Development of K-12 Engineering Outreach Materials

NASA Faculty Fellowship Program 2003
Final Report

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William Jordan, Ph.D., P.E.
Louisiana Tech University

Abstract

Six modules were created that can be used in K-12 classes to introduce students to what engineers can do at NASA. They are:

- What is an engineer and what do NASA engineers do?
- How do NASA engineers
  - solve problems
  - design structures that will be fatigue loaded
  - use an understanding of metallic crystal structures in design
  - design to avoid buckling
  - use polymeric materials in space applications

Introduction

This project has its origin in some work we have done at Louisiana Tech University. For the past four years we have taught a course entitled: ***Engineering Problem Solving for Future Teachers***. This course was created with financial support from NASA's Project NOVA and the Louisiana Tech University Center for Entrepreneurship and Information Technology (CEnIT). All of our students are Education majors, most of them are sophomores in Elementary Education.

We have had problems finding material for the course. There are many introduction to engineering books, but most are at too high a math level for our sophomore education students. NASA has much K-12 material, but very little of it emphasizes engineering. Therefore we have had to create most of our material. We have reported on our work at several engineering education conferences.[1,2,3]

The purpose of this project was to create outreach materials for the K-12 classroom that emphasizes what NASA engineers do. Material that has been used for sophomore education majors has been revised to make them suitable for K-12 students. NASA has many excellent educational materials, but most of them emphasize the science aspect of what NASA does. Very few discuss the nature of engineering and how engineers can become involved in the space program.

As a result of this project, six different modules were created. They are:

- What is an engineer and what do NASA engineers do?
- How do NASA engineers
  - solve problems
  - ~~design structures that will be fatigue loaded~~
  - use an understanding of metallic crystal structures in design
  - design to avoid buckling
  - use polymeric materials in space applications

In each of the five modules about what NASA engineers actually do, there are three parts. The first part explains the general problem. The second part gives NASA examples of this problem. To make it appealing to students, many color NASA photographs are used to illustrate the NASA applications. The third part describes student experiments that can be performed to illustrate this topic.

These modules were created in Microsoft Word and can be easily modified into web pages. Not all of the modules will be in this report. This is because some of them use material that has been copyrighted by others. The fair use doctrine would allow me to give these handouts to a small group (such as one class), but not for NASA wide dissemination. If NASA shows an interest in using these modules as part of their K-12 outreach program, then formal permission to use some this copyrighted material will be sought.

Almost all of the experiments have been tried out on groups of students. Several of them were used this summer with 7th and 8th grade students who attended a series of summer camps at Louisiana Tech University this summer on math/science/engineering topics. Modifications were made based on the student responses.

The three modules that did not use any copyrighted material are presented in the following pages:

Module I Engineers and NASA

Module II NASA Engineers and Fatigue

Module III NASA Engineers and Design to Avoid Buckling

Module I

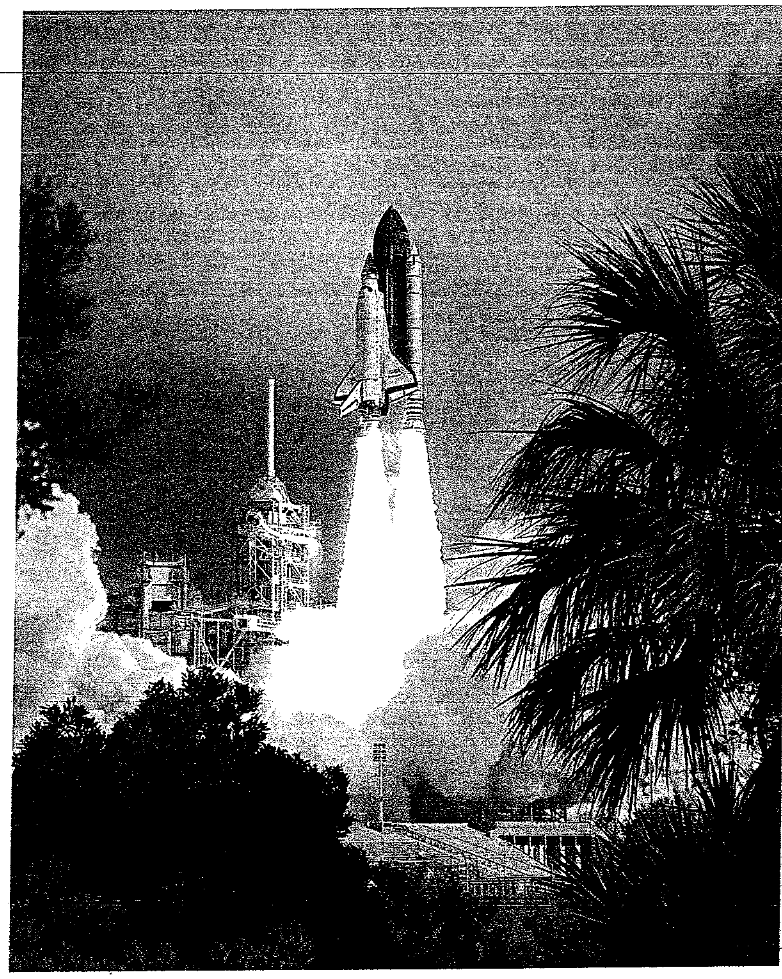
Engineers and NASA

Engineers and NASA

Engineers are different from scientists. Scientists work to discover the basic principles of nature. They can be life scientists who explore the basic nature of life itself. They can be physical scientists who study chemistry and physics to learn how the physical world works. At the most basic level scientists study our world in a systematic manner.

By contrast, engineers use science and human experience to create things. They solve real world problems. They create things that have never existed before. This process of engineering design is at the heart of what engineers do. The American Society for Engineering Education (www.asee.org) defines engineering this way:

> *"Engineering is the art of applying scientific and mathematical principles, experience, judgment, and common sense to make things that benefit people."*



While engineers use science, they also use human experience and judgment. This is because engineers can often discover what works (engineering) before knowing why it works (science). For example the ancient Romans built arch bridges that have lasted until today without knowing strength of materials. Similarly rockets have been used by many societies (for fireworks as well as weapons) long before modern rocket science concepts were discovered. Rocket based fireworks date back more than 1000 years. The British used rockets in their attack on Fort McHenry during the war of 1812--remember the phrase "rockets' red glare" from the United States national anthem.

There are two aspects to design. Most frequently engineers take something that has been made by someone else and make it better in some way. For example, today's automobiles are based on previous automobiles. While each design changes something about the car, the basic principles of how a car works remain almost the same.

Sometimes engineers design things that have never been built before. An example of this is the Space Shuttle orbiter. Before it was designed, no one had ever built a reusable space vehicle. While previous rocket designs were of some use, the basic concept was so different that many challenges had to overcome. For example, new heat resistant materials had to be created. The ones used on previous space craft were designed to partially or totally burn up during re-entry. New materials had to be created that could withstand the heat of re-entry over and over again.

Why would you want to become an engineer?

There are probably as many reasons as there are engineers. In his book *Studying Engineering*, Raymond Landis listed the following top ten reasons for becoming an engineer:

1. Job satisfaction
2. Variety of career opportunities
3. Challenging work
4. Intellectual development
5. Potential to benefit society
6. Financial security
7. Prestige
8. Professional environment to work in
9. Technological and scientific discovery
10. Creative thinking

While most engineers earn a nice upper middle class income (starting salaries in 2003 are typically over $50,000 per year), money is not the main reason most engineers become engineers. We typically become engineers because we find it to be enjoyable and challenging. The good income is nice, but not the main benefit.

How can I prepare to be an engineer?

Engineers are people who enjoy science and mathematics. If these subjects are fun for you, then engineering may be a real possibility. You would need to take as much math and science as you can while in school. In high school you should take math through algebra and trigonometry. If you can take some calculus, that would be really nice, though it is not necessary to get into an engineering college. You should take both physics and chemistry. A course in computer applications would be useful, since most engineering courses require the use of computers to solve problems and write reports. Since engineers do some work in other countries at some point in their careers, classes in foreign languages would also be useful.

What different types of engineers are there?

There are many types of engineers. The four largest groups of engineers are shown below. The descriptions of each type of engineer are adapted from the excellent ASEE web site www.asee.org/precollege.

- Electrical engineers

  ~~This is the largest engineering discipline. Electrical~~ engineers design tools, machines, and processes that use electricity. This can include something as large as an electrical power plant and as small as the small chip this is the central processing unit in your computer.
- Mechanical engineers

  Mechanical engineers use mechanics and energy principles to design machines such as engines and motors. Most machines that make other things were designed by mechanical engineers. Mechanical engineers would design most of the components in automobiles and many of the components of airplanes and rockets. Mechanical engineers also design such things as furnaces and air conditioners.
- Civil engineers

  This is the oldest engineering discipline. They design such things as bridges, roadways, dams, and airports.
- Chemical engineers

  Chemical engineers deal with the processing and treating of liquids and gases. Many chemical engineers work in the petroleum refining industry. Chemical engineers have developed many of the plastic materials we use today.

There are many other types of engineers. The web site by the National Society of Professional Engineers (www.nspe.org) contains references to many other types in their section for students. Among these engineers, types that are very important to NASA include:

- Aerospace engineers

  Aerospace engineers design and develop technology for commercial aviation, military aviation, and space exploration.
- Industrial engineers

  Industrial engineers help to organize the people, information, energy, and machines involved in production. They help to make manufacturing more efficient.

What can these different types of engineers do at NASA?

Many of the things that NASA builds are so complex, they require large teams of engineers. Engineers from many different backgrounds work together to make sure that a given space hardware works properly. The different types of engineers work together to solve these problems, they do not just work with engineers of the same background.

The most obvious type of engineer that NASA employs is the **aerospace engineer**. Many aspects of space flight are the specialty of this type of engineer. However, many NASA engineers are not aerospace engineers.

Many of the internal parts of NASA's rockets and space ships are designed by **mechanical engineers**. For example, how the parts of the space shuttle orbiter and the International Space Station dock together is a mechanical engineering problem.

There are many electronic components within the space shuttle orbiter as well as satellites. These would be designed by **electrical engineers**. **Chemical** and **mechanical engineers** would be involved with the design and operation of the Space Shuttle Main Engine.

Designing and building complex space objects is very difficult. For example, the International Space Station is the most expensive (and probably most complex) structure ever built. Assembling it in space even adds to its difficulty. Starting back in the 1960's NASA had to create new ways of organizing the work on very large and complex projects . This pioneering work was done by **industrial engineers**. Industrial engineers continue to work on the problem of organizing how to design and build such complex pieces of equipment.

Module II

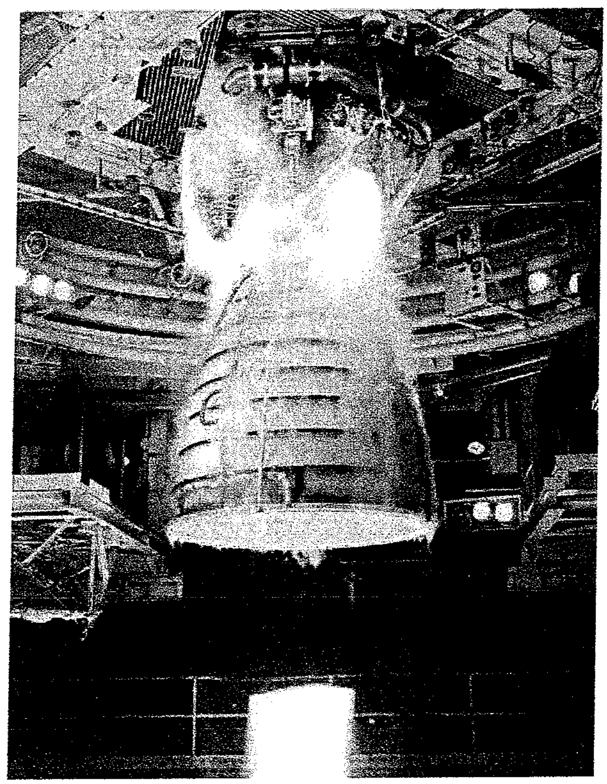
NASA Engineers and Fatigue

NASA Engineers and Fatigue

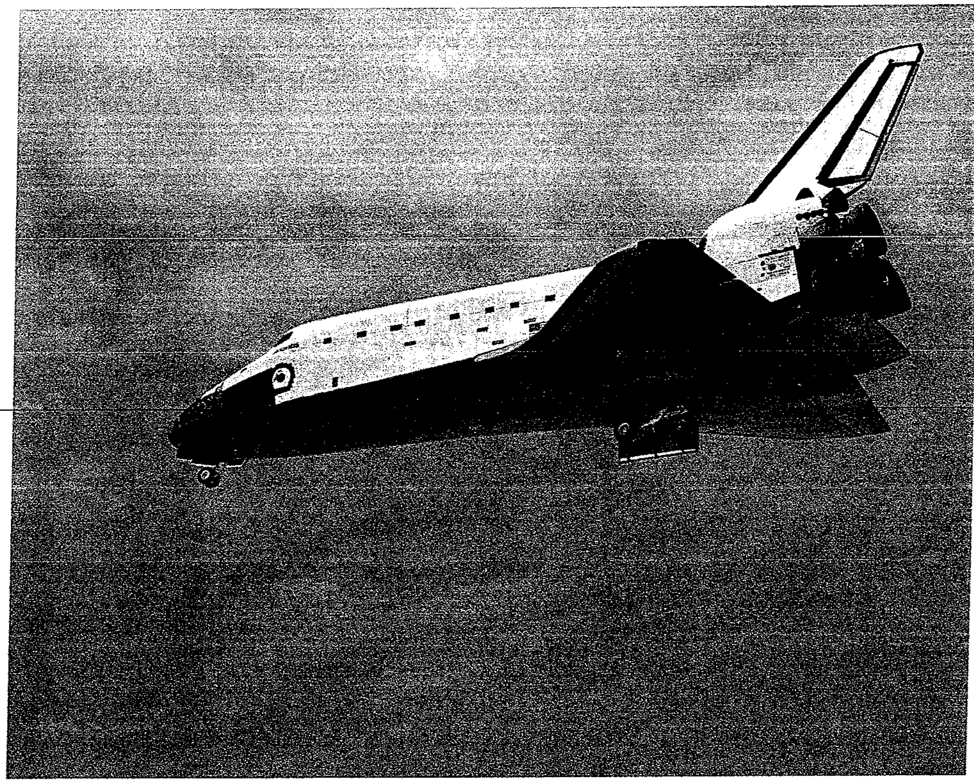
When a material has been repeatedly loaded, it may fail at stresses far below its ultimate tensile strength. This is referred to as a fatigue failure. Later on we will illustrate this by doing a fatigue experiment using paper clips. Opening and closing a paper clip once will not significantly damage it. However, if you do this a number of times, the paper clip will eventually break.

Many machines will put fatigue loading on a part. For example, every time a wheel rotates on a car, its axle is fatigue loaded. The top surface of the axle is loaded in compression (it is being pushed together), while the bottom surface is loaded in tension (it is being pulled apart). For cars, the axles must be able to withstand millions of cycles. For a typical car to travel 100,000 miles the axles will rotate more than 50,000,000 times.

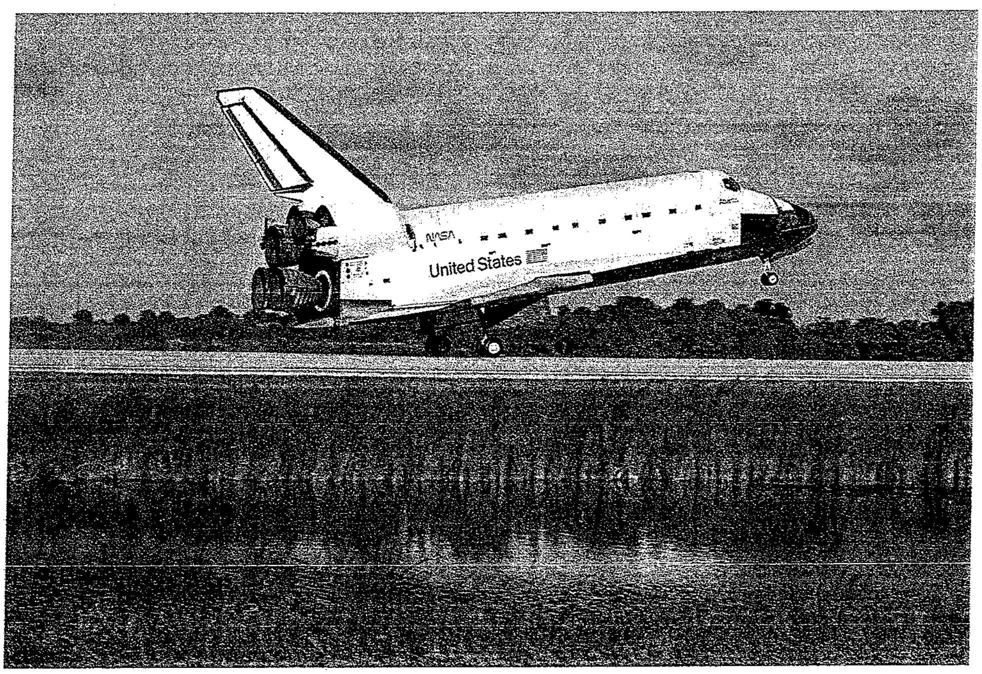
NASA has to deal with fatigue in many locations on its space vehicles. For example, consider the Space Shuttle Main Engine, which is shown to the right during a test. Each time the engine is turned on, parts of it get very hot. However, the inside surface of the engine gets hotter than the outside surface. This temperature difference produces what are called thermal stresses. Therefore each time the engine is used, there are thermal stresses being created. Each engine use can be considered to be one cycle of fatigue loading. This is an example where the fatigue lifetime does not have to be very large. Each engine would only be used a relatively small number of times before it was replaced.



However, there are other times when NASA needs to have a part withstand many more cycles. An example of this is the landing gear of the Space Shuttle Orbiter. The landing gear is shown in the photograph below. In this photograph, the nose landing gear has been lowered, but the rear landing gear doors have opened and the landing gear itself has just begun to be lowered.



A view of the orbiter just before landing is shown below. In this photo, the landing gear has been fully lowered and the vehicle is ready to touch down.



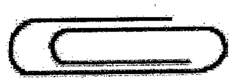
The axles in the landing gear have to rotate thousands of times during each landing. It is important for NASA engineers to make sure that the axle material can withstand this kind of fatigue loading.

Fatigue Experiment

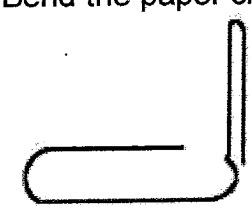
To illustrate the sorts of calculations that NASA engineers must perform, we will do a simple fatigue experiment. This would be well suited for a class of 20 or more students. It can be done individually if the student has at least twenty paper clips. To illustrate the differences in fatigue behavior of different materials, it would be good to test at least two different types of paper clips.

Each person in the class will need to obtain samples of each of two sets of different types or sizes of paper clips. Each person will bend his or her paper clip and count the number of bends required to break each paper clip. In order to assure that each person bends the paper clip and counts the number of bends the same, follow the following instructions.

Start with the paper clip as shown:

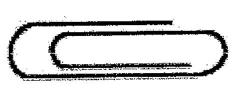


Bend the paper clip:



Bend until the paper clip is fully extended:

Bend the paper clip back:



When the paper clip returns to original position this constitutes one bend.

Each student is to obtain two different sizes of paper clips. The student should fatigue until failure 2 paper clips of each size. The number of cycles to failure for each clip should be recorded.

Students will note that not all paper clips broke with the same number of cycles. This is common when mechanical testing of materials. We therefore need to develop some way to represent the data so that it can be more easily interpreted.

Fatigue Experiment Data Analysis

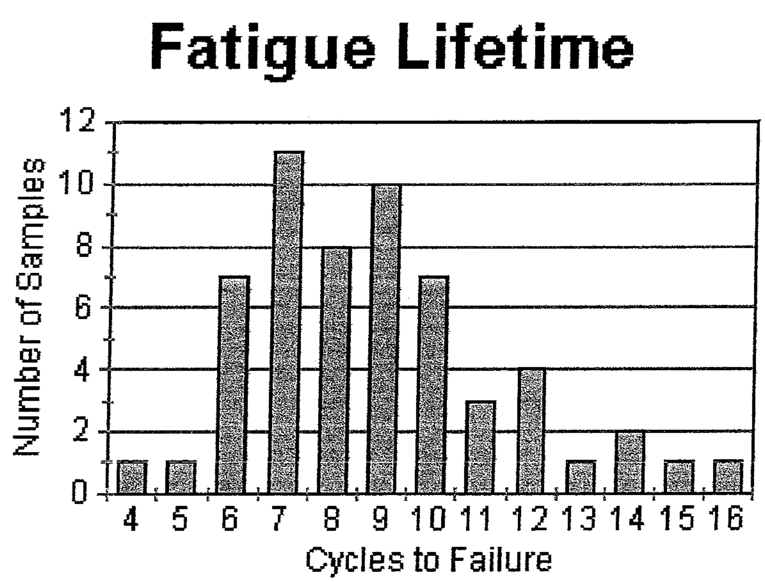
Data analysis will presented at different levels.

Elementary Students

Students should sort the list and rewrite it from the smallest number to the largest number. Note whether or not many of the numbers are very similar. Try to determine which number you think is the best number to use for fatigue life.

Middle School Students

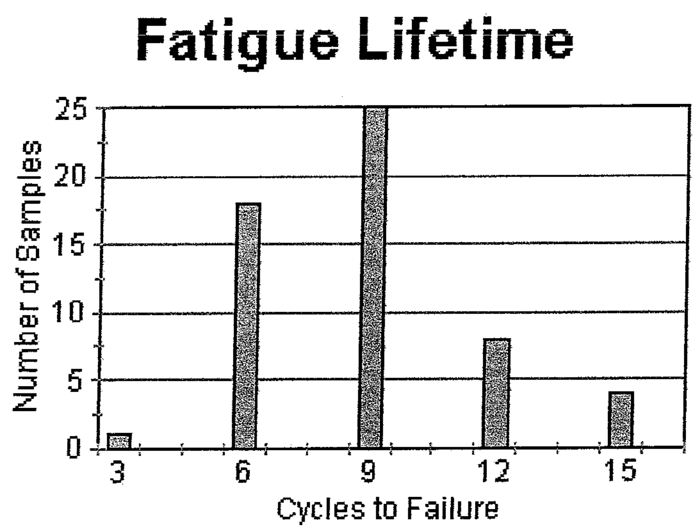
Students should use a graph to represent the data. To create a useful plot, you will first need to sort the data to determine how many samples failed at each number of cycles. Sometimes you can then plot this data directly in a bar chart as shown to the right from another fatigue experiment. This shows that most of the paper clips failed in the range of 6 to 10 cycles.



Sometimes you have too many data points to put on one bar chart. One way to deal with this is to group the data before you plot it. This is shown in the figure below which is based on the same data as shown above. In this example, we broke the data into five groups and counted how many samples in each group.

Group 1	from 2 - 4 cycles to failure
Group 2	from 5 - 7 cycles to failure
Group 3	from 8 - 10 cycles to failure
Group 4	from 11-13 cycles to failure
Group 5	from 14-16 cycles to failure

If you have twenty to thirty samples it would probably be useful to break the data into five groups.



High School Students

As a preliminary analysis of data, students should perform the graphing analysis mentioned above for middle school students.

In addition, students should perform some statistical analysis. There are three numbers that are commonly used to represent typical data. They are the mean, the median, and the mode.

Mean

The mean is the average of the data. Add up all of the cycles to failure for a given paper clip and divide by the number of samples.

Median

The median is the middle number. Students should sort all of the data from the highest to the lowest. The median is the middle number in that list. If there is an even number of samples, then the median is the average of the two middle numbers

Mode

This is the most common number.

The reason all three numbers may be used is that only one of them might not be a good representation of the typical results. For example, let us assume that a student did seven fatigue tests, and had the following results:

5	7	6	8	36	9	6

This data would have the following results.

Mean	11
Median	7
Mode	6

It is clear in this case that the one very high number distorts the results. The mean number is higher than all but one of the actual data samples. The median number of 7 or the mode number of 6 better represents the data in this example.

Examining the scatter in the data

Another issue is how much scatter there is in the data. This can be shown by the two data sets shown below.

Clip #1	3	4	5	6	7	8	9	10	11
Clip #2	1	1	2	2	7	12	12	13	13

Both of these sets have the same mean (7) and the same median (also 7). However there is much more scatter in the data of the second set of data.

This scatter can be estimated graphically by observing how many data points are on each side of the typical value (see plots done in middle school section). This scatter can also be represented by something called a standard deviation.

In this analysis we are trying to determine how far away each actual value is from the mean. Since a value that is below the mean by a certain distance has the same "error" as the one that is above the mean by the same distance, we cannot just average the distances away from the mean. What we will do is average the square of the distances away from the mean.

The following table from an Excel spreadsheet shows how this calculation can be done.

Paper Clip #1

Cycles to Failure	**Mean Value**	**Distance from Mean**	**Squared Distance from Mean**
3	7	-4	16
4	7	-3	9
5	7	-2	4
6	7	-1	1
7	7	0	0
8	7	1	1
9	7	2	4
10	7	3	9
11	7	4	16
Mean	Total		60
7			
	Number of data points		9
	Variance (total divided by N-1)		7.5
	Standard Deviation (square root of variance)		**2.74**

Paper Clip #2

Cycles to Failure	**Mean Value**	**Distance from Mean**	**Squared Distance from Mean**
1	7	-6	36
1	7	-6	36
2	7	-5	25
2	7	-5	25
7	7	0	0
12	7	5	25
12	7	5	25
13	7	6	36
13	7	6	36
Mean	Total		244
7			
	Number of data points		9
	Variance (total divided by N-1)		30.5
	Standard Deviation (square root of variance)		**5.52**

There are Excel functions that will automatically determine the mean, mode, and standard deviation without having to sort the data. The above analysis was shown to demonstrate the principles involved. In real world situations, most engineers will use some computer software that will directly make these calculations.

Approximately 2/3 of the data can be expected to be in the range of plus or minus one standard deviation from the mean. This means that for the two paper clips in question, about two thirds of the data would fall in the following regions:

Paper clip #1	4.26—9.74
Paper clip #2	1.48—12.52

Clearly, we know the results for paper clip #1 much more precisely than we do for paper clip #2.

The smaller the standard deviation, the more precisely we know the typical value of a given experiment. Standard deviations can usually be made smaller by conducting more tests. If the tests are time consuming, then this may not be possible. Better control of the quality of the part being tested can also reduce the error. Sometimes large standard deviations can come from not doing the experiments carefully enough. This is very likely the case in these paper clip tests as different students do not perform the test exactly like some of the other students.

Module III

NASA Engineers and Design to Avoid Buckling

NASA Engineers and Design to Avoid Buckling

When engineers design components of space vehicles, they need to make sure that the parts will not fail due to the physical loads that are placed upon them. When loads are applied to a solid, the solid will deform. The larger the load, the larger the amount of deformation.

If a load is acting to pull a round cylinder apart the cylinder gets longer and narrower. This is called a tensile load. If the load is pushing the cylinder together, it gets shorter and wider. This is called a compressive load.

It might be expected that the same load would damage a smaller material more than it would damage a larger material. Therefore, we would like to introduce a concept called stress. If you take the force on a round cylinder and divide it by its area, you would get the stress that is on the cylinder. This is shown in the equation below.

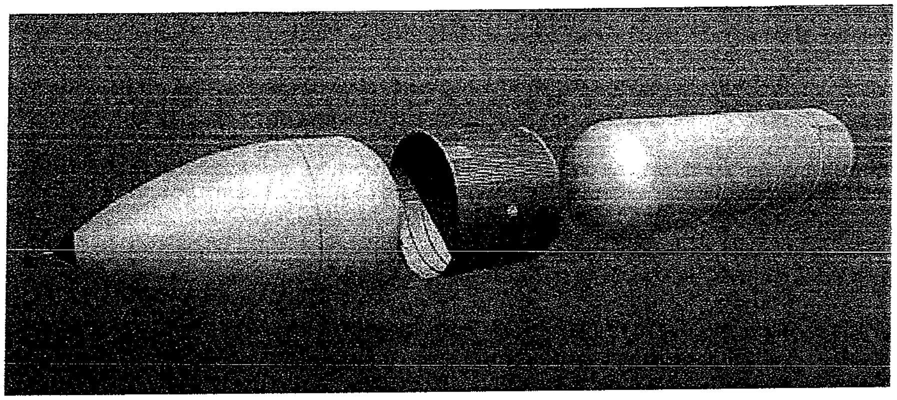
$$\text{Stress} = \sigma = \text{Load} / \text{Area}$$

Engineers frequently use Greek letters to represent various terms. In this case, the Greek letter σ (sigma) is used to represent stress. Stress has units of force divided by area. In the English system commonly used in the United States, this would be pounds per square inch. It is commonly abbreviated psi. In the metric system (called by engineers the SI system) it would be newtons per square meter. This is commonly referred to as a Pascal (abbreviated Pa).

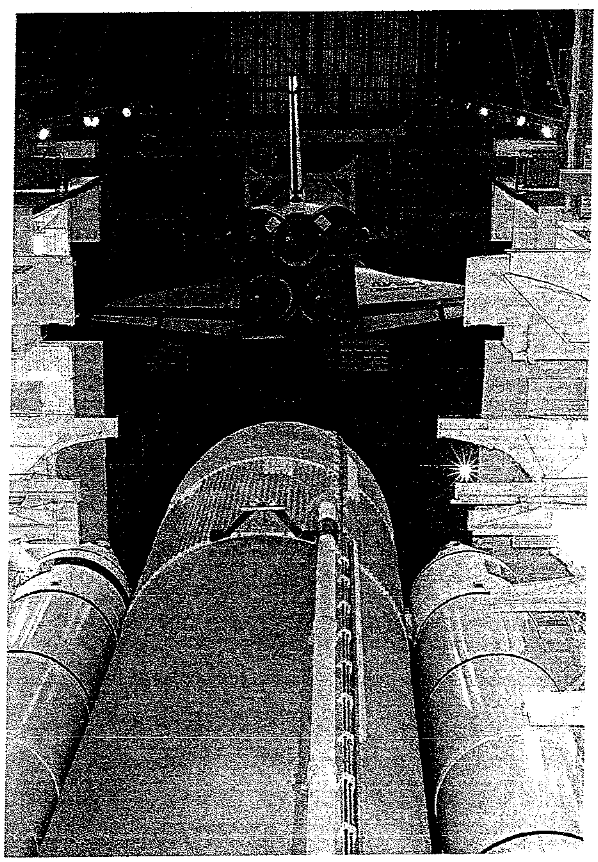
Engineers can load a sample until it fails in tension, and then calculate its strength. However, when dealing with compressive loads there is an additional issue. Structures that are tall and thin will fail at stresses below their strength level. This is because of something called buckling. When a part buckles, it no longer can hold the load that is placed upon it. However, it does not have to break into pieces as might be expected if the strength had been exceeded.

Buckling and the Space Shuttle

There are several places in the space shuttle system where buckling might occur. One location where this plays a major role in the design process is in the design of the space shuttle external tank. The external tank is a thin walled structure that in turn contains two other tanks. One of them contains liquid hydrogen and the other one liquid oxygen. This is shown in the drawing below.

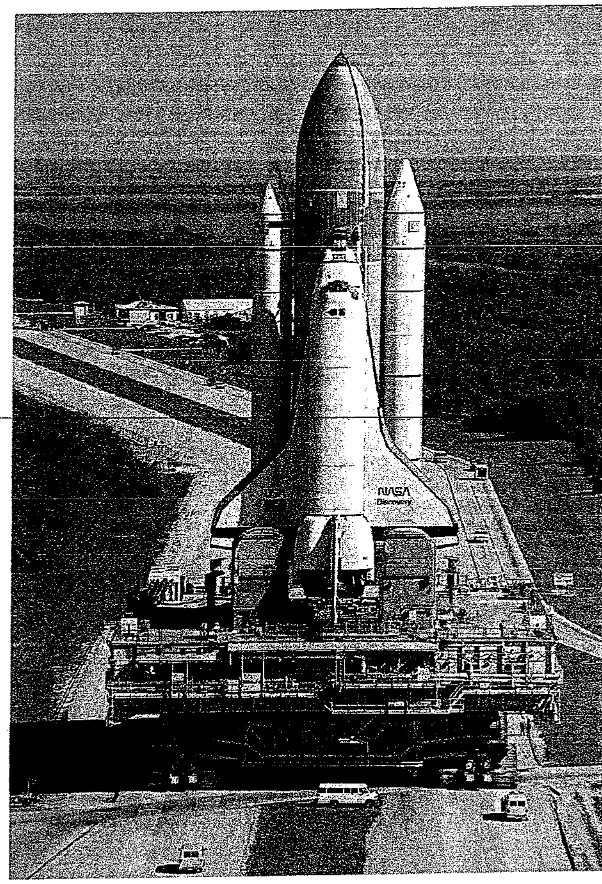


The overall outside wall of the tank provides the support for these internal tanks. The space shuttle orbiter and the two sold rocket boosters are hung on this tank during the setup of the system. The external tank provides the backbone support for the entire system. So this thin walled cylinder has to hold its own weight, the weight of the hydrogen and oxygen gases, the weight of the orbiter, and the weight of the two solid rocket boosters. It is therefore very important that the engineers design a structure that will not buckle under these loads.



The photo to the left shows the external tank with the solid rocket boosters already attached. The orbiter is about to be attached. This procedure is called mating of the system

When the entire system has been mated, then it is rolled out to the launch pad, using the crawler. This is shown below.



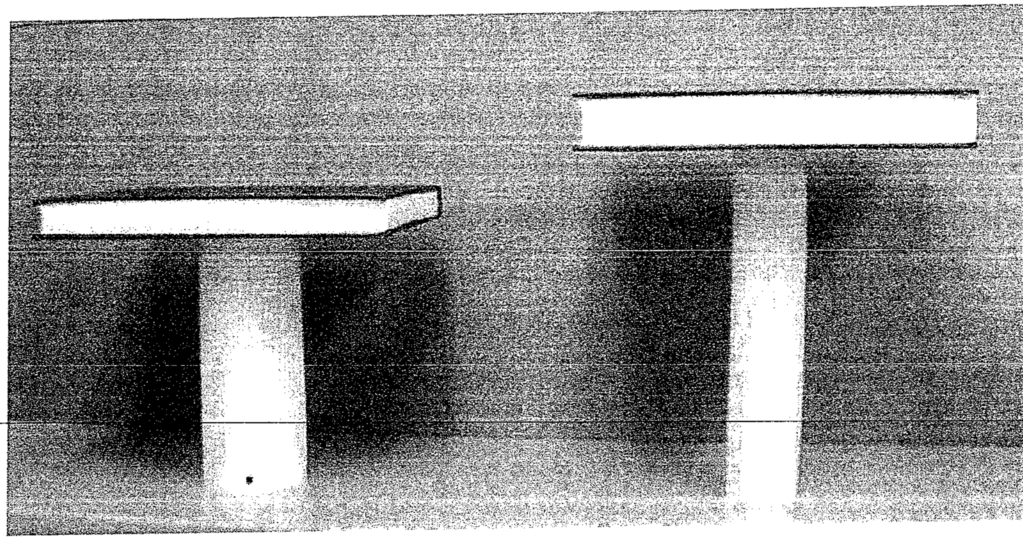
To illustrate some of these issues, we will describe two different student activities where buckling issues are involved.

Buckling Experiment

To illustrate the concept of buckling each student will need the following:

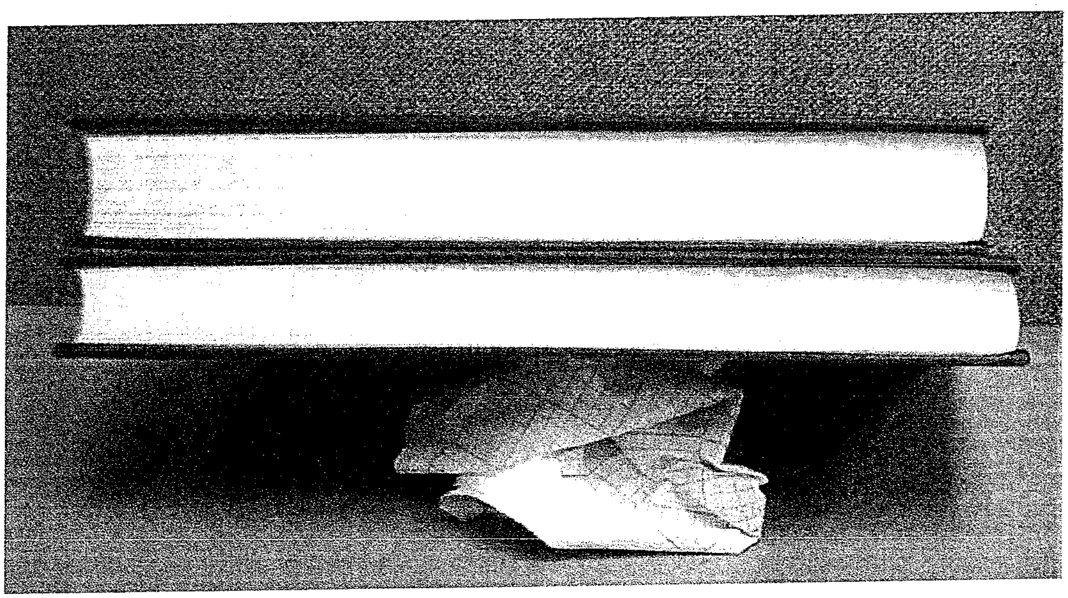
- 10 pages of paper (preferably 8.5 in by 11 in)
- Adhesive tape (or glue)
- Some heavy objects to test the system (a couple of text books will do)

Take five sheets of paper and roll them up lengthwise (to form a cylinder that is 11 inches long). Tape the ends of the paper together form the cylinder. Then take the remaining five sheets of paper and roll it up in the other direction to form a cylinder that is 8.5 inches long. These will be the two structures that we will test for buckling. See photo below for an example of this.



Before the experiment is performed, each student should think through which of these two cylinders will hold up the most weight. Write down your prediction.

Now take one of the cylinders and carefully place on its top one of your textbooks. Did it hold up the weight? If it did hold up the weight, carefully add additional books until you get to the point where the system buckles. When it buckles, note what happens. A buckled column is shown below.



While the paper may be damaged, it is has not broken into pieces. This is because while the buckling load was obtained, the intrinsic strength of the paper was not reached.

Now complete this experiment with the other cylinder.

Which cylinder held up the most weight? Was your prediction correct? Why or why not?

This experiment can be modified by using smaller books. This would result in a higher and more impressive looking pile before it buckles. Students could also modify this experiment by using more sheets of paper, or a different type of paper.

The actual loading on the external tank is much more complicated than just putting forces on the end of it, as we have done in this experiment. However, this experiment shows some of the issues that engineers have to deal with when designing the external tank.

Design of straw structure

Another illustration of this buckling issue can be demonstrated by having a contest between several teams to build a structure using plastic straws.

Each team would need to be provided the following items. Only these items can be used in the design.

- Several boxes of plastic straws. Boxes that contain straight plastic straws can be purchased at most paper supply companies. Care should be taken to make sure that the straws are straight (not the ones designed to be bent). Three boxes of straws (with 250 in each box) work well for a contest that will last about 30 minutes. A longer timed contest could require more straws.
- Something to attach the straws to each other. We recommend masking tape.

No other objects can be used in the contest.

The design contest leader needs to make several choices about the rules:

- Can the boxes be used as well? We have usually allowed them, but not announced this, to encourage students to think through the statement that they can use only what has been provided to them.
- Can the structures be attached to anything (floor, table, wall, or ceiling)? The contest rule on this should probably be announced at the beginning of the contest. When we have not forbidden it, we have had students use parts of the floor, table, wall, and ceiling in their design. We suggest that walls and ceiling be forbidden, but attachment to the floor or table allowed.

When we did not forbid using the ceiling, we have had students attach a tape up to the ceiling to provide additional stability.

- How long will the contest last? The longer the time, the taller the structures can be.
- How many team members? More team members can lead to a taller tower, but this is not always the case if a large team does not work well together.

The goal is to design the tallest tower in a limited time. The tower must be able to hold up something without collapsing. Small soccer balls work well with this. A smaller object (like a tennis ball) would provide an additional challenge as the teams need to figure out a way to hold the ball without it slipping entirely through the structure.

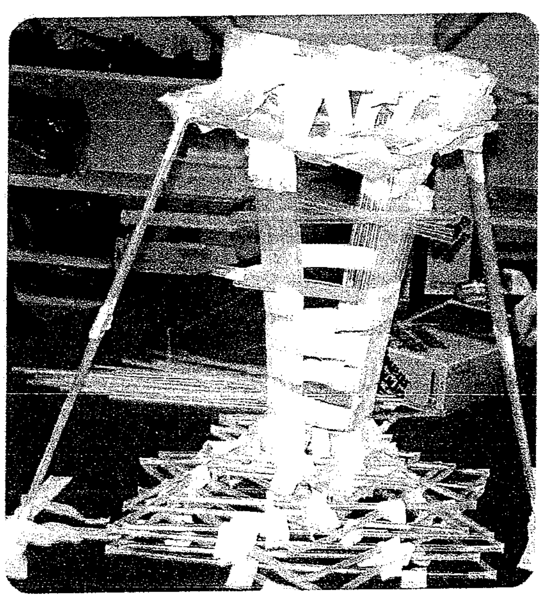
The winning team is the one that is the tallest structure that still holds up the ball.

This contest can illustrate several important design issues:

- These structures will probably fail by some part of them buckling, rather than breaking into two pieces.
- Students will learn something about which shapes are more stable than other shapes
- Students will gain practice with working in teams.

Examples of designs that have been made by college sophomore education majors are shown below.

Some students are very conservative in their design. They want to make sure that their designs will work. Two examples of this are shown below.



Some groups are very aggressive and will take advantage of all possibilities. The figure shown to the right illustrates this. When we did this contest we did not forbid anchoring the structure to other parts of the room, so these students anchored it to the ceiling. They had to climb on top of the table to accomplish this. While this group was very creative, we recommend that you do not allow ceiling or wall anchoring, for students might get hurt climbing onto things to accomplish this. However, since we did not forbid it in this particular contest, this group was allowed to win with this design.

Conclusions

Six modules have been created that can be used in outreach to introduce engineering to K-12 students and their teachers. All of them are in essentially final form as documents. Some copyright permissions are needed before three of them can be distributed NASA wide.

These documents can be modified to be on line documents. This would take some additional work.

~~Additional modules can be created. There was only time to create six modules~~ during this summer time frame.

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References

[1] Jordan, W., Silver, D., and Elmore, B., *Using Laboratories to Teach Engineering Skills to Future Teachers*, presented at the ASEE annual meeting, Albuquerque, June 2001. In CD based *Proceedings* (no page numbers).

[2] Jordan, W., and Elmore, B, *Report on our Problem Solving in Engineering Science Course*, presented at NASA Opportunities for Visionary Academics (NOVA) Leadership Development Conference (LDC), Greenbelt, MD, March 2002.

[3] Jordan, W., and Elmore, B., *Introducing Materials Science and Chemistry to the K-12 Community*, presented at the A.S.E.E. Annual Meeting in Nashville, June 2003. In CD based *Proceedings* (no page numbers).