3 How to Measure Important Properties

3.1 The Basic Tensile Test

3.1.1 Breaking Things in Style

- A guy named **Procrustes** did the first **tensile tests** if we are to believe Greek mythology.
  - The basic idea of a *tensile* or *pulling* test is to pull at your specimen from both ends, making it longer and longer until it eventually breaks. The fancy word for this is: to put the specimen under **tensile stress**.You can do the same thing in reverse by pushing, making it shorter. The fancy word is to put your specimen under **compressive stress**. Procrustes used both methods on his specimens. Good old Procrustes' experiments don't count, however, because not only were his experiments unscientific (no numbers taken or graphs recorded), worse, he didn't use steel or other well-defined metal specimens. He used what scientists nowadays elegantly call "soft matter" (or less elegantly slime bags) in the form of humans.
- The first scientists doing it (almost) right were **Leonardo da Vinci** of universal fame around 1493, and **Galileo Galilei** of "and yet it moves" fame around 1630. They didn't do a tensile test exactly, but they did consider how a wooden beam or board will bend if loaded, how that relates to its cross-sectional shape, and so on. They didn't get it quite right but that is no wonder. Doing it right is rather complicated. Just look at the science modules where this is covered and you will get a good idea why those guys could not possibly get it right at their time.
- The tensile test is now the *paradigm*, the model case for mechanical material testing, and we need to look at it in some detail. The reason is simple. What we learn from just pulling at a straight bar of some material will allow (some of) us to *calculate* what will happen when we push and pull in any way whatsoever on any piece of material of any conceivable shape.
  Bang on glass, steel, or camembert cheese with a hammer, wrap your car around a tree (be sure to wear your safety belts when you do that experiment), or perform any experiment where you deform some object. Provided we have the material data from a tensile test and the "shape" and composition of your object, some of my colleagues can *calculate* what kind of shape your specimen will assume when you do one of the experiments mentioned above. They need a bit more information about the material than what you get from simple tensile testing alone, and they need big computers, but tensile testing provides the core information.
  - Modern machines for doing tensile tests are shown below.


Tensile Test Equipment

The machines are from different companies but look quite similar. That's because they are engineered to perform the same task: breaking things in style.

- Specimen such as shown below, with standardized shape and dimensions, are clamped into the heavy jaws of the machine. The idea is to pull so that the specimen gets longer, while simultaneously recording and displaying the pulling force and the elongation.
  It's also possible to push or squeeze but the data you get are not much different from pulling. More to that in the science module.

Broken specimen (Al, Cu, Graphite)

Of course, if you rip a steel paper clip apart, you need far less force than when you rip a steel sword blade apart. Since we want to get numbers for the properties of the material or ***specific*** **properties**, we want to test in such a way that the numbers we get do not depend on the specimen shape and dimensions. This requires three special measures:

1. The **specimen** is standardized, usually it is a cylindrical rod. The top and bottom part are much thicker than the main part so the heavy clamping does not influence the results. Just look at the picture above and you get the idea. The length and diameter of the rods are not very important even so we usually keep them at some defined values. It is enough, in principle, to know those two numbers so they can be fed to the machine's computer.
2. We measure the **elongation** not in absolute units like cm, but simply in *percent* of the initial length. We don't call it elongation any more either but **strain**. I must point out that in polite scientific circles strain is actually *not* measured in percent but for reasons of simplifying math, in 1/100 of a percent. If a scientist talks about a strain of 0.01 (without saying percent or anything else, it would be a strain of 0.01 · 100 = 1% for us.
   That takes care of specimen with different lengths. A long specimen will elongate more than a short specimen for the same applied force, but the strain measured in percent of the original length will be the same for both.
3. For the same reason we will not measure the **force** but the **stress**.
   Stress is simply force divided by the cross-sectional area.
   It's stress and not force we need to know, because the results then are independent of the cross-sectional area. For cylindrical specimen that means that their diameter or thickness doesn't matter.
   A specimen with twice the cross-sectional area of our standard sample would need twice the force for the same elongation or the *same strain*. In other words: *The same stress gives the same strain*, no matter how long and thick the specimen is.

Measuring stress and strain with cylindrical specimen thus makes the results we get *specific* for the material and completely independent of the specimen size.

It's essential that you understand this. So let's repeat it:

Stress = force per area **Strain = Elongation in percent** **Equal stress gives equal strain**

Stress, strain, elongation and so on are common words of the English language but here they become not only a very special meaning but can be expressed in numbers. That will also be true for some words / special expressions coming up. That's why I give you a quick reference module in the link.

Our present-day machines are quite smart but not yet quite as smart (I hope) as you, their Boss. So before you turn on the machine and start to pull, you must tell the machine exactly how it should proceed. Now think about that. What are you going to tell your machine?

Think!

Did you realize that you can do a tensile test in many different ways? For example:

- You could tell the machine to apply a certain constant *stress*. That will produce some strain, your specimen elongates by a certain percentage. Record that strain. After that is done the stress should be increased a bit, producing a somewhat larger strain, and so on.
- Alternatively, you could tell the machine to *strain* the specimen to some extent, for example 0,1 %, and record the stress needed for this. After that is done, the strain should be increased, and so on.
- You could tell your machine to increase the stress at a constant rate from zero to some final value and to measure the strain while it does that.

Modern machines will listen, and you can program them to do your *worst*. They will not complain. My engineer in charge of the equipment won't complain either if you suggest one of the above procedures, he will just kick you out without much words.

- So you should do your *best*. That means you should do the smart thing—if you can figure it out.
Yes? You have no other suggestions? Sorry to hear that.
So just believe *me* (that's pretty smart, too).
    - What you tell the machine is that you want it to apply a certain constant *deformation rate* or **strain rate** and that it should see to it that the strain rate chosen is kept absolutely **constant** until the end. That means that the machine needs to adjust the stress at any instant to the value needed at that point in time. Next, it is to record the *stress* it needs at any moment and display strain vs. stress on its monitor.

      That simply means that you instruct the machine to elongate or strain your specimen a *defined amount per second* (that's a *rate*). You may want a strain rate of 0,1 % per second, for example. That means that a 100 mm sample will now be pulled in such a way that every second it becomes 0,1 % or 0,1 mm longer. The strain then is a simple function of elapsed time: after 1 second it would be 0,1 %, after 10 seconds it is 1 %, and so on.
      Our present-day machines are fairly smart. They can measure the strain somehow, keep track of the time, and calculate the strain rate from this. If it deviates a tiny little bit from what it should be, the machine adjusts (and records) the *stress* to a level where the desired strain rate is achieved again. There is an active feed-back control loop, in other words.
- Doing a tensile test *this* way is quite important. If you let me have your fancy wootz steel blade, I can cut off a piece, put it in my machine and rip it apart. If I tell the computer of the machine the cross-sectional area and the initial length of the specimen, it will give me solid numbers for *specific* properties of your wootz steel for the particular strain rate (and temperature) chosen.
    - However, I will get *different* numbers for *different* strain rates or temperatures. Maybe those numbers are not terribly different but the differences aren't negligibly small either. Sorry. Tensile testing is a bit more involved as it appears on the outset.
      This teaches us a little lesson:

Assigning only one number like hardness to a blade oversimplifies the case quite a bit.

- Stress, by the way, must have the *dimension* of force divided by area. This comes out as Newton/square meter or **N/m^2**.
    - Force per area is also known as *pressure* but we only use the word "pressure" when it's the same everywhere and not just in one direction. When you dive, you feel the same water pressure from *all* directions. Every surface segment of your body experiences the same stress. When Procrustes or its successor, the holy inquisition, elongated you on the rack, you feel "pressure" only in *one* direction and that is why we don't call it pressure but quite aptly (uniaxial) stress.
      Uniaxial stress, by the way, is far more punishing for specimens than pressure from all sides. The pressure you experience at a diving depth of some 10 meters is bearable. If it would be applied uniaxial, you're dead. That effect is not specific to soft matter like you but is felt by all materials.
    - A stress of 1 **Newton** per square meter is also called 1 **Pascal** (P). Pascals are quite unfortunate units (you may blame it on the French) because 1 Pascal is a *tiny* stress or pressure. In real life we always encounter Mega or **Giga Pascals**, more about that later.
    - A Newton, as you certainly know but can't remember right now, is the one and only internationally allowed unit for **force**. It's defined as the force that accelerates a mass of 1 kg by 1 m/s^2. 1 Newton (1 N) therefore is defined as 1 N = 1 kgm/s^2.
    - In other words, since you know (I hope) that the earth with its gravitational pull provides for an acceleration of 9,81 m/s^2 on its surface, it thus exerts a force of 9.81 N on a mass of 1 kg. If your mass is 100 kg like mine, the gravitational force of the earth that keeps me from floating off into space equals 981 N.
- By the way, you Americans, Liberians and Myanmarians out there: *No*, there is no such thing as a pound, an inch or worse, pounds per square inch (psi); not to mention ounce, yard, mile or any non-metric unit of length and weight measurements.

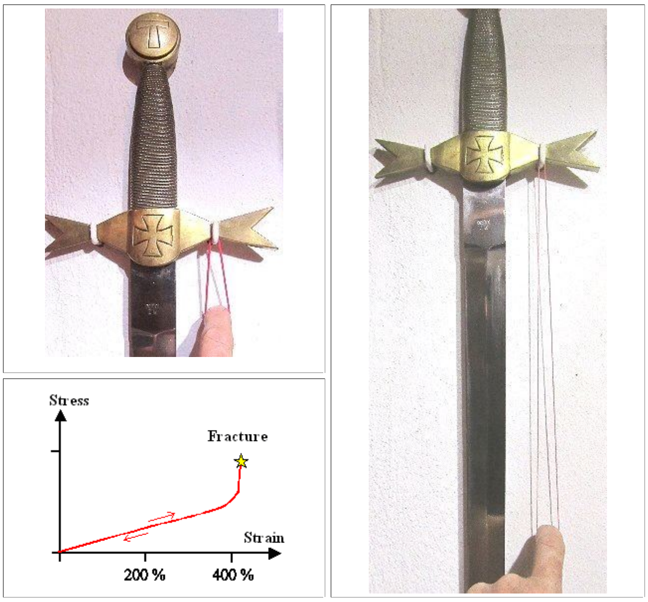
Basic Link

SI System

All these quaint old units have been outlawed by international treaties, signed by all countries except the three above, long ago. Why? Because the ***SI*** (Standard International) meter - kilogram - second system is far, far better for measuring things, not to mention science and engineering, than your God-fearing, outmoded, old and stupid, if time honored ~~system~~ non-system.
Why do a few people still use it? Could it be for the same basic reason that caused people a while back not to use superior iron but inferior bronze? Too damn lazy to learn a new trick?

Basic Link
Length, Conversion

- Now that you remembered your Newtons and so on, you can forget them again. Just bear in mind that *I* know exactly what's going on during a tensile test and that *you* can believe the data I will give you.
  - My machine, while straining the specimen with considerable power if needs be, still has time to construct a highly interesting graph and display it. This is the **stress - strain diagram**, produced for the particular strain rate chosen, and usually for room temperature. A stress - strain diagram is what we really are after in a tensile test. It gives us a lot of specific data about the specimen.
  - I give you a simple example of a stress-strain diagram done without costly equipment. You know that particular stress - strain diagram from many experiments that you did yourself. You just never put it on paper.



Stress - Strain diagram for a rubber band

I'm pulling at a regular rubber band with my finger. The resulting stress-strain diagram is shown in a qualitative way (no or guessed numbers!). A crusader-type (Templar) sword replica provides the "clamping" on one end.

  - Pulling out a rubber band by hand is exactly the same as doing a tensile test with a fancy machine. Except that you don't get precise numbers. But we don't need that here. You can easily pull a rubber band to 4 times and more of its original length, i.e. induce a *strain* of 400 % and more. Starting from strain 0 %, you have to increase the force or *stress* as we call it now about linearly for keeping the strain rate constant. In other words: twice the length takes twice the ~~force~~ stress, three times the length takes thrice the stress.
    If you let go, the strain goes right back to zero. In other words, it doesn't matter if you go up or down with the stress; you are always on the same curve. This is indicated by the two arrows in the drawing above.
    Eventually, for very large strains, you come to the end of what you can do with a rubber band. The rubber band seems to get harder; you have to increase your ~~pull~~ stress quite a bit now to increase its length just a *little* bit more. This is a warning that something is going to happen if you go on. If you ignore the warning and keep going, the rubber band will snap or fracture without straining much more.
    The stress-strain curve belonging to this behavior must look as shown. In the beginning it increases linearly; near to the end it goes up steeply.
- Here is your homework:

Ponder what basic kind of stress -strain diagram you would get while pulling at:

- **i) a diamond rod,**
- **ii) a glass rod or any other brittle substance,**
- **iii) a rubber band (let's see if you remember),**
- **iv) a copper, gold, or any soft metal rod,**
- **v) a sword blade or any hard but tough metal.**

Consider first what will happen if you just pull a little and then let go. Then pull some more, until fracture.

But first appreciate the beauty of **thought experiments** like the ones in your exercise. You don't *need* to go out and buy a diamond rod (not cheap) and the costly equipment to destroy it with. You just have to *imagine* all that - correctly, of course. You don't even have to get up. You can do the exercise while sitting in your easy chair, drinking **beer**. I just recommend access to pencil and paper. Sometimes my students do thought experiments like that upon my request; we call that an oral examination. Only the professor gets to sit in an easy chair and drink beer in this case.
But that doesn't apply to you. I won't even give you a bad grade if you get it wrong or if you don't do it at all. That's shows what a great guy I am. Maybe you should send me some money?

Important module

Beer and Swords

- When you now hook up your diamond rod and your other specimen to your brain machine, or a real paper clip to your hands, and start pulling, you might feel that nothing happens at all. But that only means that you are not strong enough, or that your vision is not good enough. If you cannot apply sufficient stress to produce strain that is visible to the naked eye, you simply need to look at your specimen through a *microscope* (low magnification will be sufficient) to see its elongation.
If you apply stress, small or large, something *must* happen. The strain might just be too small to be "obvious"! Just don't use a scale with 100 % strain in your diagram, go, perhaps, for just 1%.
By the way, a *brain* microscope is also good enough for your experiments; you still do not have to get up. Use a bit more beer, whisky or red wine if your brain microscope doesn't seem to focus properly on your first try.
Now get to it. Give it your best shot.

Think!