Lightweighting 3: Tensegrity Structures

Companion to the video: Script and Illustrations

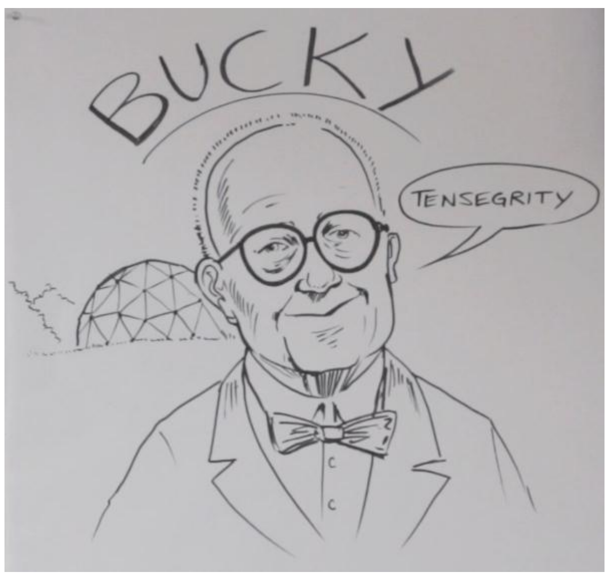
By now, you're probably seeing things everywhere that have been lightweighted.

We've talked a lot about a bike's frame, but what about the wheel? Did you ever wonder why bike wheels have thin metal spokes? It's another lightweighting strategy. But how does it work?

So far, we've seen how stress can be the enemy when trying to lightweight. Too much stress, too little materials, and you've got problems.

But not all stresses are created equal. Sometimes turning compressive stress into tensile stress can help you reduce material use enormously.

Buckminster Fuller called the strategy of using tension for structural integrity – tensegrity. It's great when using materials whose strength in tension is similar to their strength in compression.



Anything that's resisting compression forces is resisting buckling. Compression can buckle your product long before the strength of the materials fail. The longer and skinnier your parts are - like spokes - the more likely they are to buckle and the more you could lightweight them by using tension instead of compression.

How big a difference can it make?

Well, in this sculpture, the rods and cables are under the exact same amount of stress, but the much lighter cables are in tension while the rods are in compression.

Here's a simplified version of the math for buckling strength:

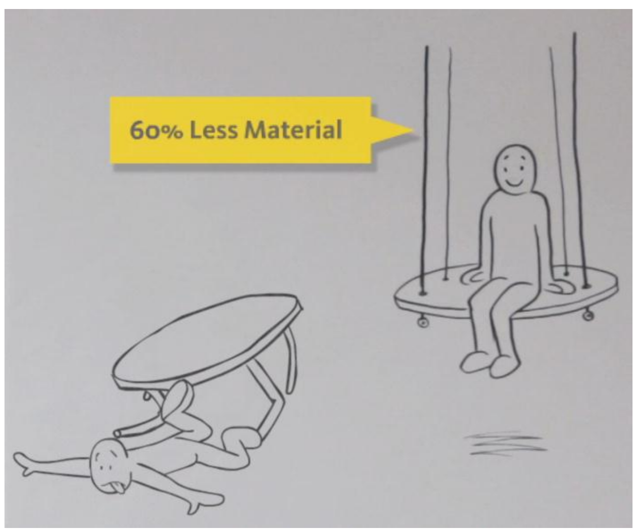
$$\text{BUCKLING STRESS} \sim \frac{\text{ELASTICITY}}{\left(\frac{\text{EFFECTIVE LENGTH}}{\text{WIDTH}}\right)^2}$$

The stress at which a column buckles is inversely related to the SQUARE of how slender the column is, so making a column three times more slender makes it NINE times more likely to buckle.

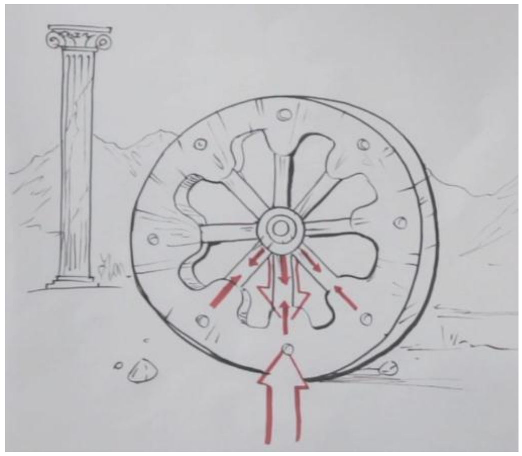
By contrast, a part under tension doesn't need to worry about this buckling equation; if it fails, it will fail at the yield strength of the material.

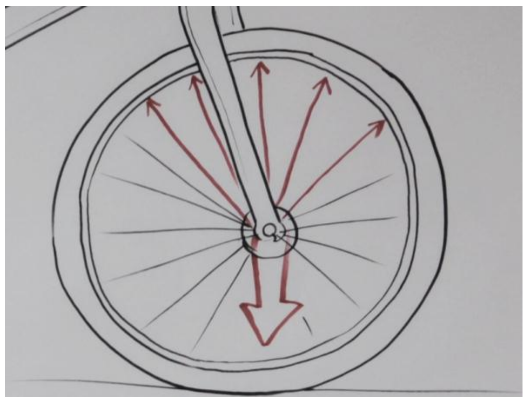
We can't exactly say how likely ANY column is to buckle under compression before it breaks in tension, because that depends on the material's elasticity.

Take aluminum, which is more elastic than steel. A cylindrical, aluminum rod that's 30 times taller than it is wide (like a thick spoke in a wheel) has about 2 and a half times more strength in tension than it does in compression. So an aluminum cable in tension could use 60% less material than a rod in compression.



Older wheels used thick spokes in compression but modern bicycles use thin steel spokes that are being pulled on rather than pushed on.

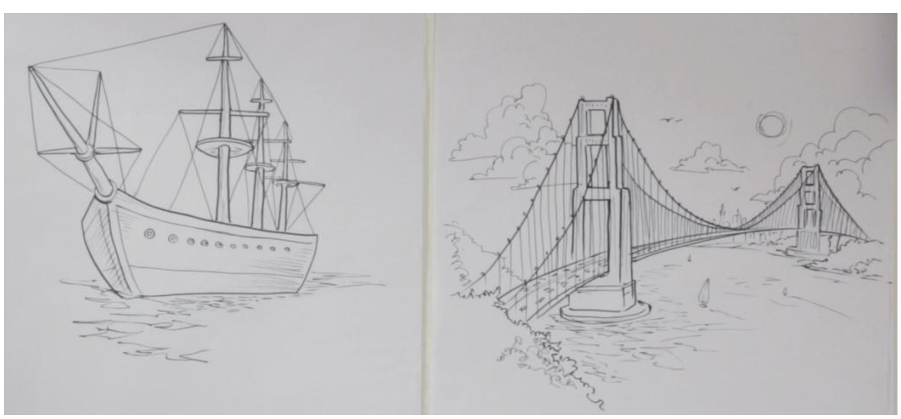




The weight of the rider at the axle is pulling down on the top of the wheel. So tension is being substituted for compression. If the spokes were being pushed on, they would certainly buckle, because they are 150 times as long as they are wide.

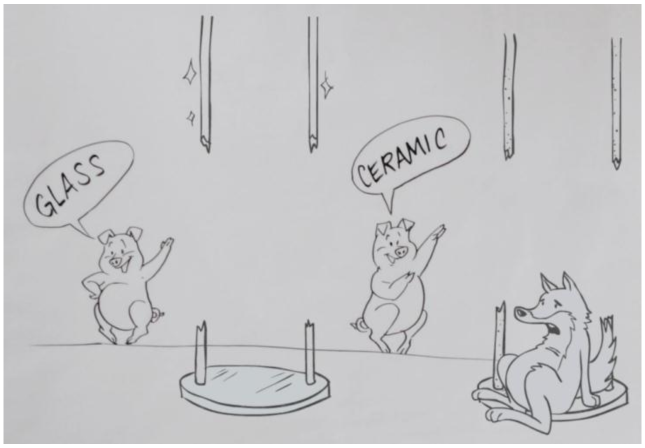
How do you make things that use tensegrity? It's easy; you can do it with almost any manufacturing method. That's why you'll see tensegrity all around you if you look for it.

Old sailing ships used ropes between their masts to create tensegrity trusses, so they could use the biggest sails and capture the most force from the wind without snapping.



Suspension bridges like the Golden Gate Bridge also do the same thing, with the deck of the bridge hanging from cables off of the tall spars.

What limits tensegrity is mostly the materials you use. It’s great when using materials that have good strength in tension, but brittle materials like glass or ceramics--they don't work so well.

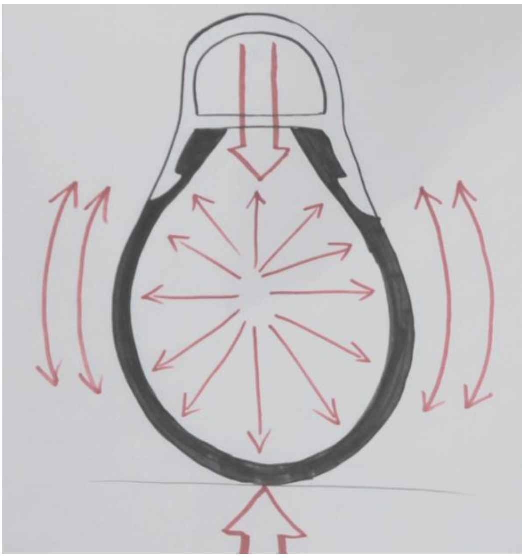


Sometimes manufacturing methods can make a good material too brittle for tensegrity, too. Casting can do this, so cast metal doesn't work as well as if it’s rolled or forged.

But other manufacturing processes improve the tensile strength of your materials, like drawing wire and braiding it into a cable, or tempering glass.

So that’s how the spokes work. But something else on the wheel is using tensegrity too.

It’s the tire. Rubber doesn't resist buckling well, obviously, but the air pressure inside the tire pushes outwards in all directions. The weight of the bike squashing the tube and tire against the ground creates a tension stress on the walls of the tire. This is how a thin sheet of rubber can support your whole weight as you bounce over bumps.



All inflated and fluid-pressurized structures work this way. The trick is finding a material that's rigid enough and won't leak. Aluminum cans are actually a good example. Their internal fluid pressure adds to their structural integrity and allows them to be stacked. And aluminum is a material that's both rigid and doesn't leak. But sometimes you'll have to combine plastic, rubber, or other materials. That's why the inner tubes of bikes are separate from the tires and why car tires have steel belts embedded in the rubber.

On this one wheel you can see tensegrity in action in two different places, turning compressive stress to tensile stress and radically reducing material use. When it comes to lightweighting, stress can be your friend. Work with it.