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Technical White Paper

Bicycle Frame Materials Comparison with a Focus on Carbon Fiber Construction Methods

Introduction

Twenty years ago, choosing a road racing bicycle frame was simple...and limited. For light weight and a smooth ride there were Columbus SL and similar light gauge steels. Large powerful riders who needed more frame strength put up with the weight and harsh ride of Columbus SP or similar stout steel. Custom frame builders could tune the feel of a bike by mixing tubes, using stronger ones where needed and paring weight elsewhere.

For aluminum, the choice was between a limber Alan or Vitus or a super-stiff, ultra-expensive custom Klein. The few exotics such as the carbon fiber Graftek and the Teledyne titanium were plush riding but costly curiosities with deserved reputations for frame failure and inconsistent handling.

Breakthroughs in materials and a growing market for high-tech cycling products accelerated the evolution of bicycle frames through the 1980's. Cannondale and Trek led the industry in popularizing aluminum frames, while better, less-costly grades of titanium and carbon fiber sparked interest in the potential of these space-age materials. Steel manufacturers fought back with new higher strength alloys and heat treatments, sophisticated shapes, and non-standard diameter tubes to reduce weight while increasing comfort and efficiency.

Now there are more choices and naturally...more confusion. If one asks "What frame material is best?" a qualified answer is required because *how* a given frame material is used can be as important as *what* material is used.

The ideal bicycle frame for a given rider would fit the rider's build and would be light. It would absorb road shock well, but it would handle crisply because of lateral stiffness and would deliver undiminished applied pedal power to the drive train. It would be durable and not subject to fatigue failures and would be strong enough to stand up to unexpected impacts and torsion forces. It would lend itself to attractive finishing and would resist corrosion or attack by the elements.

Material Facts

Steel, aluminum, titanium and carbon fiber all attempt to achieve the above criteria, but differ from each other in strength, stiffness, weight, fatigue resistance, corrosion, etc. For example using aluminum or titanium in the same tube dimensions as a traditional steel frame would reduce weight but would produce excessive flexibility. So non-ferrous metal frames typically have larger tube diameters than steel ones to gain rigidity.

Metal frames usually do not fail due to a single catastrophic load but because of small, repeated stresses (called "fatigue"). Steel and titanium have defined minimum fatigue limits—if the stresses are smaller than these limits, these smaller forces generally don't shorten the fatigue life of the frame. Aluminum has no such specific endurance limit, so each stress cycle, however small, takes the material that much closer to fatigue failure. This sounds worse than it is, however. Designers realize this limitation and attempt to "over build" their frames for a lifetime of use.

Titanium's high strength, light weight, resilience, and resistance to corrosion make it a well-suited frame material. However, being a metal, many of the same mechanical properties that limit steel and aluminum also limit titanium: metals are equally strong and stiff in all directions (a property called "isotropy"). Once the cross section geometry of a metal pipe is determined to meet strength or stiffness requirements in one plane, an engineer lacks the freedom to meet varying demands for strength or stiffness in any other plane. In metal tubes, by setting diameter and wall thicknesses to meet bending standards, this automatically determines torsional and lateral bending stiffness.

Metal frames are just variations on a single theme compared to composites. Composites consist of reinforcing fibers that are embedded in a matrix material. The most common composite is known as “glass”, meaning polyester resin (the matrix) reinforced with fiberglass. *Advanced composites* are composed of engineered fibers such as carbon, polymer, metal, or ceramic. Usually these fibers are impregnated with a thermosetting resin like epoxy. Other matrix materials include thermoplastics, metals and even ceramics. These advanced composites make structures that are as strong and rigid as metal ones of equal size, but weigh much less. Furthermore, until the matrix material is hardened by a chemical reaction or heat, the resin-soaked fibers can be molded or formed into virtually any shape.

Unlike isotropic metals, composites are anisotropic—their strength and stiffness is only realized along the axis of the fibers, which can be arranged in any desired pattern. Thus, to absorb the variable stresses of a given bicycle frame, composite frames can use multiple layers with different fiber angles for each. This puts strength only where it is needed while minimizing weight.

Along with traditional round tube and lug frame designs, composite frames can be molded with the use of internal bladders and foam in either one-piece ("monocoque construction") or multi-section frames. Also, they can be formed in a high pressure lamination process combining the frame tubes into one integral piece.

Industry Parallels

As with some other sporting industries, the future of cycling is moving away from metals. Continuing advancements in the pace setting aerospace, automotive, and boating industries have nearly assured the role of composites as the structural material of the future.

Other sporting good industries where new materials have supplanted the old, include tennis, archery, skiing, boating, golf, and fishing. Composites have replaced previous materials and eventually declined in price to widely affordable levels.

New materials replace established ones for many reasons. In sporting goods substitutions occur because a new material out performs an existing one. An example is the tennis racket where wood was once the only material for racket frames. It offered excellent shock absorption, but it swelled and shrank with the weather, warping the frame and changing string tension. Wood that was strong enough to meet the needed criteria was too heavy. Tubular steel and aluminum rackets came into vogue in the early 1970's. They were lighter than wood, were unaffected by the weather, and offered more potential power in the swing. However, the feel of metal didn't suit many players, and many did not like the impact shock these rackets radiated into their hands and arms.

Composite rackets arrived in the late seventies and changed everything. They delivered resiliency and shock damping of wood, and weather immunity of metals. Also, they were light! Within six years, composite rackets became available at all but the lowest price points, and wood virtually disappeared. At present, 95% of all tennis rackets are of composite construction.

Composite bicycle frames have been a largely American phenomenon, because the technology emerged from the aircraft and boating industries. Manufacturing composites requires greater technical expertise and money for product development. Consequently, these products usually must enter the market at the high end. As a result, there have been few high-end American bike companies that have been willing to learn this technology to develop innovative composite framesets.

Many bicycling engineers who have envisioned composite frames haven't enjoyed the proper circumstances to create a widely marketable product. With more people becoming convinced that composites can deliver even more performance out of a bicycle, these designs are finally being recognized as a superior choice.

The Benefits of Carbon

A bike frame is a considerably complex structure with performance characteristics that include lightness, rigidity, durability, and shock absorption. Aluminum and titanium frames have become popular because they challenge steel frames in at least two areas of performance: lightness and corrosion resistance. But, at the high end of the industry, composites will likely eclipse frames made from any metals in all performance areas.

The metallurgical composition of a metal tube can't be varied over the length of the tube. In contrast, composites can be infinitely varied over the length of the tube. Some of the variations include different fiber angles, different plies, different ply thicknesses, and different combinations of materials. So the properties of the end product made from composites can be tailored to precise specifications. It is also easier to customize a composite tube for varying degrees of stiffness than it is to customize a metal tube. Additionally, the tooling cost for metal tube production is several orders higher than that of composite tube production.

Composite tubes are typically formed around a mandrel (a metal dowel, typically steel that is later withdrawn) by either "filament winding" (winding strands at various angles), "roll wrapping" or "braiding." Another method called "pultrusion" pulls fibers through a heated die that melts a thermoplastic matrix. Each manufacturer has its own special number of layers and orientations of fibers to create its desired combination of strength, weight, and stiffness. This is the beauty of carbon fiber: with metals the choices are much more limited, but with carbon fiber they are almost limitless.

Tailoring a bicycle frame is not new, it's been done with steel frames for years through the butting process, where tubes are thickened at the joints to handle stress and thinned out in their long center spans to reduce weight. What if the size and shape of each tube are matched precisely to the predicted loads of pedaling and road shock? What if the material could be distributed precisely where it is needed. What if the rigidity of each tube, through some complicated shaping or milling process, varied from one plane of bending to another or from one end to another? The frame could be built to be rigid to lateral pedaling loads, but fine-tuned in the vertical plane for compliance to road shock. Shaping and milling a metal frame in this manner would be nearly impossible. But, composites can be relatively easily molded into structural members with complex cross sections.

Figure 1 shows the specific stiffness of the four main materials used in making bicycle frames. Specific stiffness is defined as tensile modulus divided by density or simply, the stiffness to weight ratio. One might ask: “If carbon fiber has such a high stiffness to weight ratio, why aren’t carbon fiber frames lighter than they are?” The answer is that carbon fiber has a huge advantage in tension but in practice, it is difficult to direct all the stresses imposed on a structure. It is up to the designer to take this into consideration and to do their best to load the fiber in tension.

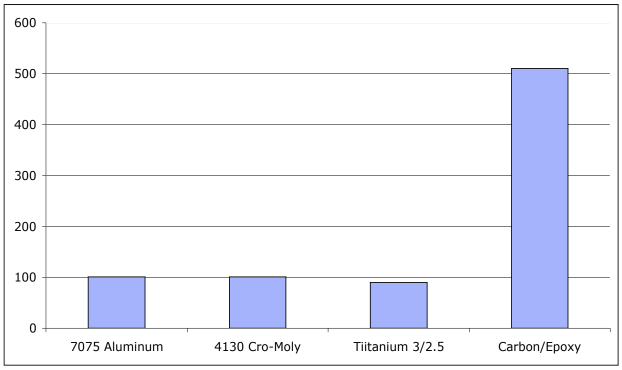

Figure 1: Stiffness to Weight Ratio (in tension)
Source: "Materials Selector," *Materials Engineering*, December '92

Composites can be molded into structural members with complex cross sections with relative ease. They also have some very impressive mechanical properties. The 6061 and 7000 series aluminum used in bike frames is roughly one-third as heavy as steel, one-third as stiff, and, at best, is about 80% as strong as the 4130 cro-moly steel used in most bike frames. Titanium is roughly two-thirds the weight of steel, one-half as stiff, and about 60 percent as strong as steel. The carbon fiber composite most used by bicycle manufacturers is less than one-quarter the weight of steel, but it is about as stiff (which makes it almost four times as stiff on a weight-to-weight basis), and it is roughly four times as strong in tension. Carbon fiber also has a better fatigue life than steel, titanium, or aluminum, and the resins typically used to bond the fibers offer extremely good vibration damping.

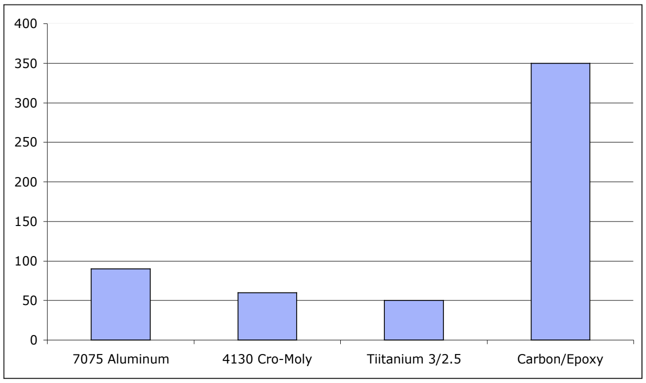

Figure 2: Strength to Weight Ratio
Source: "Materials Selector," *Materials Engineering*, December '92

Vibration and shock damping are two important factors that affect the cyclist. However, they are two of the least understood subjects in materials science. There are so many variables involved—including how atoms in a material absorb and dissipate vibrational energy, how the structure is built, what type of paint and plating are applied—that it is hard to predict how a structure will react to vibrational input. Composite's vibration damping is far superior to any metal, which is why it is the preferred material for race car springs and high performance airplanes. The smooth ride quality is one of the first things people notice about carbon fiber bicycle frames.

Sophisticated finite element analysis programs and laminated-plate theory help define the properties of a composite structure. An inherent difference between composites and metals is that composite products are constructed in layers, or plies, of directional material. Interfacial adhesion and the potential for *delamination* (separation) under shear or compressive loads must be considered when analyzing an advanced composite design. This information is essential when addressing the variable requirements of a bicycle.

Composites differ from metals in that they don't carry loads equally in all directions, but bear loads best in tension. A composite is similar to a bundle of strings soaked in a layer of glue or resin. The bundle can bear more weight, and flex less, if pulled from end to end or flexed like a diving board than if compressed or loaded transversely. The changing face of the bundle's performance occurs because the real strength of the bundle comes from the string, not from the resin. The primary function of the resin is to lock the fibers in place, transfer loads among fibers, protect the fibers from environmental forces, and give the structure impact strength. The directional nature of the fibers' load-bearing abilities changes the rules of structural design.

Comparison of Materials Used in Bicycles

STEEL		**TITANIUM**	
Pros	**Cons**	**Pros**	**Cons**
• Inexpensive	• Heavy	• Light	• Expensive
• Strong	• Corrosive	• Strong	• Designs limited by available tubes
• Stiff	• Designs limited by available tubes and lugs	• Resilient and "lively" feel	• Not easily repaired
• Resilient and "lively" fee	• Brazing and welding produces weaker, heat-affected zones	• Shock absorbing	• Bad welds are easily hidden
• Easy to work with and repair		• Non-corrosive	• Stiffness is traded off for light weight

ALUMINUM		**CARBON FIBER**	
Pros	**Cons**	**Pros**	**Cons**
• Inexpensive	• Fatigue risk requires "over-building"	• Lightest	• Expensive
• Light	• Lacks resilience and has "dead" feel	• Strongest	• Technology still evolving
• Adequately strong	• Not easily repaired	• Best shock absorption	• Strength and stiffness are design dependent
• Very stiff for the weight	• Bonded joints prone to failure	• Unlimited design applications	• Fully molded styles have very limited sizes
• Non-corrosive in non-salty environments	• Heat treatment can be inconsistent	• Non-corrosive	
		• Material has high fatigue resistance	
		• Some designs are easily repaired	

History of Carbon Fiber Frames

The remarkable properties of composites have found their way into the bicycle industry. Carbon fiber frames first appeared in the mid 1970's. The number increased in the 1980's as more carbon fiber frames and a few components began to trickle into high-end bike dealers and parts catalogs. But these efforts were mostly limited attempts to save weight and often lacked careful engineering and commitment by the manufacturers. The lasting impression of most carbon fiber products was that they were quirky, flexible, fragile, and very expensive.

Over the past fifteen years, several more innovative carbon fiber framesets have entered the market. These have successfully challenged metal frames in two areas of performance—weight and ride comfort. But even some early versions of a few brands also had a poor record of reliability. Multiple warranty returns to fix cracks, loose dropouts and other unbonded metal parts were common.

For these reasons many of the industry's big players continued to view carbon fiber as a novelty. Some manufacturers simply have been content with the old standard: bicycles out of metal. Others either haven't been motivated or perhaps able to spend the time, energy, and money to learn composites technology and develop composites manufacturing techniques. Several companies have dabbled in composites by bonding carbon tubes (mainly seatstays) into aluminum and titanium frames. While there is a small amount of improvement in vibration damping on these frames, they still do not take advantage of the benefits of a full carbon frame.

Even so, composites have made many advances since the mid '80's. Resins, fibers, and epoxies are a lot stronger today. What is more important, understanding how to use these materials has increased tremendously, due in part, to development of sophisticated analysis programs. Composites are more than high-tech weight savers; they are superior structural materials that are revolutionizing the way we build bicycles. A well-designed composite frameset performs better than a metal one. After taking some tentative steps, it has become a viable material in the bicycling industry. A few manufacturers have taken the necessary steps, and have a relatively firm grasp on the capabilities, potentials, and limitations of composites.

One of the major driving forces into the advancement of composites within cycling has been the use of carbon bikes by accomplished racers. Three time Tour De France winner and Professional World Cycling Champion Greg LeMond, in his constant pursuit of higher performance, has helped further this cause more than any other cyclist by using the most advanced technologies available. His pursuit has included extensive use of carbon bikes in most of the world's most prestigious professional bike races. Greg was instrumental in pushing for the use of higher grade carbon fiber known as “high modulus” fiber. He was also unusual in that he sponsored the bikes for his own team where usually, riders have no choice but to ride what the bike sponsor provides. Of course, the sponsor advertises that “so and so selected our product” but rarely is it true.

Even Higher Technology

High modulus fiber is simply a more refined carbon fiber. The term “modulus” refers to “Young’s Modulus”, a measurement of stiffness. The higher the number, the stiffer the fiber. The process for making the higher modulus fibers involves stripping off the outer layers of the individual fibers, leaving the stronger core. A few companies are using a limited amount of high modulus fiber. It is expensive, and is used sparingly. The most advanced bicycle frame as of this writing is made with high modulus carbon co-mingled with boron fiber. The boron fiber is interesting because of its incredibly high stiffness in compression. Combined with the high tensile stiffness of the carbon, a synergistic result is achieved where the overall stiffness of the tube is greater than that predicted by the properties of the individual fibers. The ultra tough boron fiber also protects the more brittle high modulus carbon fiber. These advanced properties have found favor in the landing gear of fighter jets as well as a modern bicycle frame.

Building Frames with Carbon

One direction that carbon fiber bikes have taken is a mimicry of the conventional metal-tubing bicycle. These are essentially the same as a bonded aluminum bicycle, but with carbon fiber tubes substituted for some or all the aluminum tubes. The idea of joining tubes in a triangulated structure is a familiar one that is logical for a designer to begin with. It reduces the number of unknowns because it allows the carbon fiber frame to be modeled after a successful design. It also allows production of different sizes and angles by simply creating new lugs to join the carbon fiber tubes. Traditional cyclists are likely to appreciate this approach as well. While forced to deal with the strangeness of carbon fiber, they are not asked at the same time to accept a completely new idea of what is a bicycle. However, putting both rigidity and ride comfort into a diamond frame made of metal has always resulted in a compromise. The diamond frame is a triangulated structure that stiffens up vertically as efforts are made to stiffen it laterally. In any way that carbon fiber is used, these attributes can be realized through good design, because they are intrinsic to the carbon fiber material. The question is the degree to which these benefits are realized.

Several other, less-traditional, approaches to building frames with carbon fiber exist. Foam-core and bladder-molded frames are sometimes referred to as "one-piece" molded structures. By "one-piece" it's meant that the frame is molded as a single complete unit. Some indeed are, while others are molded in several pieces and then glued together to give a one-piece look. These processes can be complex, but they generally give engineers freedom to place carbon fibers wherever they wish. Extensive seams resulting from the overlap of material required by the molding process can sometimes create weak areas in the frame. Extremely careful attention must be paid in both the design and manufacturing of these frames to ensure proper quality control.

Another method is the use of a high-pressure lamination process. Here, a lug-less frame is created where the structural members forming the frame are carbon fiber tubes that are melded together with an epoxy-impregnated carbon fiber fabric. Gussets are integrally and simultaneously formed with the joining of the tubes. Along with increased design freedom, eliminating the dependency on lugs also eliminates the inherent weakness found in the tube and lug joints of many other designs. In turn, fine tuning of the frame's ride characteristics is possible since the same material is used in the tubes as in the tube transition areas. The fiber flow between the tubes is continuous which allows for an even distribution of stress flow throughout frame, virtually eliminating fatigue problems.

The Importance of Good Design

The beneficial properties of composites as a frame building material are exceptional. That is, *if* they are designed with carbon's specific characteristics in mind. With proper design, a carbon fiber-tube bike can be stronger, lighter, stiffer, more fatigue resistant and more comfortable than a steel-, aluminum-, or titanium-tubing bicycle. Certainly these advantages are significant. These attributes can be realized through good design, because they are intrinsic to the carbon fiber material. However, the development of carbon bicycles has come with some challenges. Besides the simple failure to optimize ride quality, many designs have been plagued by spotty reliability including tube and lug bonding failures, parting line cracks, loose component attachments, delaminating bottom bracket and head tube sleeves.

The following section discusses some primary design considerations—most of which are inter-related—that should be addressed in building a carbon bicycle.

1) Experience and Real-World Testing

Sorting out the variables to satisfy the opposing goals of a bicycle frame has fallen onto the shoulders of composite engineers. Using extensive knowledge of composites and computers, some have engaged in a sophisticated analysis of a bicycle frame using a finite element analysis program. Ultimately, though, experience gained through trial and error and extensive ride testing is the best route to tuning a vehicle's ride qualities. Sophisticated computer analysis techniques can provide a jump on the design process, but the trial-and-error can not be ignored. The most important test is rider judgment.

Maximizing the benefits of carbon fiber in a bicycle requires extensive knowledge of composites combined with knowledge of how this applies to real life cycling. Manufacturers have a tendency to place too much emphasis on only a one of these areas while neglecting the other. Extensive product testing under extreme and demanding conditions needs to be followed by design refinements based on that experience - and the process needs to be ongoing. Such design elements as bike handling, fit, comfort, stiffness, durability, location of attachments, ease of maintenance, etc., are all issues that simply can't be learned on a computer alone.

2) Ride Quality

Engineers have sought new ways to use carbon fiber to reduce weight without compromising rigidity. Some early models gave carbon fiber a reputation for excessive flex, a rap that's largely been remedied by today's frames. However, others have taken it to the other extreme and made frames too stiff laterally and vertically, giving them a “dead” feel.

Some of these problems can be attributed to manufacturers inappropriately taking previous tubing dimensions from aluminum and steel (standard and oversized) bikes and replacing them with similar dimension carbon fiber tubes. Although good shock damping characteristics are inherent in many advanced composites, these characteristics must be optimized by designing them into the specific structure of the frame. The challenge lies in creating tubes that offer an appropriately stiff ride horizontally, retaining vertical compliance (a forgiving ride), while at the same time withstanding the rigors and abuse of every day riding, racing, and transporting the bicycle.

Other ride quality problems stem from bonded joints. Where two materials of non-similar properties (i.e., carbon and aluminum) are combined, an area of material discontinuity is created. Stresses are therefore unable to flow smoothly throughout the frame, resulting in stress risers at those areas. Besides higher possibility for frame failure in this area, it also leads to a bike that does not absorb road vibration and shock well.

3) Sizing

Similar to buying an expensive suit or dress, proper fit is one of the most important factors in choosing the correct bicycle frame. However, with a bicycle frame, correct fit is tantamount since the cyclist's biomechanics, aerodynamics, comfort, and handling abilities are all greatly affected by frame geometry. Forcing multiple body sizes, shapes, and riding styles onto an incorrectly fitted frame greatly sacrifices the cyclist's overall performance. Given the correct size, many cyclists can do well with the fit of a properly proportioned production bike. Others, who don't fall into the range of "normal" physical proportions, are better suited to a custom tailored frame.

Most carbon fiber frame designs–particularly those employing full size molds–are limited in their ability to offer a full size range. Many molded aerodynamic frame manufacturers are cost-constrained by complex, expensive molds. As a result, they can only offer limited sizes and some have been forced to subscribe to the one-size-fits-all theory. Some have done so while touting such things as aerodynamic frame benefits.

Several of the molded aerodynamic frames are particularly subject to the cost constraints of molds due to their complex shapes and can only offer limited sizes. In reality, the difference between good and fair rider position accounts for a much greater gap in athletic efficiency than the difference between an "aero" bike and a round tube bike. Professional athletes spend far more time and effort refining their position on the bike to be biomechanically efficient as well as aerodynamically efficient. Proper fit should never be compromised for flashy tube shapes. Luckily, most companies now offer a wide range of sizes with a select few able to make a truly custom frame.

4) Interfacing Carbon with Metal Parts

One of the greatest drawbacks of a metal-tubed frame is in the joints. Almost all frame failures occur near the joints, usually for one of two reasons: fabrication of the joint may weaken the tubing (through overheating), or the design of the joint may cause a concentration of stress that leads to failure. As the old saying goes, a chain is only as strong as its weakest link.

Conventional carbon frame-building methods using carbon tubes bonded to aluminum lugs is a controversial method. Will the adhesive bond have adequate strength? Will there be an electrolytic reaction between the carbon fiber and the aluminum (galvanic corrosion)? Will the materials expand at different rates when subjected to temperature variations (thermal expansion)? Also, by simply switching the tubing material from metal to carbon fiber, there is no reason for the problems of joints simply to go away. The glued joints are located at the areas of highest stress—particularly the bottom bracket cluster and the head and down tube juncture—on a bicycle frame. Material discontinuity (where two dissimilar materials are joined) creates stress risers (concentrated areas of stress). Coupled with galvanic corrosion, thermal expansion, or an inadequate bond, these areas can catastrophically fail. Failure can, at best, be a distressing experience for a cyclist at high speeds and more than an irritation if it means downtime from their bike.

Bonding failures can stem from an act as simple as storing a bike in a vehicle. Under even a moderate sun, the interior can easily achieve temperatures more than 180 degrees Fahrenheit. Similarly, transporting a bike in the cargo space of a plane (which can become extremely cold at high-altitudes) can have detrimental effects on the structural integrity of the frame. At these temperatures—particularly if repeated and if followed by rapid heating or cooling afterwards (like hosing off a bike to clean it)—thermally induced changes can take place in the various frame materials and its bonded on parts. For frames with materials of different expansion coefficients, this can lead to failure. Failure can occur in areas ranging from tube and lug joints, to bottom bracket shells, head tube sleeves, shifter- and water-bottle bosses. Two ways of addressing this issue are to use materials with similar coefficients of thermal expansion to join the tubes without bonding and to use mechanical retention systems along with bonding for parts attachments. If metal must be used it should be titanium. Titanium, unlike steel and aluminum, is not susceptible to corrosion. Although a metal, it also has thermal expansion characteristics fairly similar to carbon fiber while aluminum and steel are quite different.

The attachment of parts poses another challenge in the building of composite bicycles. Aluminum readily corrodes when joined with carbon fiber due to the substantial difference in the galvanic corrosion potentials of the two materials. Corrosion poses a problem not only for aluminum lugs bonded to carbon tubes, but also in other areas like bottom bracket shells, head and seat tube sleeves, water bottle bosses and shifter bosses. Besides galvanic corrosion, the different fatigue characteristics and thermal expansion rates of the two materials increase the potential for failure to occur at the connections.

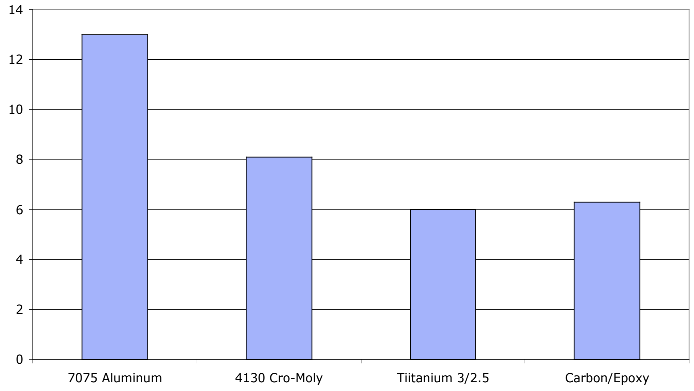

Figure 3: Coefficient of Thermal Expansion
Source: "Materials Selector," *Materials Engineering*, December '92

Bonding to carbon fiber has always been a problem for carbon frame builders. There are too many variables involved with adhesive bonding (shelf life, mixing and metering accuracy, transportation problems, human error, etc.). And, it's simply too hard to tell if a chemical is performing the required function correctly or incorrectly. The potential problem of having these bonds fail and the parts fall off while *in motion* could lead to disastrous consequences for the rider (and accompanying riders) if they were to fall into rotating spokes or under a wheel. If aluminum must be used, it should be insulated from the carbon to prevent galvanic corrosion. Some designers rely on anodizing to insulate the aluminum. This has proven to last only a few years at best. Others rely on the adhesive itself to insulate the aluminum from the carbon. This can be done with a special glass filled adhesive used in parts that are bonded in fixtures that prevent the parts from touching each other during the curing of the adhesive.

One attempt at solving the bonding dilemma is to drill holes in the structure and blind rivet the part onto the carbon fiber laminate and attempt to reinforce the area around the drilled hole with some form of backing plate. Drilling holes in composites: degrades the laminate by interrupting and cutting the fibers, provides a spot where delaminations can start, creates dramatic increases in stress risers in the respective area, and decreases fatigue life. This can occur in areas as large as tube and lug joints, or as small as bottom bracket shells, head tube sleeves, and bonded on shifter- and water-bottle bosses.

The best solution lies in creating a system where, if the attachment of metal parts is required, they should be formed with a material that exhibits similar properties to carbon fiber. An important requirement is that the material used should have a coefficient of thermal expansion similar to carbon. Titanium is the most appropriate metal for use in applications requiring metal mated to carbon since it is highly resistant to corrosion and it has a similar thermal expansion coefficient to carbon's. Additionally, if bonding is required, it should be combined with a mechanical retention system. Mechanically retained parts reduce or eliminate the reliance on bonding alone.

5) Consistency in Manufacturing

Consistency in manufacturing with carbon fiber is an issue that continues to confront many manufacturers. Each method has its own inherent challenges.

With molded frames a different mold is required for each frame size. Pressure is required inside the tubes to expand them such that they compress against the mold cavities. This pressure is usually applied by way of expandable rubber mandrels or bladders or by applying pressure by co-curing the composite with an internal foam core. These curing processes must be performed at elevated temperatures that cause the foam to expand and compress the composite material, while the bladder-molded frames are internally pressurized with air or gas. The foam remains inside the tube as a permanent part of the structure, as often do the bladders. It's difficult, however, for the bladders and foam to apply sufficient and consistent pressure. This is especially true at the tighter curves where the bladder will tend to bridge across the radius. The absence of adequate pressure results in irregular compaction and possible voids (air pockets) which could result in delamination of the plies of composite material.

Additionally, seams are usually created at the areas where the carbon is joined or overlapped. These raised seams require extensive and careful sanding or filing around most of the frame to assure a smooth finish. Too much sanding and filing can sever the fibers and weaken the respective area. This problem can be compounded if the carbon pieces become wrinkled or pinched—rather than properly overlapped—before being compacted.

Apart from the difficulty in ensuring consistent quality, bicycle frames manufactured by this process are generally more expensive and hard to produce in varied sizes and geometries. Manufacturers of molded frames have become much better at working with simple parts and shapes, such as the fork and seatstays. However, more complex shapes like a bicycle frame create more potential for inconsistency. The fewer the pieces the easier it is to control the process.

Consistency is generally very good in the manufacturing of structural tubes formed around a mandrel. Tubes can be created through one or more processes: hand lay-up, roll-wrapping or table rolling, braiding, or filament winding. Of these methods, filament winding and braiding offer several structural advantages over hand lay-up or table rolling methods. Filament winding maximizes load transfers in a composite structure since the fibers are typically placed under tension (the way in which carbon fiber best transfers loads). Winding the fibers under tension allows fiber to accept loading immediately after application before the matrix material is stressed beyond its ultimate limits. The matrix material's primary functions are to provide shape to the structure and position the fiber such that an applied load can be efficiently transferred to the fiber. When fiber in a load bearing structure is wrinkled or uneven, matrix failure can occur since the resin strength is significantly less than that of the fiber. This resin breakdown, although often gradual, will significantly reduce the functional life of the composite structure because fibers in the structure won't be loaded evenly, causing some fibers to fail before all the structure fibers begin to work together. This gradual breakdown of matrix and fiber can lead to lower fatigue life of the structural member.

Structural efficiency and maximum fatigue life in filament-wound tubular structures is further optimized since material seams or overlaps do not exist in material layers. Proper attention to the position of layer seams or overlaps in table rolled or layed-up tubular structures is necessary to maintain static load design properties. However, seams and overlaps add inefficiencies in weight over filament wound structures.

6) Damage Resistance

Like damping, impact resistance is not found in every composite, but it can be designed in. The bicycle frame is historically subject to stress from minor crashes, falls, and simply abusive storage and transportation. Such things as the cumulative effects of numerous abrasions (leaning the bike against a parking meter or wall) or the single catastrophic event such as jamming a chain between a frame tube and the rotating chain rings are a concern for carbon manufacturers. Some manufactures have used an aluminum core in the tube wrapped with carbon fiber and Kevlar®. This metallic core provides insurance in case of severe abrasion, as well as eliminating problems associated with bonding non-similar materials, although this makes for appreciably heavier tubes. Fabricating the tubes with a margin of strength that will tolerate some minor abrasion despite the loss of a number of fibers should be easy. In order to prevent minor abrasion, the choices are: use urethane enamel coatings, use a sacrificial outer layer, or use a Kevlar or boron outer layer in the tubes.

Pre-fabricated tubes formed around a mandrel are generally the most damage-tolerant. Bladder molded frames, because of lower compression pressures and inconsistent wall thicknesses are generally more susceptible to impact damage. With any tubing, appropriate minimum wall thickness must be balanced with appropriate tube diameter (diameter/wall thickness ratio) to ensure a bike that combines optimal ride characteristics *and* damage resistance.

7) Finish

How a frame is finished can tell a lot about the consistency of manufacturing. A frame made with lots of pinholes and surface voids must be treated with a body filler (e.g., Bondo) and painted with a primer/filler and finally a top coat. This tends to hide the problems of a frame's construction as well as add excessive weight. If a crack forms in the paint, it is difficult to tell whether it is a serious structural flaw or a minor cosmetic problem. One thing that paint does well is to protect the epoxy from ultra-violet rays. Clearcoats that filter UV rays are commonly available however. On a clearcoated frame, it is much harder to hide manufacturing defects. Non-coated frames can be protected from UV with wipe on, wipe off products such as 303 Protectant℠. Getting a good finish on composite frames is difficult and is one of the main reasons more companies do not attempt to build a full carbon frame.

Manufacturing Method Comparisons

Following, the primary methods of carbon bicycle frame production are outlined. Included are examples, benefits and drawbacks to each respective design.

Carbon Tubes/Aluminum Lugs

Examples:
- Look KG series
- Time Helix
- Older Trek 2000's

Pros:
- Inexpensive carbon design
- Lighter than steel frames
- Traditional look
- Simple design
- Generally good impact resistance of tubes

Cons:
- Limited by metal lug design
- Weak spot at lugs susceptible to catastrophic failure (due to galvanic corrosion, thermal expansion, or inadequate bond)
- Fail to optimize benefits of carbon
- Bonded and blind-riveted parts
- Discontinuity of materials leads to non-optimized ride quality
- High stresses at joints
- Non-repairable

Carbon Tubes Bonded to Aluminum Tubes

Examples:
- Pinarello Prince
- Many other Taiwanese-sourced brands

Pros:
- Least expensive way to add carbon to a welded frame
- Lighter than steel frames
- Traditional look
- Simple design
- Generally good impact resistance of tubes
- Custom geometry possible

Cons:
- Fail to optimize benefits of carbon (particularly fatigue resistance and vibration damping)
- Carbon/aluminum interface not insulated, causing galvanic corrosion over time
- Discontinuity of materials leads to non-optimized ride quality
- Overlap of the two materials at joints create redundant structure
- Non-repairable

Carbon Tubes Bonded to Titanium Tubes

Examples:
- Seven Odonata
- Serotta Ottrott
- Several Taiwanese-sourced brands

Pros:
- Inexpensive way to add carbon to a welded frame
- Lighter than steel frames
- Traditional look
- Simple design
- Generally good impact resistance of tubes
- Custom geometry possible

Cons:
- Fails to optimize benefits of carbon (particularly vibration damping)
- Adhesive bonding to titanium can be difficult to do properly
- Discontinuity of materials leads to non-optimized ride quality
- Overlap of the two materials at joints create redundant and heavier structure
- Non-repairable

Carbon Tubes/Molded Carbon Lugs

Examples:
- Trek OCLV
- Parlee
- Colnago C-40
- Calfee Luna and Dragonfly

Pros:
- Lightweight
- No galvanic corrosion problems at lugs
- Better approach than metal lugs
- Good cost-benefit ratio (Trek OCLV and Calfee Luna)
- Custom geometry possible (although difficult)

Cons:
- Uneven load path at the lugged joints causes the forces to concentrate at the bonded interfaces leading to possible failure. (unless accommodated with substantial bond surface area)
- Use of blind rivets and bonding-on of fixtures (opportunity for warranty problems to surface)
- Bladder molded lugs have seams, parting lines, and discontinuous wall thickness (Trek only)
- Extensive use of aluminum for head tube sleeve, bottom bracket, and drop-outs (except for the Luna and Dragonfly which employ aluminum insulated from the carbon with fiberglass and uses Ti dropouts)
- Use of body filler and requires paint to cover the filler (Trek only)
- Uneven distribution of stresses at joints (although Luna and Dragonfly have tapered lugs)
- RTM fabricated Lugs have high resin-fiber ratio and are expensive (Colnago only)

Foam-Core

Examples:
- Softride Ironman (no longer in production)
- Zipp 2001 (no longer in production)
- Some Aegis and Kestrel frames

Pros:
- Ability to form complex shapes (aerodynamic, aesthetics)
- Can create a stiff frame
- One-piece molded version can have continuous fiber flow in shell

Cons:
- High void contents
- Irregular compression over foam core

- Expensive
- Use aluminum sleeves/dropouts
- Seams and parting lines created in molding process
- No weight savings
- Foam susceptible to water absorption
- Limited sizing due to expensive molds

Bladder-Molded

Examples:
- All current Kestrels
- Aegis
- Trek OCLV lugs
- Giant, EPX
- Other Taiwanese brands

Pros:
- Ability to create complex shapes
- Continuos flow of material over molded areas
- One-piece frames won't catastrophically fail
- Easily repaired

Cons:
- Limited sizes and geometries
- Seams and parting lines intrinsic to bladder molded frames and/or lugs
- Difficult to control wall thicknesses
- Use aluminum and cro-moly parts without insulation from carbon
- Impact resistance at “tubes” not as good as with pre-fabricated tubes
- Increased surface area of complex and aerodynamic shapes increases weight
- Necessary use of body filler and paint
- Difficult in getting consistent quality (worker dependant)
- Bonded areas (in multi-piece structures) susceptible to cracking

Carbon Tubes/Carbon Joints/Pressure Lamination

Examples:
- Carbonframes Sapphire and Tetra
- Calfee Tetra
- 1991-1993 LeMond Carbon

Pros:
- Lightweight
- Fatigue life for fiber reinforced joints is appreciably longer than that of adhesive bonds
- Carbon-to-carbon laminations create optimal joint strength and stress flows
- Lugless frame construction
- No unreinforced drilled holes in the structural carbon
- Use of structural reinforcing gussets to replace seams and for increased lateral stiffness
- All primary metal parts are made of titanium
- Highly customizable to specific rider geometry, rider weight, and riding style
- Easily repaired

Cons:
- Limited aerodynamic frame benefits

Conclusion

Carbon fiber exhibits the most desirable performance characteristics of any of the frame-building materials explored to date. It can be designed to be laterally stiff under heavy pedaling forces and still be light. It can absorb road shocks well, and still handle crisply while delivering undiminished applied pedal power to the drive train. It can be durable and not subject to fatigue failures while remaining strong enough to stand up to unexpected impacts and torsion forces. It can lend itself to attractive finishing and resist corrosion or attack by the elements. And it can be formed in an attractive, functional way allowing it to move through air resistance easily.

The big question is which specific designs best *maximize* these benefits and minimize any drawbacks. Certain designs and their manufacturing methodologies exhibit strengths in certain areas while making compromises in other areas. The best carbon frame design is that which offers the most performance benefits to the rider while minimizing the drawbacks.