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Making Things, Part 6

Strength of materials

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At a glance...

- Stress
- Strain
- Yield points
- Stress-strain diagrams
- Toughness
- Ductility
- Strength

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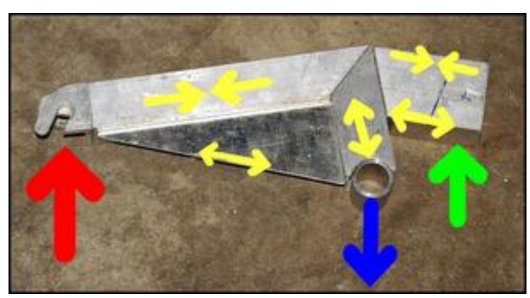
In this series, we've so far covered...

...the design of structures to take into account compression tension and bending loads (see Making Things, Part 1)....



...placing strategic holes in members so they're lighter but barely less strong (see Making Things, Part 2 and Making Things, Part 3)...

...the use of taps and dies (see Making Things, Part 4)...

...and using jigs and templates (see Making Things, Part 5).

Well, now we're back, and this time we're looking at some of the fundamental characteristics of materials – their strength.

Common Sense

You don't need to be a materials engineer to think you already have a pretty good feel for the subject. For example, you know that some grades of steel can be bent much further than others and still return to their former shape when the load is removed. An example is spring steel – it (duh!) springs back to its original shape when the load is removed. Try to bend a sheet of glass in the same way and you'll just end up with a bunch of fragments on the ground.

But do you **really** know this? The other day I had to make an anti-roll bar – just a little one, 10mm in diameter. I didn't want to change the temper of the steel by heating it at the points where it was to be bent, so I formed the bends with the spring steel rod kept dead cold. So how could I bend it – after all, it's spring steel, isn't it? The answer is that spring steel can be bent just like any other steel – you just have to bend it to the point that it takes a "set"; that is, it retains its bent shape.

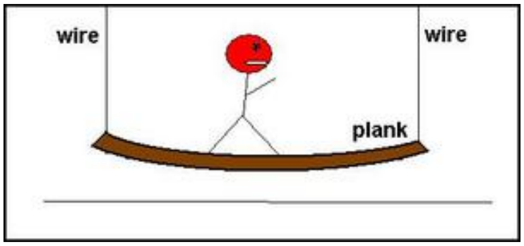
So it's simply not true that spring steel always returns to its former shape when the load is removed. It depends on how big that load is, and so how far the steel has been bent.

Some materials - eg sweets - will deform without shattering if pressure is applied slowly or if they're hot. But if they're cold or you chew down quickly, the lolly shatters. The material's properties are quite different in different situations.

So clearly while common sense and experience can give you some feel for the properties of materials, in other cases materials behave in ways that you'd not initially expect. So what are some universal characteristics of materials that can be used to give a guide to their usefulness in certain applications? It's a subject that can get complex really fast – but it's also one where when you have the basics in mind, the rest just follows.

Stress

Think of 'stress' and you probably think of having to get out of bed in the morning and head off to work, only to have to be nice to the pain-in-the-arse boss. That's pretty stressful! But when dealing with the strength of materials, stress has a very important meaning.



This diagram, taken from Part 1 of this series, shows a very thin person with a big red head. But it also shows a plank that's being suspended at each end by vertical wires. The wires are in tension. But how much tension are they actually being subjected to?

OK, here we need to look at some numbers. If Fred-the-Big-Red-Head weighs 75kg and the plank is another 25kg, the total mass being suspended by the two wires is 100kg, or 50kg each wire. So the force trying to stretch each of the wires is 50kg downwards, or to put it another way, 50kg under the influence of Earth's gravity. The acceleration of gravity is pretty close to 10 m/s/s, so the force in Newtons is 50 x 10, or 500 Newtons. [Force = Mass x Acceleration.]

Wherever there's a structure – whether that's a car or a bridge or a plank with Fred on it – there are forces involved. Those forces are measured in Newtons.

So each of Fred's wires is being subjected to a tension force of 500 Newtons. How do the wires react? Well, that pretty obviously depends on how thick the wire is. If it's incredibly thin fuse wire, the wire will stretch and break. If it's a bloody huge wire cable like that used on the winches of tow trucks, well, it won't even notice it.

The greater the cross-sectional area of the wire, the less it will be worried by the force exerted by Fred and his plank.

So since cross-sectional area is vital, how much is involved here? If the wire is 2mm in diameter, the area is worked out by: diameter x diameter x 3.14, all divided by 4. So, 2 x 2 x 3.14 = 12.56 divided by 4 = 3.14 square millimetres.

Now we know the force (500 Newtons). And we know the cross-sectional area of the steel wire trying to withstand the force (3.14 square millimetres). From that we can calculate the actual stress as easy as anything – it's just the force divided by the cross-sectional area, or in this case, 500 divided by 3.14. That's 159 Newtons per square millimetre.

Now it just so happens that Newtons per square millimetre is the same as saying MegaPascals, or MPa. So, to make sure that Fred won't fall down, the steel wire has to be able to cope with a strain of 159 MPa.

Well – can it?

Here's where the theory suddenly stops and the reality begins. Is steel wire strong enough to take a stress of 159 MPa? Will Fred fall down? Or is the wire strong enough that Fat Freda also be able to join Fred on the plank?

The good news is that if the wire is made from structural grade steel, Fred won't fall down. The listed yield strength of structural steel is 250 MPa. With only a 159 MPa stress, Fred is safe.

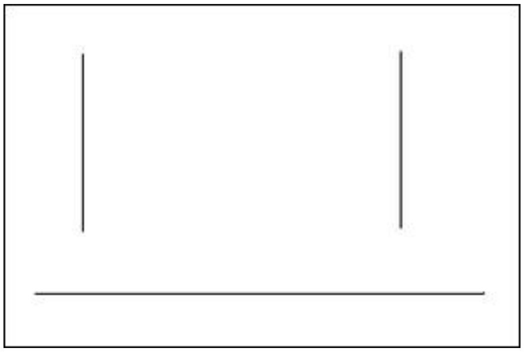
But if 100kg Fat Freda joins Fred on the plank, the stress doubles to 318 MPa. That means normal structural steel's no good (yield point of 250 MPa) and neither is 6061-T6 aluminium (yield point of 275 MPa). But ASTM-A242 high strength low alloy steel would be fine – it's got a yield point of 345 MPa.

So if you know the force involved and the cross-sectional area of the material resisting that force, you can easily work out the **stress**. If you do the calculations in Newtons and square millimetres, the answer is in **MPa**, which are the units used in most (metric) strength of materials spec sheets.

Yield Points and Stuff Like That

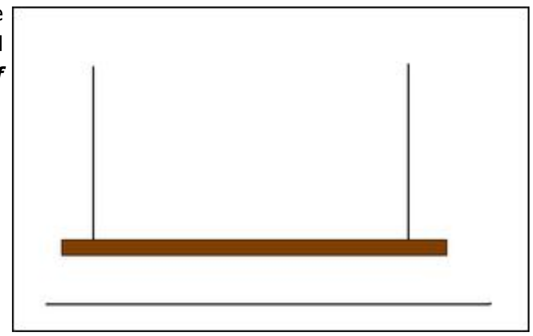
The perspicacious amongst you will have realised that something bloody important was just blithely skated through in the above text. The calculation of the stress level was fine but what about the evaluation of whether the material was actually strong enough to handle the stress? The benchmark used was 'yield point' but what does that mean and is it a good benchmark?

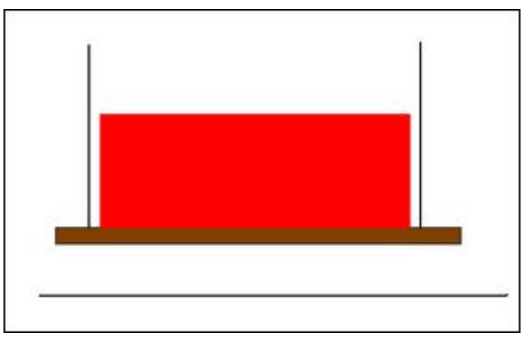
OK, let's take a look at how materials behave when subjected to stress. Again we'll think about a mild steel wire working in tension.



But let's ditch Fred and the plank, and start off with just two wires dangling vertically. While they're subjected to their own weight (and so the stress level rises as you move down the wire!), the wire is easily able to withstand this stress. Let's say each wire is exactly 2 metres long.

Now let's add the plank. The stress level in the wires will have risen and as a result, the wires will have stretched a tiny amount. ***The amount of stretch is called "strain".***

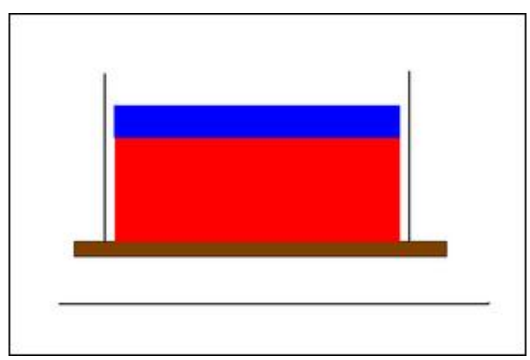




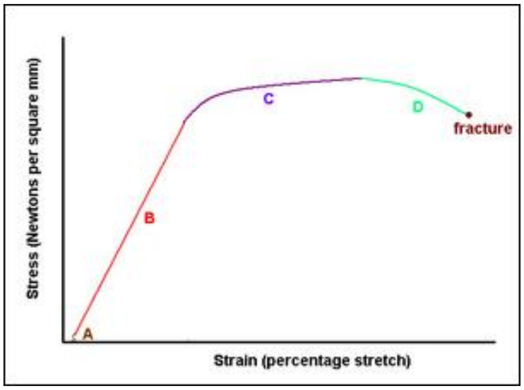
Now let's add a big heavy block of Red Stuff. Red Stuff is very rigid (so the plank doesn't bend) and weighs a helluva lot. Like, it's something like lead, man. The wires will definitely now have been subjected to strain – that is, they will have got longer. Let's say the strain is 0.05 per cent.

Now let's add a block of Blue Stuff. If you though Red Stuff was heavy, you ain't seen nothing like Blue Stuff – man, it's heavy. The wires stretch a bit further – let's say the strain (ie the stretch) is now 0.1 per cent.

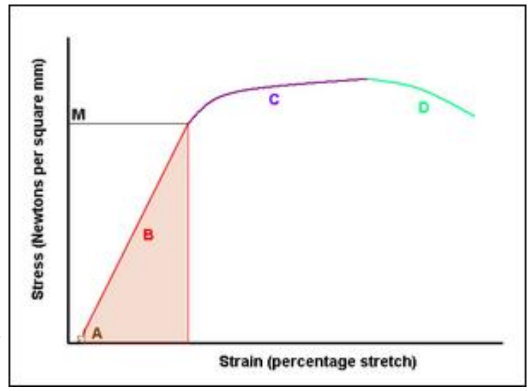
Now, to save me having to invent heavier and heavier stuff that's different colours, let's just graph the stress (the Newtons per square millimetre) versus the strain (the percentage stretch).



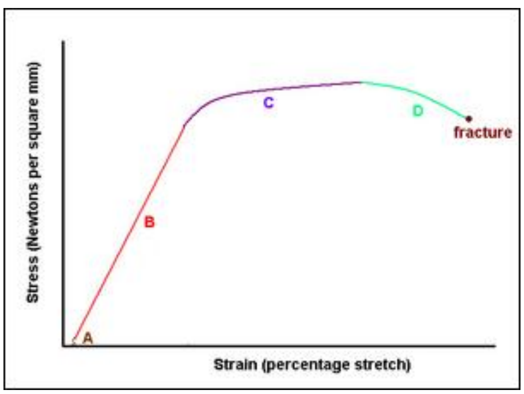
Along the horizontal axis is strain, or amount of stretch. Up the vertical axis is stress, or how much load is being borne per square millimetre. There's a bit of an initial wriggle in the curve (brown A) as the clamps holding the plank settle, and then the line angles upwards at a constant gradient (red B).



And it's the red B part of the line that's most important. For these stresses, the material deforms linearly. So, double the stress and the strain also doubles. And, most importantly, remove the stress and the material returns to its original dimensions. It's the area under the graph (shown here shaded in red) that indicates how the material can be used in practice – up to the maximum stress shown on the vertical axis (M) and resulting in the strain (stretch) shown on the horizontal axis.



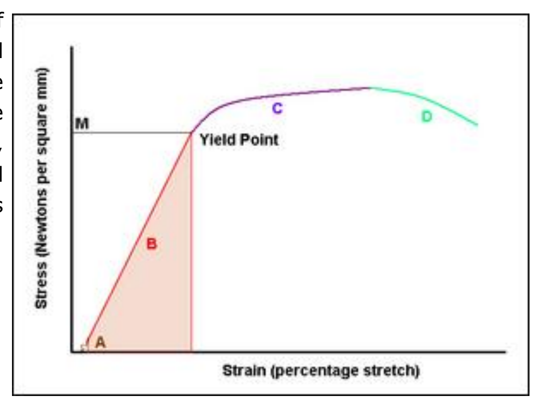
Simply put, the bigger the highlighted area under this part of the curve, the tougher the material – it has both strength and the ability to elastically stretch without being permanently deformed.



You can see that the linear behaviour, where the material stretches in proportion to the stress, stops happening after the stress reaches a certain value. In fact, at purple C, the bloody stuff starts to stretch further and further at smaller and smaller increases in stress levels. It's basically gone beyond what it can withstand, and importantly, this 'plastic' stretching is also not recoverable. That means the material will stay bent, even when the load is removed. That's good if you actually want to bend the stuff (eg make that sway bar or stamp a panel) but it's bad if the material is supposed to be supporting a load like an engine...

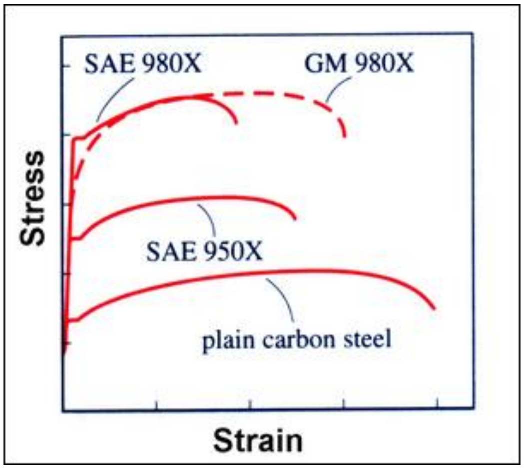
And from thereon as stress rises, things just get worse. The material starts to 'neck down' (get thinner) and so sows the seeds of its own destruction. When the line ends at green D, the material breaks. Ouch!

The yield point of the material occurs at the end of the section of the graph where the material stretches proportionally with stress. Note that the ultimate strength of the material is higher than the yield point (the curve keeps going up for a while, doesn't it?), but after this ultimate strength load has been applied and removed, the structure is permanently deformed.



Different Steels

That's damn' near enough for one article but take a look at these stress-strain curves for four different steels. As their names suggest, they're used in car body manufacture.



First up, take a look at plain old carbon steel. You can see that it can handle a fair amount of strain before failure. Moving up to SAE950X it's clearly stronger steel but when overloaded, it can handle less strain before fracture. SAE 980X is the strongest of all but it can handle the least strain after it starts to stretch badly. But GM 980X looks pretty good, doesn't it? It's strong but when its starts to really stretch is does so more progressively than the others. The other point to note is that each of these steels has a very sudden yield point – much more so than the stress-strain graphs used above.

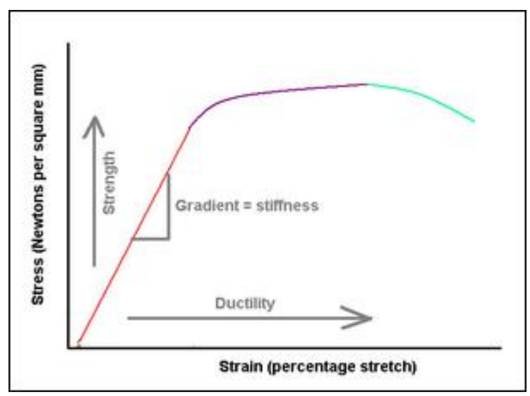
Conclusion

The key points are:

- Stress is the force acting on the member divided by the area of that member
- Stress is measured in Newtons per square millimetre, which is the same as MPa
- Strain is the stretch (or compression) of the material under the stress
- Stress-strain diagrams shows the relationship between the two for a given material
- Most metals have an initially linear relationship between stress and strain
- When the linear relationship is exceeded in stress level, the material deforms plastically and doesn't recover its shape after the load is removed
- The area under the linear part of the stress-strain graph shows the material's toughness

Whew!

Another way of looking at the stress-strain graph of a material is to say that:



- The gradient of the linear part of the stress-strain graph indicates the stiffness of the material, ie how much strain occurs for how much stress. The steeper the gradient, the stiffer the material
- The height of the graph indicates strength ie how much stress the material can withstand. The greater the height, the stronger the material.
- The distance the graph extends across to the right indicates ductility ie how much the material can be deformed before breakage. The further the graph extends across to the right, the more ductile is the material.

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