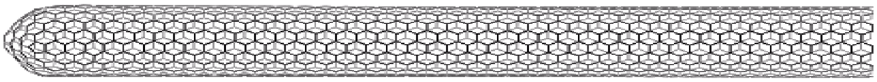

Take Me to the Top, Bucky!

Teacher Packet

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Content Area: Chemistry, Physics
Grade Level: Grades 9 - 12

LESSON RATIONALE

Since the discovery of nanotubes in 1991, speculations from experimental and theoretical studies of their electronic, chemical and mechanical properties have placed them in the limelight of the rapidly growing field of nanotechnology.

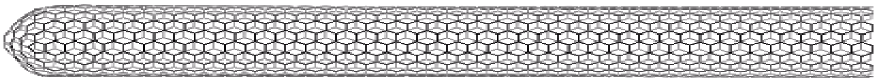
Research indicates that carbon nanotubes are 100 times stronger than steel with only one sixth the weight (ONL, 2006) and are as flexible as plastic. Despite their extreme strength, they have an extraordinary length to diameter ratio. If the diameter of a typical carbon nanaotube (1 nm) was scaled up to let's say the diameter of a human hair (100 μm), it would be in the range of 100 m long! Carbon nanotubes are expected to be used to strengthen composite materials or reinforce polymers and metal matrices. The development of carbon nanotube materials is expected by some to revolutionize materials as we know them to the extent that "Every industrial process we've got we're going to throw out the window" (Flight, 2006).

One exciting application currently being pursued for carbon nanotubes is in the design of the space elevator, the centerpiece of which will be a carbon nanotube composite ribbon. While just a few centimeters wide and nearly as thin as a piece of paper, the ribbon will support mechanical lifters that will carry cargo and humans into space and back.

This activity focuses on the mechanical properties of carbon nanotubes in the context of high-strength nanotube composite materials, such that might be utilized in projects such as the space elevator. Students will design, construct and test a composite ribbon, modeling one possible application of the carbon nanotube.

Instructional Objectives

- Introduce students to the concepts of stress and strain as they pertain to the materials applications.
- Learn about how the properties of materials can be enhanced through the use of composites.
- Experimentally measure the elongation of a ribbon versus applied stress and display the results graphically.
- Design and test a composite structural material.



Standards

Indiana State Standards

High School

CP.1.15	Understand and explain that whenever the amount of energy in one place or form diminishes, the amount in other places or forms increases by the same amount.
CP.1.17	Know and explain that transformations of energy usually transform some energy into the form of heat, which dissipates by radiation or conduction into cooler surroundings.
CP.1.20	Realize and explain that the energy in a system is the sum of both potential energy and kinetic energy.
P.1.2	Measure or determine the physical quantities including mass, charge, pressure, volume, temperature, and density of an object or unknown sample.

National Standards

High School

- Standard A: Science as Inquiry
  - Design and conduct scientific investigations.
  - Formulate and revise scientific explanations and models using logic and evidence.
  - Recognize and analyze alternative explanations and models.
- Standard B: Physical Science
  - Motions and forces.
- Standard E: Science and technology
  - Identify a problem or design an opportunity.
  - Propose designs and choose between alternative solutions.
- Standard F: Science in Personal and Social Perspectives
  - Science and technology in local, national and global challenges.
- Standard G: History and nature of science.
  - Science as a human endeavor.
  - Nature of scientific knowledge.

LESSON PREPARATION

Materials (per class of 24 students, working in groups of two)

Item	Number/Amount
Masking tape (¾ inch to 1 inch)	1 roll
Scissors	12
Ring stand	12
Support ring or clamp	12
Spring scale (50 N or 10 pound)	12
Wooden blocks (1½ in x 2½ in by ½ in thick)	48
Polyester string	1 roll
C-clamps (1 in to 2 in)	24
Paper ruler template	12
Low temperature hot glue gun (see NOTES)	12
Glue sticks	48
Permanent marker	6
1 mil thickness polyethylene drop cloth	1
Graph paper	24 sheets
12 inch rulers	12

NOTES:

The C-clamps need to be able to accommodate two thicknesses of the wooden blocks used. If ½ inch thick blocks are used, 1 inch clamps will be adequate.

Use the **low temperature** mini glue guns. The high temperature guns will melt the plastic sheets. The guns can be purchased at Wal-Mart and hobby stores for about $2.00 per gun. A package of 100 Glue sticks is about $4.00.

Polyester string from any craft store works well and is very inexpensive. Braided fishing line works fine as well, but is more costly.

As an alternative to drawing paper graphs, students can input their data to Excel or other spreadsheet and generate their graphs electronically.

A word about the polyethylene drop cloth: **not all 1 mil thickness drop cloths are created equally**! Most manufacturers do not name on the package the polymer that is used. Some are high density, some are low, and some are polypropylene or other materials. They all have different tensile strengths! One brand that works well is Film-Gard, (sold at Home Depot). If other brands are used, try them first. It may be necessary to alter the width of the material accordingly to get a range of stretching that is reasonable, practical and safe.

Time Allotment

45-60 minutes to design and construct ribbon
60-90 minutes for testing the materials, graphing and analyzing results

Getting the Materials Ready

1. Provide students with **two strips** of 1 mil polyethylene plastic sheet that measure 1 ½ in wide by 10 in long..
2. Cut one 4 foot length of the string for each group.
3. The wooden blocks can be cut from ½ inch plywood. A small wood molding like parting stop can also be used, cut to 2½ inch lengths. Provide 4 blocks for each group.
4. Print or copy the paper rulers and cut them apart. Give one ruler to each group.
5. Demonstrate the use of the hot glue gun to the students and caution them that the tips as well as the extruded glue are hot. It is in fact a hot glue gun!

Background

The tower to space – a matter of strength

In 1895, the Russian scientist Konstantin Tsiolkovsky gazed at the newly constructed Eifel Tower and dreamed. He envisioned a celestial palace in **geosynchronous orbit** above the earth, attached to the earth by a spindle shaped cable. (NASA, 2006).

This space aged version of “Jack and the Beanstalk” may not be as far fetched as it seems. In 1960 another Russian scientist actually proposed the design for a transport system into space using a geosynchronous satellite as a base from which a cable or ribbon could be fabricated back to the surface of the earth. The ribbon would provide a means of support by which a vehicle might transport goods from the earth to an orbiting space base.

Based on the Russian design, four American engineers undertook the task of determining what sort of structural material might be required to construct such an elevator to space. They concluded that the strength required would be at least twice that of any known material. Engineers around the world toyed with designs and materials for the ensuing 25 years, but the discovery of nanotubes in 1991, and then developing the ability to grow them, brought the science of super strong materials to new horizons.

The earth is constantly spinning. If a cable is anchored to an earth platform, with a counterweight attached far enough away at the other end (62 000 miles up), the cable will be held taut by the pull of the counterweight and the earth’s rotation. “If you can maintain a taut cable, you have the makings of a space elevator” (Flight, 2006).

The cable, known to elevator scientists as a ribbon, would be fabricated in space and dropped in stages to a floating platform similar to an offshore oil rig near the equator. An elevator car, roughly the size of a jetliner cabin, and able to carry hundreds of people or tons of cargo, could climb and descend the ribbon, powered by an electromagnetic drive. It is projected that the trip from the earth to geosynchronous orbit (22 000 miles) might be accomplished in just a few days (Flight, 2006).

The right material, the right properties

Solid materials are often characterized by their mechanical qualities. These qualities might include hardness, malleability, ductility or tensile strength. These mechanical characteristics determine how the material will respond to various forms of stress, how or if the material will fail under stress, and whether it will show warning signs before failure actually occurs.

The application of a force or stress to a material is known as **loading**. An engineer would consider several types of loading conditions in designing or selecting materials (tension, compression, bending, shear, and torsion). The suitability of a material for a particular application is dependant on the performance of the material under these loading conditions. The load condition that we will be looking at in this activity is **tension**, the stress in which the two ends of material are pulled apart.

Tensile strength is a measure of how a material will respond to tension, the result of forces being applied, pulling in opposite directions. When a small tensile stress is applied, a material can stretch and then return to its original length when the stress is removed. This is referred to as an **elastic deformation**. The greater the stress applied, the greater the deformation. If the material reaches the limit where it no longer returns to its original shape, it becomes permanently deformed. This is referred to as **plastic deformation**. The maximum tensile stress that a material can withstand before it is permanently deformed is called the **yield load**. Once this yield point is reached, the material will continue to stretch and if the yield load is not removed it will continue to lengthen until it breaks.

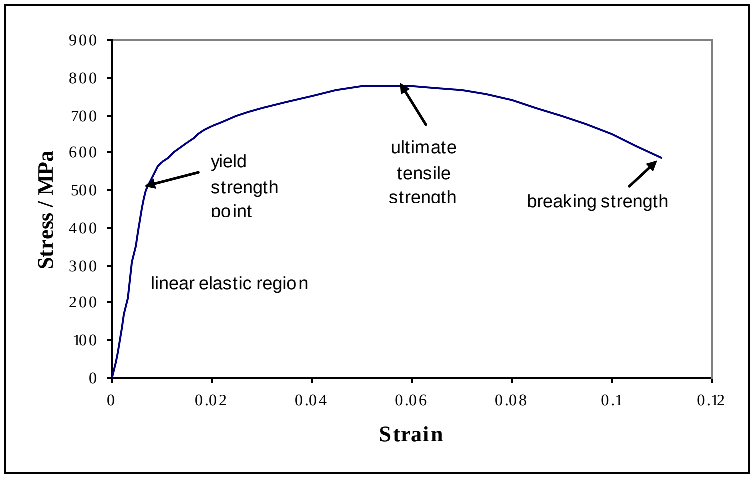
Strain versus stress

A test of tensile strength is a fundamental mechanical test in which a carefully controlled specimen is subjected to a load (a stress) while measuring the elongation (proportional to strain) of the specimen.

Stress (σ) is a measure of force (Newtons, N) per unit of area. If the area over which the force is applied is expressed in square meters, the ratio of force over area, N/m^2, is known as the **Pascal**, Pa, a measure of pressure. Stress is commonly expressed in units of either Pascal, megapascal (MPa) or gigapascal (GPa) (Beals, 1999).

Strain is the response of a system to an applied stress. When a material is loaded with a force, it produces a stress, which then causes a material to deform. Engineering strain is defined as the amount of deformation in the direction of the applied force divided by the initial length of the material. This results in a unitless number, although it is often left in the unsimplified form, such as inches per inch or meters per meter (NTD).

The product of a tensile test is a graph depicting a load versus elongation curve which can then be converted into a stress versus strain curve. Since the ratio of stress versus strain is proportional to the ratio of load versus elongation, the load-elongation curve will have the same shape as the engineering stress-strain curve. The stress-strain curve relates the applied stress to the resulting strain. Each material has its own unique curve (See **Figure 1**).



The height of the curve of the stress-strain graph is called the tensile strength of the material, which is a measure of the stress the material can withstand before beginning to tear apart.

Young's modulus of elasticity (E, also referred to as the elastic modulus) is the ratio of stress and strain and can be represented by the equation

$$E = \frac{\sigma}{\varepsilon}$$

The units of Young's modulus are the same as the units for stress, since ε is a dimensionless quantity. When the results of this ratio are displayed graphically, E is the slope of the line. The steeper the slope of the line, the stiffer is the material.

DOING THE LESSON

Opening questions/Pre-Lab Discussion

Begin the activity by framing the concept of an elevator to space – the need, feasibility, political and social implications, the technologies involved in such an endeavor and why, though the idea was proposed and designed, no attempt was made to seriously consider construction until the discovery of the carbon nanotube. An excellent introduction to the application of carbon Nanotubes, in relation to the space elevator, is available through NOVA's website:……….

The lesson pertains to the structure versus the properties of a material and how a property such as tensile strength can be improved upon or enhanced, to make a material more suitable for a specific application. This can be accomplished by the altering the physical shape or structure of the material or by the use of a composite construction. Students can be questioned to elicit their own ideas about what can be done to improve the strength of a material.

- What does strength mean as it pertains to structural materials?
- What makes a material strong?
- What is an example of something that is very hard but not very strong?
- What is an example of a material that is strong but not very hard?
- What can be done to improve upon the strength of a material?

Students will be provided the materials and allowed to design and construct a composite material – a structural ribbon, modeling a structural concept that which might be used in an endeavor such as an elevator into space. The goal will be to allow them to create a composite structural material that will be superior in strength to either of the materials alone. The first task for the students will be to brainstorm the design and construction of their prototype.

Consider discussing the following pertinent aspects:

- The types of loads that engineers take into account in the design of a material
- Structure what tensile strength is and how a test of tensile strength is performed
- The experimental set-up that will be used and how data will be measured
- How task responsibilities will be divided in the group

Students will begin by measuring the tensile strength of a double layer of 1 mil thick polyethylene sheet. They will then construct and measure the tensile strength of their composite ribbon, made from a combination of a double layer of polyethylene sheet with a fiber filament between them.

They will graph their results, compare the tensile properties of the two ribbons and discuss the differences in mechanical behavior of the polyethylene plastic alone ribbon versus the composite construction.

Activity

Part 1: Measuring tensile strength of polyethylene sheet

For Part 1, you will need the following items:

- 1 strips of polyethylene plastic measuring 1 ½ inches by 10 inches
- 4 wooden blocks, 1 ½ x 2 ½ inches, ½ inch thick
- 2 small C-clamps
- Ring stand

- Spring scale

You will be measuring the tensile strength of a double layer (two strips) of polyethylene plastic. You will then design and construct a composite ribbon, again using two strips of plastic, but this time incorporating a layer of string filaments between them. Once you have constructed your composite ribbon you will measure its tensile strength. You will then graph both sets of data to compare the tensile characteristics of each.

1. Construct two data tables in your notebook to record your measurements, ***Data Table 1*** for the polyethylene sheet alone; ***Data Table 2*** for the composite ribbon. Label each table appropriately.
2. Attach a 90° rod and clamp, or support ring, securely at the very top of the ring stand.
3. Suspend the spring scale from the support so that it hangs directly over the base of the ring stand.
4. Take the first two of the polyethylene plastic strips and lay one on top of the other.
5. Very lightly, mark off a 15 cm section in the middle the ribbon with a marker. Be careful not to wrinkle, tear or depress the surface of the plastic.
6. Place one end of one of the double layer ribbon squarely between two wooden blocks and clamp it firmly in place into one of the C-clamps. The blocks should just meet the line at one end of the ribbon.
7. Clamp the other end of the ribbon in a similar fashion using the second C-clamp, so that the 15 cm section of ribbon lies exposed between the clamps.
8. Hook one C-clamp on the scale so that the ribbon hangs freely. You will need 30 to 40 cm of free space below the hanging end of the ribbon.
9. Tape the paper ruler behind the hanging ribbon so that the 0 cm mark lines up with the very top of the 15 cm test segment of exposed ribbon.
10. Record the reading on the scale from the weight of the ribbon and clamps in ***Data Table 1***. This weight will be the initial stress.
11. Record the initial length (to the nearest 0.1 cm) of the test section of the plastic ribbon. This will be the initial length of the test strip, with no force applied to the ribbon. Any elongation of the ribbon, as a result of the mass of the clamp hanging from the bottom, will be assumed to be negligible, relative to the experimentally applied forces.
12. Apply a force of 1 N to the ribbon by gently pulling on the bottom clamp. Hold the force constant and record the length (to the nearest 0.1 cm) of the plastic ribbon under the applied stress.
13. Repeat the above process in 1 N increments, recording the length of the ribbon at each weight. Continue until the ribbon breaks or continues to stretch indefinitely.

If the ribbon continues to stretch, make a quick visual reading and relax the tension until you are ready to make your next measurement.

14. Record any effects you observe on the ribbon as a result of the forces you apply.

Part 2: Construction of a composite ribbon

Now that you have examined the tensile properties of a single sheet of plastic, your next challenge is to design a composite ribbon, utilizing the same type of plastic, but adding a second component, to enhance the mechanical properties of the plastic alone.

The composite can be modeled using the polyethylene ribbon substrate and adding to it fibers, representing carbon nanotubes. The pieces of string will be laid out and hot glued into position. The design and construction will be left up to each lab team. Using the materials available, and your own ingenuity, you will design and test a product, superior in tensile strength to the original plastic ribbon.

You will be provided the following materials, in addition to the hardware used in ***Part 1***:

- 1 more strips of plastic ribbon (identical in size and composition to the ones that you used previously)
- A 4 foot length of string
- A hot glue gun with glue sticks

The glue is a low density polyethylene that will bond to the plastic ribbon and string when melted. **The tip of the glue gun and the glue coming out of it will be hot!** The glue cools and hardens rapidly, however, so you will have to work fast, where appropriate.

1. Assemble and lay out your materials.
2. Take the 4 foot length of string and cut it into pieces, each measuring about 6 cm in length.
3. Brainstorm with your partner how you would like to utilize the materials and what sort of a composite ribbon you would like to design; how you will arrange the pieces of string between the layers; how you will attach them in place and how you will bond the two layers. You will again test the middle 15 cm of the ribbon, as you did before.
4. Draw a model of your ribbon design on a piece of notebook paper or in your laboratory notebook, as instructed. Include a drawing of the components and indicate how you intend to incorporate them in your construction. Make any necessary notes that you will follow during the construction process.
5. Show your plan to your teacher.
6. When your model has been approved by your teacher, you may begin construction of your composite ribbon, following your proposal.

7. Show your finished product to your teacher before proceeding with the tensile test.

Measuring the tensile strength of a composite ribbon

Now that you have completed your project you will perform the same test of tensile strength that you performed previously on the single layer material. The increments in which you will supply stress will be multiples of 2 N rather than 1 N, as before. The data collected below will be recorded in ***Data Table 2***.

1. Like before, mark a 15 cm section of the composite ribbon you have constructed and clamp the ribbon between two C-clamps, with the 15 cm test length exposed.
2. Hang the ribbon from the scale on the ring stand. Record the initial length of the ribbon in your data table.
3. Apply a force to the ribbon by gently pulling on the bottom clamp and measure the corresponding length of the ribbon. Begin with a force of 2 N. Record the length of the ribbon under the applied stress.
4. Repeat the above process in 2 N increments, recording the length of the ribbon at each weight.
5. Continue until you reach the maximum capacity of the scale. DO NOT EXCEED THE SCALE CAPACITY OR YOU WILL CAUSE PERMANENT DAMAGE TO THE SCALE.

Wrap it up

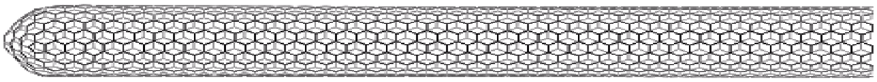
Construct a graph, using your experimental data from both **Data Table 1** and **Data Table 2**. Scale your axes to fit the data and incorporate both sets of data on the same graph. Graph tensile force (pounds or Newtons) on the vertical y-axis and the length of the test strip on the horizontal x-axis. Draw a best fit line through each set of data and include a key to identify each curve. Give your graph a descriptive title and remember to label and include the units on each axis.

Relative to the string filament, the increase in strength from the addition of the glue alone to the polyethylene is insignificant. Yet, it does introduce an untested variable. This is a good point of discussion and if time and interest permit can be quickly tested using a third polyethylene strip with only glue applied.

Follow-up

In the follow-up discussion, consider the use of the ribbon the students constructed as a model for a nanotube composite ribbon, such that might be used in the construction of the space elevator.

- Why did you cut the string?
- What does the string represent?
- Would engineers actually use plastic sheet?



- What sort of factors would engineers have to consider in the physical aspects of the ribbon?
- Why did you use a double layer of plastic for first tensile test, rather than a single layer?

Allow the students adequate time to consider the utility, purpose, strengths and limitations of the model. You might even invent some analogies to help students grasp the enormity of the difference between the diameter and length of nanotubes. They are indeed very strong, very flexible and very long.

Talk about the tests of tensile strength and how they compare, not only in terms of strength, but also with regard to the physical behavior of the ribbons during the tests.

- Describe what happened to the single sheet of plastic as it stretched.
- How did the composite ribbon behave differently?
- Is the composite ribbon equally strong in both directions?
- Do you think the temperature of a material changes if it stretches?
- What is the load called that is opposite in direction to tension?

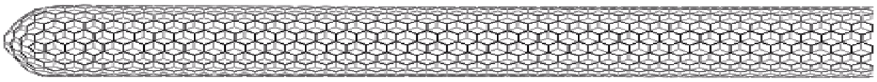
You may wish to ponder alternative testing schemes. Consider for example that, since the composite ribbon did not stretch very much using a 20 N or 50 N scale, we need a means of applying enough stress to make it break. It might be interesting for students to hear each other's ideas.

Compare the designs among the students. Students may run the segments of string parallel to the length of the ribbon; others may criss-cross them in a pattern. Consider the structural need for an elevator ribbon and what some of the mechanical properties of some familiar materials are.

- Does the ribbon need to be equally strong in all directions?
- Is a masonry wall is strong in all directions?
- What examples of things can you think of in which the materials used to make them are composites?

Sum up the activity by bringing the discussion to the idea of the space elevator in general.

- Why would scientists want to build the earth bas at sea and on the equator?
- What if the space ribbon was constructed of a conductive material?
- What would be the consequence of a conductive ribbon moving through the magnetic field of the earth while in orbit?
- Would a ribbon to a space station be floating up to the station or dropping down to it?
- What would happen if the ribbon would break?



- It has been said that the country that is the first to build an operating space elevator will hold the monopoly for the world. What are the ramifications of this statement?
- What sort of national and international issues should be considered in a proposal of building an elevator to space?

Resources

Beals, M., Gross, L., & Harrell, S. 1999. Spider silk: Stress-strain curves and young’s modulus. May 18, 2006. http://www.tiem.utk.edu/~mbeals/spider.html.

Charity, Mitchell. (2006) Printable metric Rulers. http://www.vendian.org/mncharity/dir3/paper_rulers/.

Flight, G. (2006). The 62,000 mile elevator ride. Money. http://money.cnn.com/magazines/business2/business2_archive/2006/03/01/8370588/index.htm.

NASA (2006). Tethers in Space. http://liftoff.msfc.nasa.gov/academy/TETHER/tethers.html.

NDT Resource Center. (2006). Tensile Properties. http://www.ndt-ed.org/educationResources/CommunityCollege/Materials/Mechanical/Tensile.htm.

Oakridge National Laboratory (ONL). (2006). Exploring Carbon Nanotubes. http://www.ornl.gov/info/ornlreview/v35_3_02/nanotubes.shtml.

Additional Reading and Resources

Elevator 2010. http://www.elevator2010.org/site/index.html

Audacious & Outrageous: Space elevators. (2006). http://science.nasa.gov/headlines/y2000/ast07sep_1.htm

The A to Z of Materials, www.azom.com.