



Taking the Witchcraft Out Of Advanced Composite Bicycle Frames

Design, Materials, Fabrication and Competitive Analysis

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Executive Summary

Building advanced composite bicycle frames isn't a matter of having the most exotic ingredients or the fanciest terminology: it's a matter of quality engineering, materials, and fabrication. After all, just like everything we make, the proof of a composite frame is in the riding.

Our FACT (Functional Advanced Composites Technology) isn't a magic ingredient. It's a proprietary term we use to distinguish our advanced composites development and fabrication process from the competition's. Specifically, these differentiators come in four main categories:

- **Appropriate materials.** Proprietary use of high-strength, high-impact, and other materials as needed to produce the best results. Not the materials themselves, but how, where, and when we use them.
- **LSD** (Lay-up Schedule Development). LSD is an engineer's term to describe the process of dictating the fiber type, ply, weave, angles and orientation that's optimal for each specific area of the frame or other structure being designed. LSD means all these factors are calculated specifically for each of the approximately 200 composite sections of a Specialized FACT frame, creating a degree of tunability that's unmatched by metals or other design processes.
- **Proprietary vibration-damping technology.** Less vibration throughout the ride means a less fatigued rider with more energy at the end of it. The longer—and rougher—the course, the greater the benefit. FACT technology achieves its remarkable vibration-damping characteristics in two ways:
 - o **The LSD process** is used to optimize shock damping along with light weight, strength, rigidity, and other parameters; our composite transmits measurably less vibration than their composite.
 - o **Patented Zertz technology.** Even without Zertz viscoelastic dampers, our frames reduce vibration significantly better than the competition's. Add Zertz to the frame, fork, and selected components, and the advantage is huge.
- **Proof.** Overall, Specialized composite frames are lighter *and* stiffer *and* more shock absorbent, with appropriate strength and crashworthiness characteristics for the most demanding races in the world.

1.

Bottom line is, FACT technology makes lighter, stronger, stiffer, better-riding and more shock-absorbent framesets. And we can prove it.

Frame Engineering, Lay-Up Development, & Testing

The **anisotropic** (directional-specific) nature of advanced composite materials allow specialized engineers use weaves and ply designs to create frames or components that are stiffer in one or more axes, while remaining more compliant in others. Engineers can also “tune” the weave structure, ply angles, fiber alignment and lay-up patterns of a particular component to optimize performance characteristics for its intended use. The resulting pattern of directional layers of composite material fibers (in this case, carbon) is called a **lay-up**. The overall protocol we use at Specialized for developing lay-ups is called **Lay-up Schedule Development**, or **LSD** (yes, LSD).

Design. In the case of frames like the Tarmac or Roubaix, lay-up is initially optimized for stiffness and strength from theoretical calculations using ProMechanica FEA (Finite Element Analysis) modeling software on our in-house workstations. Tube shapes are determined according to function (needs of the specific frame area(s)), aesthetics (making ‘em look good without sacrificing their functional characteristics), and most efficient use of our composite mold/lay-up resources. The advanced surfacing capabilities in Pro/e allow the use of organic shapes (run your hand along the top tube of a Roubaix to see what we’re talking about; you can feel the tube change shape in three dimensions as you move your hand along its length).

Testing, Tuning, and More Testing. Initial frame prototypes are lab-tested to achieve required strength at all junctions and load points. The lay-up is also revised to achieve required strength and stiffness. After initial structural testing, we start ride testing in several sizes, with a number of riders to get their “perceived” feedback (i.e. *how does a frame climb, sprint, corner and “feel” overall?*).

We measure the frames in the lab for stiffness and compare riders’ test perceptions to the lab data. In addition to weight (easy to measure, all you need is a scale) and stiffness (we measure stiffness in a bunch of different ways, including *bottom bracket deflection* under simulated pedaling loads and **overall torsion** (twisting) from head tube to rear dropouts) We also measure how much vibration is transmitted through the frame; subtract that number from how much vibration we put into it in the first place and we can measure **vibration isolation** (also called **attenuation** or **damping**¹).

Then comes the “tuning” process: multiple iterations (versions) of the frame’s lay-up are generated to balance stiffness, vibration damping, perceived road feel, and of course, overall strength. Even with all our high-powered software and multiple road tests from skilled riders, it takes a minimum of 2 or 3 iterations to optimize all parameters.

With the final lay-up determined, we conduct a number of destructive lab tests (with multiple samples for each size) to verify the lay-up is stable and predictable.

¹ Although technically correct, we prefer not to use the term **shock absorption**, since it can easily get confused with the shock absorbers used in frame or fork suspensions.

Materials

We use carbon fiber from the world's three biggest fiber vendors; they all make a full line of fibers to achieve various stiffness, strength, cost, and weight factors.

Prepreg. The preferred manufacturing method for fabricating complex shapes (like bicycle frames) involves lay-ups of composite material that is impregnated with epoxy in a **matrix** (the “glue” that holds all those carbon or other fibers together). Lay-ups that already have epoxy in them are called **prepreg** (for “previously impregnated”). There are two basic types of prepreg sheets: **uni** (or unidirectional), and **woven**.

Uni sheets have fibers that are oriented in the same direction unidirectional) on a sheet. Various uni sheets can be stacked together at different angles, from 0° (vertical) all the way up to 90° (horizontal). Which angles the engineers develop for which portion of the frame is one of the big reasons composite frames can be tuned so precisely. The uni sheets make up the main part of the composite structure. A complete Roubaix frame, for instance, may have several hundred sheets of mostly uni prepreg, each sheet with the specific mix of layers and fiber angles appropriate to that area of the frame.

Here are some of the Uni sheets of prepreg we use in our frames:

- **True High Modulus** fiber (remember *modulus* is just an engineering term for fiber stiffness). The stuff we use is rated at 390 GPa (gigapascals), or 57Msi (millions of pounds per square inch. That's about 70% stiffer than the standard aerospace-grade material most carbon bicycle frames are built out of.

Note: High-modulus carbon is good for strength and stiffness, it tends to become more brittle (less strong) as it gets stiffer (see charts). In general, you wouldn't want to build a whole frame out of high-modulus material, so we hybridize (mix) our high-modulus carbon with a number of other materials and modulae (stiffnesses), to make frames as light as possible without sacrificing strength or durability. The general idea is to put the higher-strength material where the loads are save as much weight as possible everywhere else with high-modulus stiff material.

- **Intermediate Modulus** (what other companies call *high modulus* or *enhanced modulus* or even *Satellite-Grade*) carbon fiber is used to maximize strength and keep weight low in the highly stressed parts of the frame, like the top and down tubes. Because of its relatively high modulus and strength, this material is a good all-around workhorse for premium composite frames.
- **Standard Modulus.** Aerospace-grade carbon fiber. It's used in conjunction with the other materials for improved impact strength in specific areas.

Woven sheets come in a number of types. Here are some examples of woven prepreg we use in our frames:

- **1K woven.** In this case, the *K* refers to the yarn size/ number of carbon strands in the fiber. 1K is an exceptionally fine weave, perfect for creating a low-density, beautiful surface layer on our top-of-the-line frames without adding weight. It's also

very expensive (about 2.5 times the cost of 3K woven) and very labor intensive to lay up, so we save our 1K fiber for S-Works level frames only.

- The **3K woven sheet** is another beautiful woven fiber that provides some additional abrasion resistance for medium-grade frames. On the other hand, it's less tunable than uni sheets (not to mention heavier than either uni or 1K woven), so we use it on the surface layer of selected frames.

We also use other materials like Kevlar or even woven **glass fiber** (fiberglass) in selective locations for impact strength due to its high elongation (how far it can stretch before breaking) capability. Note: A structure that contains different advanced composite fibers (like high-impact glass and carbon) is called an **advanced composite hybrid**.

Finally, glass is used as an insulating layer, or **scrim**, one way of preventing galvanic corrosion between carbon frame material and aluminum fittings.

Materials Used in Specialized Composite Frames

Frame Material	Modulus (GPa)	Tensile Strength (MPa)
High Modulus		
SW Roubaix	390	4610
Intermediate Modulus		
SW Tarmac	294	5490
Roubaix Pro/Comp	285	5790
Roubaix Pro/Comp	295	5800
Standard Modulus		
Tarmac Pro/Comp	230	4900
Roubaix Elite	240	4900

Fabrication

Manufacturing The Prepreg Lay-Up. The major lay-up in the TT and DT of our frames is composed of five main layers ("stacks") of uni carbon sheets in different angle orientations. Some fibers run fore/aft. These are referred to as "zero" fibers (0°, remember?). These fibers give the frame a lot of strength for in-line impacts and loads. This makes the zero fibers good at resisting bending (or **axial**) loads. Some fibers run at plus or minus 45° and/or plus or minus 22.5°. These fibers which give the frame its torsional (twisting) stiffness.

Each frame has a detailed **laminat schedule**. The tubes have 5 or 6 main plies but there are nearly 200 pieces of carbon fiber in a frame's laminate schedule (that's why Laminate Schedule Development—LSD—is such an involved process). This allows for butted sections at the joints to handle loads better and keep the overall weight low. All of these sheets are cut and placed by hand. Quality control is key, and strict adherence to QC processes and inspection is necessary. The carbon fiber lay-up is assembled from the cut and oriented sheets to form a prepreg **assembly**. This assembly is loose and flexible (well, sort of) and ready to be molded and cured.

Molding. Prototypes & production parts are made in steel tooling. The steel tooling defines the exact outside shape and surfaces (the part of the frame you can see). A big steel tool or **mold** (like the main triangle of a Roubaix or the top deck on a Tarmac) takes 8-12 weeks to make, depending upon the frame design. That's because it's entirely hand finished, weighs a couple hundred pounds, and is accurate to within a few thousandths of an inch in every aspect. The frame comes out weighing just a tiny fraction of the tool, but—assuming it's made right—has the same level of accuracy.

An **air bladder** is made of pressure-resistant (you'll see why in a minute) nylon and runs throughout the inside of the lay-up. Its function is to internally pressurize the composite material in the lay-up against the tooling surface to eliminate internal voids (craters) in the composite structure (that's the "Optimal Compaction/Low Void" Trek's talking about in their OCLV trademark frames, although they achieve it by wrapping composite material around composite lugs, not by using internally pressurized air bladders).

The prepreg assembly is placed in the mold (with the bladder pre-installed inside the lay-up), and the mold is closed and locked down. The bladders are connected to pressurized air fittings.

The closed mold moves on a conveyor into an electric oven where the mold's temperature is raised to 155° C (that's 311° F, or if you really want to be scientific, 428.1° K). This high temperature allows the epoxy in the prepreg to become liquid and uniformly intermingled in the composite lay-up when the bladders are pressurized to 150 psi. This intermingling is called **wet out** and it's critical to the integrity of the molded structure. Too little pressure in the bladder and the composite won't wet out effectively, leaving high-epoxy areas that add useless weight, and low-epoxy areas which weaken the structure. Too much pressure, and the epoxy gets squeezed out of the composite altogether.

Note: some manufacturers use a process called RTM (for Resin Transfer Molding). In RTM, the composite is laid into the mold dry, and epoxy is forced in under pressure. Assuming the processes are used correctly (optimal wet out), there's no structural difference between an RTM part and one made from prepreg. Generally, RTM is more successful with simpler shapes (like plates or links or lugs) and less successful with more complex shapes (like frames or forks). In terms of the performance of the finished product, there is no particular advantage to RTM versus prepreg.

The mold stays at this temperature for about 30 minutes depending on the size of the mold (the Tarmac's mold is so big it takes 45 minutes). Now the mold must cool. Due to the size of the steel tooling, this takes another 20-30 minutes depending on tool size.

Once the frame temperature has cooled enough, the epoxy is cured and cannot be changed. *Note: composite structures made with an epoxy matrix that stays the same once it's cure are called **thermoset**. Structures that are made with a different matrix that can be heated and changed over and over are called **thermoplastic**. Old-timers in the bike business may remember when some people thought thermoplastics were superior materials for making bicycle frames and components. Without getting into the physics of it too much, those people were wrong. And nowadays, mostly out of business.*

Finally, the operator can remove the cured composite from the mold and the structure is ready for assembly and finishing.

Roubaix. The Roubaix design uses a monocoque (one-piece²) structure for the entire front triangle. The chainstays and seatstays are each individual monocoque structures. The chainstays and seatstays are bonded to the front triangle and then over-wrapped with carbon (a **tow**) where the sections come together, to form strong and secure joints. Note: we call this construction method a *triple monocoque*, since three monocoque subsections are molded into a single piece. *Note: This is a far more secure construction than the simple bonded joints many of our competitors use. If designed properly, this method adds no weight and creates a more secure structure.* Given this painstaking process, only ten Roubaix frames can be made per day from each tool (size).

A Digression: Why Is A Monocoque Better? By making a single lay-up for the entire front triangle, bonding of lugs and tubes is eliminated. This has a number of advantages:

- Stress concentration at the end of the lug is eliminated with monocoque.
- There is no chance for bonding problems, poor glue fill and uneven glue thickness around the bond (depends on accuracy of bonding fixturing)
- Less chance that the frame will be out of alignment (since it's less dependent on fixturing than a bonded frame)
- No redundant overlapping structures putting unneeded material (weight) material in the wrong places. Bottom line: more strength/stiffness, less weight (note the charts that follow to see for yourself)
- Since there are no bonds, the paint won't crack down the road. (Bonded joints are famous for paint cracking problems.)
- Carbon lugs are difficult to make really good and light (but easy to make heavy and/or poorly).

Tarmac E5. The Tarmac's E5 head and down and seat tubes, BB and chainstays are welded, aligned, heat treated and precision-machined as a single lower alloy undercarriage. The undercarriage must be aligned twice as precisely as a SW Aerotec frame.

The undercarriage is treated with a gold-colored non-oxidizing coating³, wrapped with a nonoxidizing⁴ prepreg carbon laminate, and placed in a single monocoque molding tool. This means that the Tarmac's carbon structure is a single monocoque piece. The alloy connection points on the undercarriage are **co-molded** with the monocoque composite laminate structure, meaning they are joined in the same mold at the same time with the same epoxy. This forms the most secure joint possible and eliminates bonding concerns at the critical areas like the head and seat tubes. It also explains why only five Tarmac E5 frames can be made per day for each size frame.

Tarmac (Carbon). The new all-carbon Tarmac is made in the same triple monocoque construction method as our Roubaix frames, but from a completely different layup schedule, which, in addition to its tighter wheelbase and more upright steering geometry, gives the Tarmac a completely different ride and road feel.

² Technically, a monocoque is any structure where loads are carried on the skin of the structure, i.e., there are no internal supporting members. By this definition all standard bicycle frames are monocoques. However, in composites, the term is more generally used to mean "single-piece".

³ Using a chromate conversion process known as **Alodine** or **Irridite** (not anodized).

⁴ Since carbon and aluminum can react together chemically (called oxidation or **galvanic corrosion**), this particular wrap of carbon uses a special (and expensive) red-colored nonreactive epoxy matrix that insulates the two materials from each other.

Competitive Analysis

There are a number of proprietary (and confidential) tools and protocols we use to compare our frames to the competition's, but there are two universally accepted comparisons we can talk about: weight & stiffness.

Obviously, there's only one weight test: we take a finished 56cm or equivalent frame and weigh it. (All weights include paint, Zertz inserts (if used) and equivalent hardware*).

While there are a number of commonly accepted stiffness measurements, two are most useful for comparisons purposes:

- **Torsion Test.** This is overall frame torsion measurement from head tube to rear dropouts. The higher number indicates the frame is stiffer. This measurement is a good indicator of how well a frame will handle in turns and how stable it'll be at high speed.
- **BB Pedal Stiffness Test.** Again, a higher number is better. The stiffer the structure is to the rider's pedaling forces, the faster the frame will respond to rider acceleration.

Finally, stiffness values are corrected to compensate for the weight of the frame (**specific stiffness**). This makes for a better comparison between light and heavy frames.

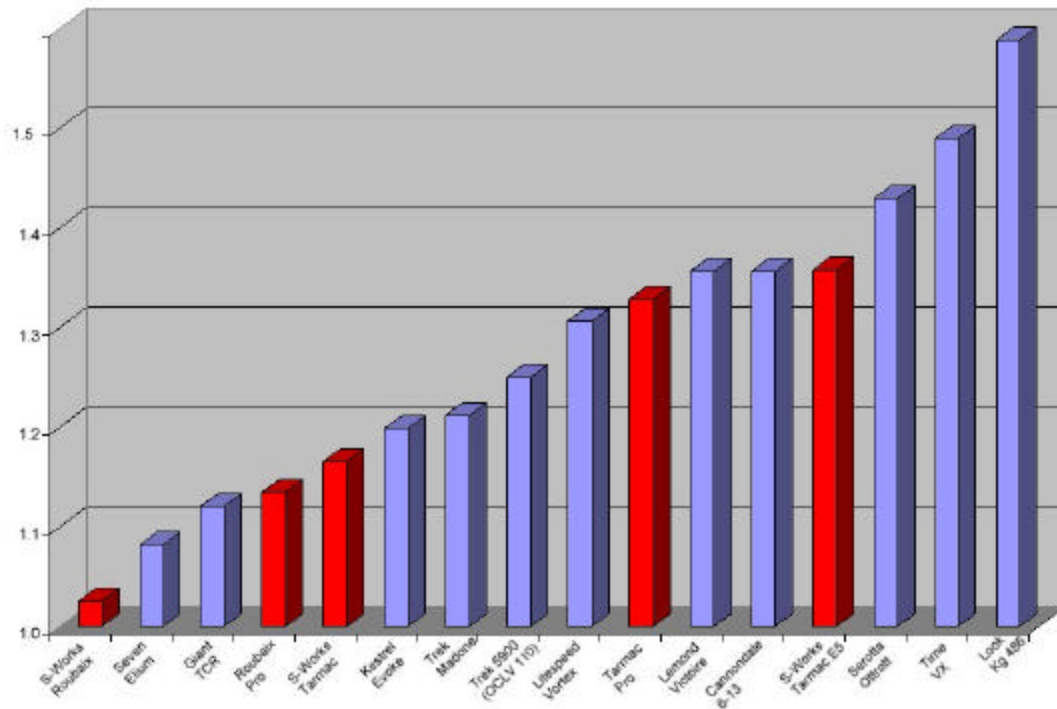
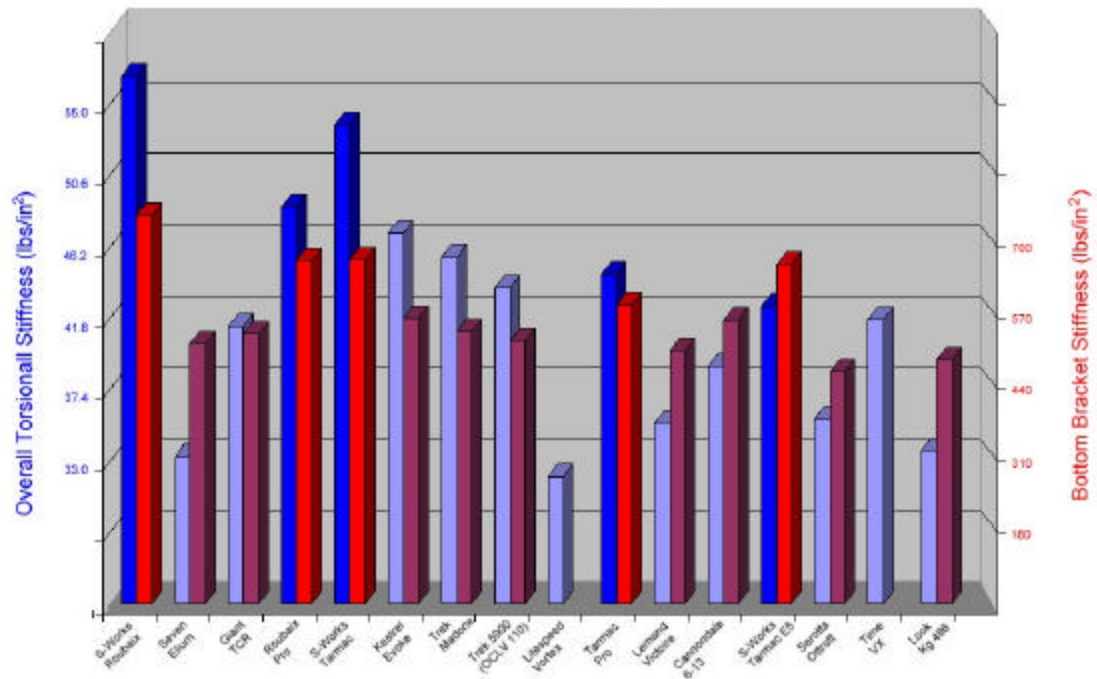
Physical Properties of Composite (and one Ti) Road Frames

Frame	Size (cm)	Weight (g)	Torsional Stiffness (lbs/in)	Specific Stiffness (lbs/in)	BB Stiffness (lbs/in)	Specific BB Stiffness (lbs/in)	Frame type & notes
S-Works Roubaix	56	1025	58.4	56.9	740.0	722.0	Triple Monocoque
Seven Elixir	56	1082	32.8	30.3	522.0	482.4	Bonded, non-integrated
Giant TCR	L	1120	30.0	26.8	635.0	567.0	Monocoque
Roubaix Pro	56	1135	54.3	47.8	744.0	655.5	Triple Monocoque
Kestrel Evoke	56	1199	55.1	45.9	636.0	530.4	Monocoque
Trek Madone	56	1212	53.7	44.3	668.0	551.2	Bonded Lugs
Trek 5900 (OCLV 110)	56	1250	52.7	42.2	800.5	640.4	Bonded Lugs
Litespeed Vortex	57	1307	37.7	28.9	NA	NA	Welded Ti
Tarmac Pro	56	1328	57.2	43.1	736.0	554.2	Triple Monocoque
Lemond Victoire	57	1356	44.3	32.7	638.0	470.5	Bonded Lugs, non-integrated
Cannondale 6-13	58	1356	49.7	36.6	714.9	527.2	Welded aluminum tubes w/carbon tube sections
S-Works Tarmac (carbon)	56	1165	62.4	53.6	745	639.5	Triple Monocoque
S-Works Tarmac E5	57	1358	55.5	40.8	857.0	631.1	Carbon/Aluminum Monocoque
Serotta Ottrott	56	1430	47.1	32.9	616.0	430.8	Bonded, non-integrated
Time VX	58	1490	59.4	39.9	NA	NA	Bonded Lugs
Look Kg 480	55	1588	48.8	30.7	721.0	454.0	Monocoque

***Notes:**

1. Frames without integrated headset are weighed with spec'd headset cups.
2. Frames without integrated DT cable stoppers are weighed with supplied Shimano stops.
3. Weight of seatpost clamp is not included for any frame.
4. Frame weight includes BB cable guide.
5. Note 1cm difference in Tarmac E5 and Tarmac (carbon)

Weights of Composite Road Frames (Kg)

Specific Stiffness of Composite Road Frames
(Stiffness for Weight)

Appendix A: Tarmac E5 Lay-up

HOW CARBON FIBER AND ALUMINUM GOT MARRIED



PREPREG COMPOSITE IS
LAID-UP BY HAND



COMPOSITE LAYUP WITH E5
ALLOY UNDERCARRIAGE IS
PLACED IN THE MOLD



CLOSED MOLD ON
CONVEYOR TO HOT PRESS



CURED CO-MOLDED
MONOCOQUE FRAME
IS REMOVED FROM
THE MOLD FOR
HAND FINISHING



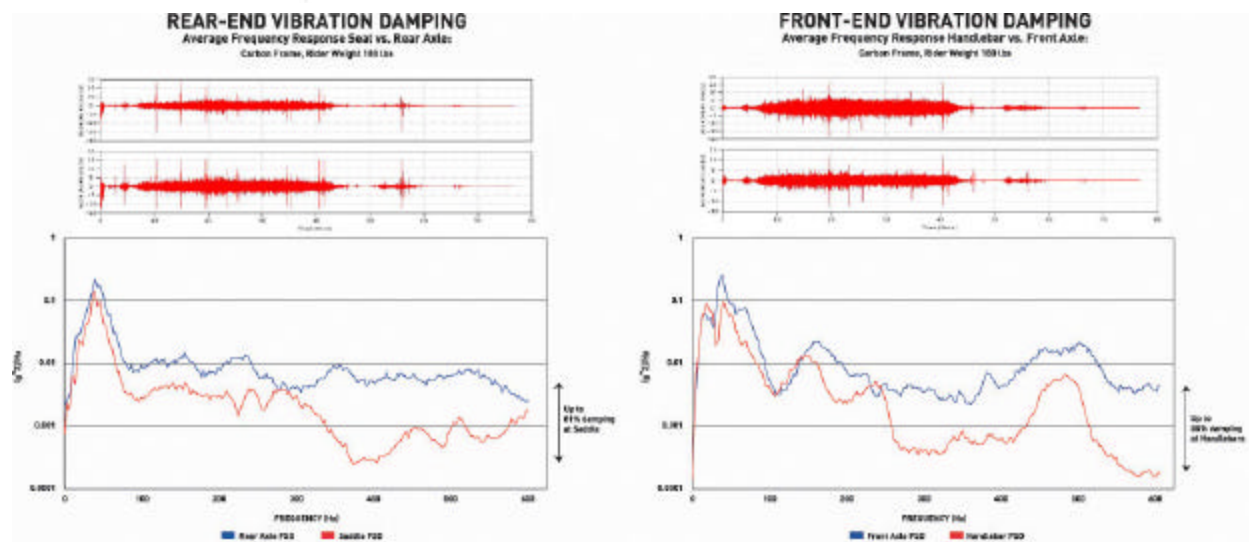
Appendix B: Roubaix Vibration Damping

roubaix

where vibrations go to die.



Specialized Engineer Luc Callahan demonstrates Roubaix vibration damping.



Our engineers test our bikes with four on-board accelerometers to capture road vibration on our SOMAT data acquisition system. The accelerometers are placed at the front and rear axles, the handlebar and saddle.

The raw accelerometer data is converted to a PSD (Power Spectrum Density) chart in the frequency domain using an elaborate software conversion known as an FFT [Fast Fourier Transform] $P(f) = \frac{1}{T} \left| \int_0^T x(t) e^{-j2\pi f t} dt \right|^2$. The data shows the reduction of transmitted vibration from the front axle to the handlebars and from the rear axle to the saddle throughout the frequency spectrum.



Glossary

Aerospace Grade	Not an indicator of particular fiber strength or modulus, merely that it's been certified for use by subcontractors for aerospace vendors (like NASA, USA DOD, Boeing, or Airbus). Generally, aerospace-grade carbon has higher performance specs than regular "commercial-grade" carbon, but there's no particular benchmark. See also <i>Satellite Grade</i> .
Advanced Composite	Composite made principally from carbon or other advanced (non-glass/non-wood) materials.
Air Bladder	Pressurizing insert in a molded composite structure that pushes composite material against the mold interior during the molding process to insure optimal fiber compaction, conformity, and wet out.
Alodine	Trade name for the (chemical) chromate conversion process that puts a gold-colored non-oxidizing coating on the Tarmac's aluminum frame sections before co-molding to the carbon sections. <i>Note: not to be confused with anodizing.</i>
Anisotropic	Directional. Metals are isotropic materials, since they have the same strength and stiffness characteristics in all directions. Depending on how they're used, composites can be either <i>isotropic</i> or <i>anisotropic</i> . See also <i>Isotropic</i> .
Aramid	A family of composite fibers. The best-known aramid fiber is DuPont's Kevlar®.
Axial	Bending (across an axis).
Co-Molded	Parts of a structure molded at the same time, and in composites, using the same <i>matrix</i> .
Composite	For purposes of bicycle frames, fibers of carbon or other material held in place by a <i>matrix</i> , usually epoxy.
Damping	Vibration isolation or attenuation. <i>Note: if you look in the dictionary, you'll see the two words are equivalent, but in bicycles and motorcycles, <u>damping</u> refers to absorbing vibration, while <u>dampening</u> means making something wet. So our FACT composite products always damp vibration, never dampen enthusiasm.</i>
FAW (Fiber Area Weight or Fiber Density)	Engineer's term for how much fiber there is in a given area. It has nothing whatever to do with fiber strength, stiffness, or even what kind of fiber is in the sheet, just the density of the material.
Galvanic Corrosion	The reactive oxidizing process that takes place between carbon and aluminum (or other materials), resulting in a whitish powder and weakened structure. See <i>Alodine</i> , <i>Scrim</i> .
Glass	Glass fiber (fiberglass), used in composite frames for abrasion and impact resistance.
Graphite	Carbon. In the last 15 years, the term graphite is seldom used to refer to fibers, so carbon fiber is the preferred term
Hybrid	Combination of different materials (such as carbon/glass or carbon/aramid) or fiber modulae (high- and-standard-modulus) in a composite lay-up.
Isotropic	Having the same properties in all directions. See <i>Anisotropic</i> .
Irridite	See <i>Alodine</i> .

Lay-up	The various layers, plies, weaves, materials, and fiber patterns and directions in a particular “stack” of composite material.
LSD	Lay-up Schedule Development. The protocol that lets Specialized engineers specify the precise mechanical characteristics of each of a frame’s approximately 200 composite sections.
Matrix	The epoxy or other “glue” that holds composite fibers together.
Modulae	Fancy-pants plural of <i>modulus</i> .
Modulus	Stiffness. Engineers use a number of different modulus terms to describe different ways of measuring stiffness in a material.
Monocoque	In composites, a one-piece structure.
Prepreg	Composite fibers pre-impregnated with <i>matrix</i> (usually epoxy).
RTM	Resin Transfer Molding. A process where dry material is laid into a mold and a <i>matrix</i> is forced in after the mold is closed and pressurized.
Satellite Grade	Term used mostly by the golf-club industry (except they call it “satellite-grade graphite”). Presumably “satellite-grade” carbon material has been certified for use by satellite manufacturers, but there’s nothing in the materials engineering literature to indicate this, and no major commercial composites materials vendor offers “satellite-grade” carbon fiber prepreg for sale. See also <i>Aerospace Grade</i> .
Scrim	An insulating layer of glass or other material to prevent <i>galvanic corrosion</i> between materials (in bicycle frames, usually carbon and aluminum).
Specific (strength or stiffness)	Strength or stiffness for weight. If two frames have the same stiffness (or strength), the lighter one will have higher specific stiffness (or strength).
Thermosplastic	A composite <i>matrix</i> that can be reheated and reformed.
Thermoset	A composite <i>matrix</i> that can be heated and formed only once (like epoxy).
Tool	In molded composites, a term used interchangeably with mold.
Torsion or Torsional	Twisting loads or forces.
Tow (pr “Toe”)	An exterior layer of composite material wrapped around a joint or fitting to secure it.
Triple Moncoque	Proprietary Specialized term for a one piece frame in which three subsections are assembled separately and then molded together into a single piece.
Tuning	The process of changing a structure’s lay-up to optimize stiffness, weight, vibration damping, road feel, overall strength, and/or other parameters.
Uni	Unidirectional; a sheet of composite within a lay-up in which all the fibers run in the same direction. See <i>Woven</i> .
Viscoelastic	Class of materials having the combined properties of mechanically “ideal” fluids and

elastomers.

Wet Out The process of evenly distributing epoxy matrix throughout a composite structure.

Woven A sheet of composite within a lay-up where the fibers run in different directions within a single sheet. See *Uni*.

Zertz™ Specialized trade name for its patented *viscoelastic* vibration-damping inserts