistently repeatable manufacturing process and a solid 'margin for error' in the component strength.
Photo • Raoul Luescher

A large number of frames consist of separate components that are bonded together. In some cases an additional wrap of carbon is applied over the junction for added strength.
Photo • Phil Latz

Raoul Luescher has been involved with composite materials for almost 20 years. He has been employed by Boeing Aerospace, the Composites CRC and the Australian Institute of Sport. He has extensive experience in quality control of composites and has designed and built many composite items including bike frames, wheels and components. If you need assistance with damage assessment or repairing a carbon composite part, Raoul can be contacted at whodesigns@bigpond.com