Klein 1979

BICYCLE FRAME DESIGN CONSIDERATIONS

Definitions

Stiffness as applied to bicycle frames can be simply defined as the ability to resist deflection. A frame that does not deflect or flex very much for the amount of force applied to it (relative to other frames) is stiff.

Strength can be simply defined as the ability to resist permanent deformation or breakage. A frame that undergoes a great deal of force in an accident and does not sustain breakage or permanent deformation is relatively strong. Note that stiffness and strength are not the same thing. A fishing pole is an example of something that is relatively strong (it requires a lot of force to permanently deform or break it) but not very stiff (it deflects easily).

Density is the weight per unit volume of a substance. For example, aluminum is much less dense than lead.

Material Properties

Materials used in the construction of bicycle frames have varying strengths, stiffnesses (Moduli of Elasticity), and densities which are well documented and can be easily reviewed.

Stiffness to Weight Ratios

All steel alloys have virtually identical densities - .284 lbs./cu. inch. The Moduli of all steel alloys are also virtually identical - 30×10^6 psi. It is surprising to most cyclists that all steels have the same stiffness to weight ratio whether it is Reynolds 753, 531, Columbus or gas pipe. All the sales hype in the world can not change this fact. The strengths of steels vary tremendously, but strength does not affect the riding characteristics of a frame. Sufficient strength is required however, to prevent failure--i.e., permanent bending or breaking of the frame.

All aluminum alloys have virtually identical densities - .097 lbs./ cu. inch and all have virtually identical Moduli - 10×10^6 psi.

All titanium alloys have virtually identical densities - .162 lbs./ cu. inch and all have virtually identical Moduli - 15×10^6 psi.

Boron in fiber form has a density of .089 lbs./cu. inch and a Modulus of 58 x 10^6 psi.

Using the formula (10^6 lbs./sq. inch)/(lbs./cu. inch) we get the following relative stiffness to weight ratios. The higher the number, the better the material is. Steel - 105.6. Aluminum - 103.1. Titanium - 92.6. Boron Fiber - 651.7. Steel, aluminum or titanium have similar stiffness to weight ratios as raw materials. Boron is about six times better. As we will see later, however, other aspects of the design of the structure will decrease the utility of boron and show aluminum to be a better material than steel.

Strength to Weight Ratios

Within each materials group strengths vary a great deal. Factors such as brittleness, stress corrosion, unbrazability and unweldability make the highest strength alloys unuseable, unsafe or difficult for bicycle frame construction. The steel, aluminum and titanium alloys used to make bicycle frames are not the strongest alloys available but are often the strongest alloys practicable. Reynolds 531 has a yield strength of 120,000 psi. Reynolds 753 is 150,000 psi. However, yield strengths are about two thirds these figures at the lugs where brazing heat weakens the tube, thus steel tubes may be butted at these points. Thicker material makes up for the loss of strength.

Useable and safe aluminum alloys run 40,000 to 50,000 psi. Remember that aluminum is one third the density of steel so the 50,000 psi alloy is as strong as an equivalent weight of 150,000 psi steel. If the aluminum frame has welded and subsequent heat treated construction the weld zones retain their 50,000 psi strength making them about 50% stronger than the braze zones on a 150,000 psi steel frame - on a per weight basis.

Commercially pure titanium has a yield strength of 75,000 psi. Titanium is one half the density of steel so commercially pure titanium is as strong as an equivalent weight of 150,000 psi steel. The strength loss in the weld zones of pure titanium is small.

Boron in fiber form has a very high strength. However, fiber materials such as boron and graphite have good properties only along the axis of the fibers, not in the other two directions and in the special case of graphite, only in tension. More over, the epoxies used to bond the composite tubes into metal lugs on most composite frames are not of high strength, thus providing a weak link. We prefer to view the high Modulus fibers as a stiffening aid instead of taking chances on them as a load bearing structure. In the case of the Klein, boron is used to increase the stiffness of the aluminum frame about 15%, and in the precise places we want it. We do not depend on it for strength.

The conclusion is that adequate strength is achievable in steel, aluminum or titanium alloys. With the proper construction techniques aluminum alloy frames can have greater strength in the weld zones than the best steel frames at the respective braze zones.

Discussion

Overall, steel, aluminum and titanium alloys are surprisingly similar. Apparently, aluminum and titanium have gained a reputation of being "whippy" because time and time again manufacturers attempt to build very light frames out of them. The better strength factors allow one to make a lighter bicycle frame but the higher strength does nothing for the stiffness. The same is true of Reynolds 753 (light gauge) which results in a light and "whippy" frame. It is not surprising that Reynolds also makes 753 in the same approximate gauge and weight as 531 Standard and that this tubing, not the light 753, is the one sometimes used by the Raleigh road team.

Design Consideration - Tubing Diameter

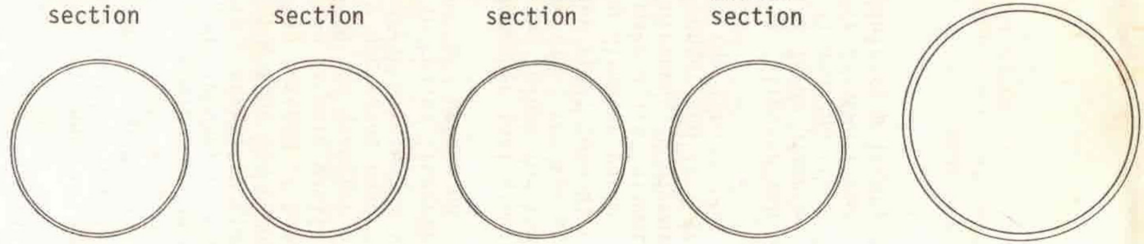
The stiffness of equivalent weight tubes increases as the square of the diameter. The larger diameter tube has a thinner wall, is stiffer and weighs no more than the smaller tube. So why not make a bicycle frame out of the same material they use for beer cans? You could, and the frame would have an extremely high stiffness to weight ratio but it would crumple very easily (known as crippling failure). This is because there is a stability limit to how small the wall thickness to diameter ratio of a tube can become - about 1:50 before the tube becomes prone to crippling instead of bending failure, and like the beer can demonstrates, crippling is more easily performed than bending. As the wall becomes less that 1/50 the diameter of the tube the inherent strength of the tube rapidly decreases regardless of the material strength. For tubes that fall safely within the 1:50 ratio the bending strength of equivalent weight tubes increases linearly with the diameter. The larger diameter tube is stronger and weighs no more than the smaller tube.

Remember that aluminum is much less dense than steel. It has three times the volume for the same weight. An aluminum tube would have about a three times thicker wall than an equivalent weight steel tube. A 1.0" diameter steel tube with a wall thickness of .020" would have a wall thickness to diameter ratio of 1:50. With the same weight of aluminum you could make a 1.5" diameter tube with a wall thickness of .040" and a safe wall thickness to diameter ratio of 1:37.5. The aluminum tube would be 50% stronger and 125% stiffer than the steel tube even though it weighs exactly the same.

The following table of Down Tube Comparisons graphically illustrates that the large diameter aluminum tube offers considerable advantage over both 531 and 753 frame tubes in both strength and stiffness. The welded and heat treated frame, in addition, has no extra weight in the lugs. The result is a light, durable, high performance racing frame.

DOWN TUBE COMPARISONS

	Steel Chrome Molybdenum			Steel Chrome Vanadium			Aluminum Magnesium Silicon
	Reynolds 531 Standard double butted			Reynolds 753 (Light Gauge) double butted			Klein 816 straight gauge
	unbutted section		butted section	unbutted section		butted section	
Wall thickness	.024"		.036"	.020"		.024"	.049"
Diameter	1.125"		1.125"	1.125"		1.125"	1.500"
Wall thickness/diameter ratio	1:47		1:31	1:56		1:47	1:31
Weight oz./inch	.377		.560	.315		.377	.347
Weight average for tube[1]		.447			.339		.347
Relative stiffness	88		128	74		88	137
Stiffness average for tube[2]		100			79		137
Material strength 1,000 psi[3]	120		80	150		100	50
Relative strength	101		100	106*		84	149
Strength for entire tube[4]		100			84		149



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1 Averages are based on Reynolds double butted tube configuration of an 11" unbutted section, 3" butted sections on each end of the tube and two 2" taper regions.

2 The stiffness of a butted tube is calculated in the following manner. Add the deflections of each section of the tube to obtain the total deflection (for a unit load) and take the reciprocal (inverse) to obtain total stiffness. Stiffness is load required per deflection.

3 Butted sections are about 2/3 the original material strength after brazing.

4 An average figure here would be meaningless. The tube will fail at it's weakest point.

* Strength is probably less because the 1:50 wall thickness to diameter ratio has been exceeded.