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Measuring Young's modulus with a tensile tester

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Abstract

We use a tensile testing machine to create stress-strain plots and determine Young's modulus for some ductile and plastic materials. Supplementary videos are also provided.

Keywords: elasticity, materials science, physics education

Young's modulus is a key concept in elasticity theory and mechanics of solids [1, 2]. Measurements of Young's modulus in a classroom setting have been studied many times in the literature. These studies typically focus on simple or inexpensive ways of measuring Young's modulus [3, 4]. Related studies describe alternative indirect ways of measuring the modulus [5, 6]. Nunn, for example, developed a technique for classroom use by which one can determine the Young's modulus of a solid using the speed of sound in that material [7]. In this article, we will perform accurate measurements with a tensile testing machine to create stress–strain plots and determine Young's modulus for several materials. We also discuss some possible limitations of our method of measurement.

Young's modulus is defined to be the ratio:

$$E = \frac{\sigma}{\epsilon} = \frac{F/A}{L/l},$$

where σ is the tensile strength (defined as force applied per unit area), ϵ is the tensile strain (defined as displacement per unit length), F is the applied lengthwise force, A is the cross sectional area of the sample, L is the total displacement, and l is the test length which was initially between the two grippers in the device. This ratio defines how a sample of material deforms in a response to a force which is applied lengthwise. The stress analysis device which we use to measure this modulus in our demonstration is the Tinius Olsen 25ST with a 25 KN load cell. We will mention here that the device and analysis software which we use are somewhat sophisticated and will likely only be available at a metrology laboratory at a university. High school students may be able to contact a technician at an Engineering department at a local university and ask if they can view a demonstration. The novelty of our result is to present complete stress–strain plots which are hard to obtain in a classroom environment with limited equipment. The technical method which we have used in carrying out our experiments can be compared with measurements which students can obtain using alternative means. We also provide several videos of the tests which may be useful to students. Note that we have chosen everyday materials for

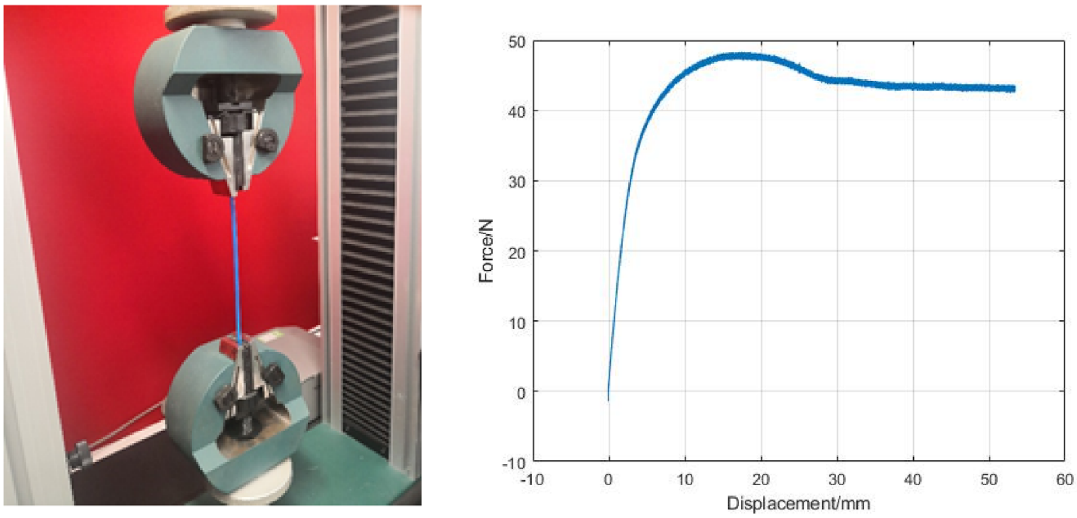

Figure 1. Stress testing with a plastic straw (left) and the associated force-displacement plot (right).

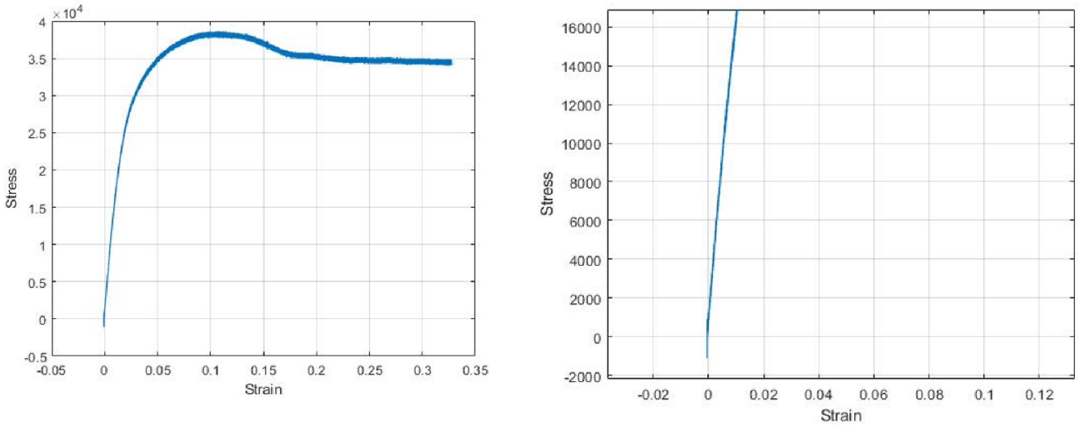

Figure 2. Stress–strain plot for a plastic straw (left) and the linear region (right).

our tests to aid with comparisons in a classroom environment.

A pedagogical point here is that different materials can have very different relationships between stress and strain. For example, students might intuitively think that a plastic straw would not have much resistance to stress because the straw is easy to cut or snap. However, in figure 1, we show a plastic straw (similar to a drinking straw) being used in our apparatus, along with the raw force-displacement plot. This plot can be converted to a stress–strain plot by dividing the force by the cross sectional area and the displacement by the original test length. This is done in figure 2 (left-hand image) to produce a stress–strain plot for the plastic straw. We can see from the plot that the plastic straw has an initial elastic region where the relationship between the stress and the strain is close to linear.

In the mathematical modelling of elasticity phenomena, this is known as linear elasticity. Since E is defined as the ratio of tensile strength to tensile strain, students should know that Young's modulus can be found by taking the gradient of the curve in figure 2. This only holds when the graph is linear because Young's modulus is

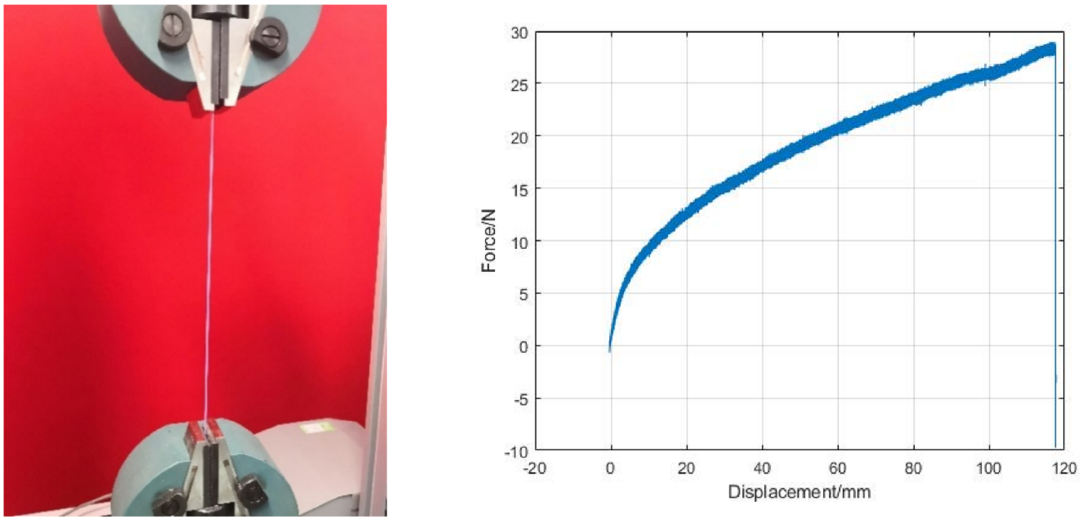

Figure 3. Stress testing with flexible plastic cord (left) and the associated force-displacement plot (right).

strictly speaking not valid outside of the linear elastic region. This turning point where the graph stops being linear is called the elastic limit and at this point, the material becomes stretched and deformed far enough that non-linear effects are introduced and the material cannot return to its original length [2]. This can be checked afterwards by seeing that the top of the straw has been stretched into a position from which it cannot recover.

In figure 2 (right-hand image), we zoom in on the region of the stress–strain plot which is approximately a straight line. Young's modulus can now be found from the gradient of this line. In this case, $E = 1.75 \times 10^5$ Pa, or 1.75 GPa. The type of irreversible deformation which occurs beyond the elastic limit due to dislocations of the material on the atomic scale is typically known as plastic deformation in the literature. This is to be contrasted with an elastic deformation, which is reversible and does not cause a permanent change to the structure of the material.

In figure 3, we figure 3, we repeat the experiment with flexible plastic wire cord. Students might guess that since the material is flexible, it will have a lot of resistance to tensile strain and that it will stretch out by a large displacement before suddenly breaking. This approximate behaviour is indeed observed in figure 3. The applied force is lower than the force for figure 1, but the corresponding displacement (and hence resistance to strain) is lower. The sudden drop corresponds to the point at which the cord breaks so that a force is no longer being applied. For completeness, we plot the stress–strain plot for the plastic cord in figure 4. In this case, the tangent of the linear region tells us that Young's modulus can be estimated at around 1.25 GPa.

We will now attempt to test a material which is neither ductile nor plastic. In figure 5, we show a stress test with a piece of nylon rope. It might intuitively be guessed that a piece of rope could undergo a huge lengthwise applied force but that it will not stretch very much and will break at a very high tensile strain. This type of behaviour is typical of materials which are strong but not ductile. In figure 5, we show that this greater stress resistance is indeed observed when the rope sample is placed in the tensile tester. The sudden drop in the graph occurs because the grip used in a tensile tester device causes the rope to fray as it moves upwards such that rope strands start to be worn away by shearing forces. This then causes the rope to slip and the force drops off before the full force-displacement plot can be obtained. In figure 5, we attempted to avoid this problem by tying knots at the end points of the rope to allow for more grip but slippage still occurs. This is a limitation of our method, but nevertheless one can see that the behaviour which occurs for the rope is somewhere

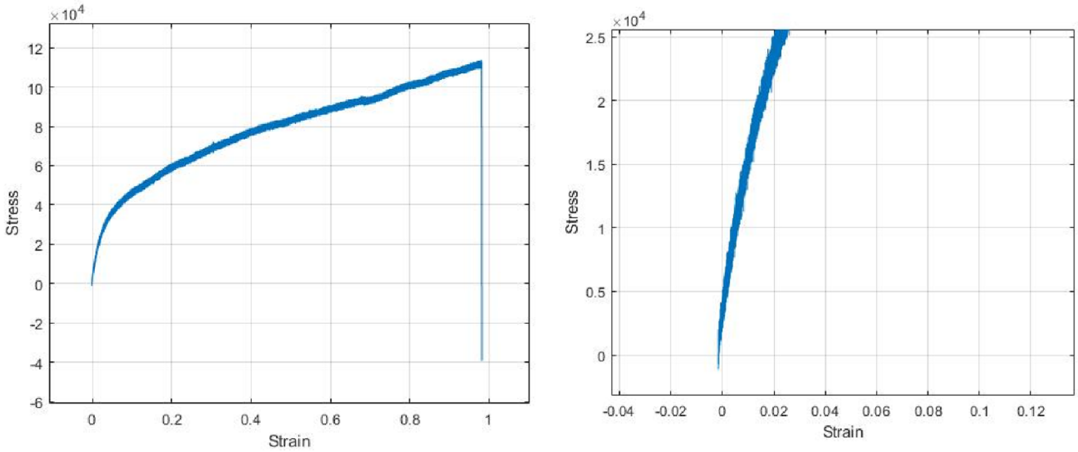

Figure 4. Stress–strain plot for a plastic cord (left) and the linear region (right).

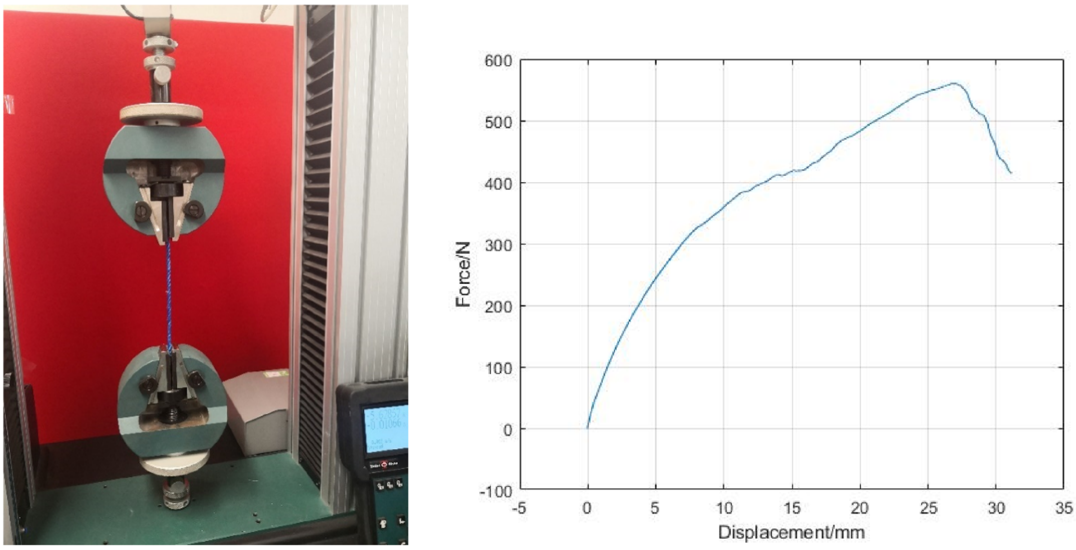

Figure 5. Stress testing with nylon rope with a force-displacement diagram.

between that of a brittle and a ductile material. The rope is clearly not ductile, since as stated earlier, ductile materials like steel typically yield under an applied force, before hardening and then finally breaking (see figure 1 for an example).

We have also included videos in the supplementary material so that students can see the tests being performed on the apparatus. In video 1, we use the rope sample and demonstrate how the rope sample is pulled until it is tense. As the name of the device suggests, it is necessary to have this tension before we can perform any measurements. In video 2 (sped up 4×), we show the stress test being performed on the plastic cord. Note how after some time the cord starts to turn white (corresponding to hardening and passing beyond the elastic region) before the cord finally breaks. In video 3 (also sped up 4×), we show the stress test for the plastic straw. It can be clearly seen the straw is stretched by a substantial amount and that it also turns white as it is deformed, starting to form a neckpinch in the middle under tension.

Data availability statement

No new data were created or analysed in this study.

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Hollis Williams is an Engineering PhD student at the University of Warwick. He is interested in various aspects of physics education and theoretical physics and has published articles on fluid dynamics, quantum mechanics and particle physics.