# MSET Demonstration Package

Buckling

## Mentis Sciences Education Toolkit Vision and Development History

Located in the historic Mill District of downtown Manchester, Mentis Sciences is an engineering firm which provides advanced material design and manufacturing capabilities to Department of Defense customers. Mentis specializes in the design, development and testing of advanced composite materials with a goal of providing unique flexibility, rapid development and prototyping for various composite applications.

Mentis Sciences, Inc. was founded in 1996 by John F. Dignam, following more than thirty years of service at the Army Materials Research Lab, where he served as the Director of Missile Materials. John F. Dignam spent most of his lifetime promoting national security and developing the most effective material systems to aid in countering global threats. He founded Mentis Sciences to continue promoting innovation, expertise, and emerging materials and manufacturing technologies, that will enhance U.S. security and promote economic growth.

His legacy continues under the strong and visionary leadership of John J. Dignam, who brings unique and innovative technical expertise to solving some of the nation's most daunting engineering challenges. The core values of ethics, integrity, community service, and commitment to excellence instilled by John F. Dignam live on with John J. Dignam and the Mentis team, and are apparent in every aspect of the company's structure, personality, and operations.

Mentis Sciences Internship Program recruits local high school students in good academic standing who reside in the HUBZone area of Manchester, NH. Successful youth with good attitudes and high motivation to work and learn have come through various avenues including non-traditional avenues like the Manchester Police Athletic League, The Salvation Army, and Manchester's Office of Youth Services.

Mentis makes a serious commitment of its resources to support the internship program by providing short courses in STEM related disciplines, student engineering activities and mentoring activities. In result of these courses, Mentis Sciences started to see a gap in STEM education. Biology and Life Science concepts were often the focus of science in the classroom, technology often included a smartphone app and engineering was nonexistent. Our interns and every student deserve to be introduced to STEM concepts with tools and resources that allow them to experience concepts hands-on and in a collaborative environment.

With this vision for our students, Mentis transferred skills used in their own manufacturing facility every day and descaled the concepts and tests into one integrated unit. Mentis has developed an integrated STEM toolkit that configures to complete 40 STEM tests. With limited lab space and budgets for lab testing equipment being tight, the Mentis Sciences Engineering Toolkit (MSET) departs from the high cost limited functionality of current educational testing systems.

The MSET offers a unique view into the world of material testing and physical science. Data indicates the MSET Program increased student participation in the classroom, interest in STEM careers and opportunities for females in STEM. Students develop a deep understanding in STEM, engineering and physical science concepts.

In many ways, the internship program and new shared vision has provided Mentis employees a new sense of purpose in their work. Mentis is now expanding their vision for the MSET program, beyond their own interns and are offering the MSETs STEM educational opportunities to other schools and educational partners in their community and around the United States.

Mentis believes that every student, no matter their upbringing or education status, should have the opportunity to learn, pursue their dreams and have the high-quality resources to so. This enrichment MSET program has proven to be beneficial, providing life-changing experiences for interns, students, as well as Mentis employees. We are excited to share it with you.

# Buckling Introduction

In this unit students will explore the buckling properties of various length columns and apply engineering principles to determine the relationship between the materials elastic modulus, length of the column and how the column is orientated. Students will record and process the data from the experiment and use provided equations to develop the stress caused by buckling. The goal of this exercise is to prepare students and apply these concepts in an inquiry-based project where they design a structure.

The materials in this section have been created and organized to assist teachers in the design of lessons that use the MSET equipment and applied inquiry-based projects that are aligned with the Next Generation Science Standards, as well as the Massachusetts Science and Technology/Engineering Curriculum Framework.

## Teachers

Teachers should review the Understanding by Design unit plan with particular attention to the Essential Questions students will be expected to answer by the conclusion of the unit. Throughout the lessons and experiences, teachers should assess students' progress toward their capacity answering the essential questions. Finally, teachers should use the rubric to assess students' comprehension and application of the foundational principles associate with the lesson, experiment and materials covered in the unit.

## Students

*It is assumed that students participating in this unit will have experience in the following areas:*

1. The concepts of stress, force, inertia, elasticity, and buckling.
2. Basic knowledge of geometry including concepts such as radius, area, volume, etc.
3. Basic algebra knowledge.
4. Basic mechanical skills to configure MSET based on written and visual instructions.

## Table of Contents

## UbD Chart – Buckling

# Desired Results

### STANDARDS/ESTABLISHED GOALS

**<u>Next Generation Science Standards</u>**

Engineering Design:
HS-ETS1-4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints in interactions within and between systems relevant to the problem.

Forces and Interactions:
HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass and its acceleration.

HS-PS2-3. Apply science and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during collision.

**<u>Massachusetts State Standards</u>**

Technology and Engineering:
HS-ETS1-4. Use a computer simulation to model the impact of a proposed solution to a complex real-world problem that has numerous criteria and constraints on the interactions

HS-ETS3-4(MA). Use a model to illustrate how the forces of tension, compression, torsion, and shear affect the performance of a structure. Analyze

### *Transfer*

Students will be able to independently use their learning of critical load, buckling, and Euler's formula to make relevant decisions when designing a structure using columns.

### *Meaning*

UNDERSTANDINGS
*Students will understand that…*

1. The amount of force compressing a column without buckling or failure is relevant to designing structures, such as buildings and equipment.
2. Critical load of a column depends on elasticity, moment of inertia, and length/slenderness ratio. In order to increase stability, one must either increase its moment of inertia, shortening the column, or using material with more elasticity.
3. Euler's formula is used to calculate the critical load of a column, and that formula utilizes all the factors mentioned in Understanding #2.

ESSENTIAL QUESTIONS

1. How can determining critical load on a column help engineers to design structures?
2. How can a column be made to be more stable and less likely to buckle or fail?
3. How can one calculate critical load of a column and what adjustments can be made to assure stability.
4. How is buckling related to experiments (Experiment #5) that analyze the support span of an object and its effect on deformation of said object?

### *Acquisition*

*Students will know…*

- Buckling is a sideways deflection caused a lack of equilibrium that's a result of compression on an object.
- Euler's Formula

*Students will be skilled at…*

- Use Euler's formula to determine critical load

| | | |
|---|---|---|
| situations that involve these forces and justify the selection of materials for the given situation based on their properties.<br><br>Introductory Physics:<br>HS-PS2-1. Analyze data to support the claim that Newton's second law of motion is a mathematical model describing change in motion (the acceleration) of objects when acted on by a net force.<br><br>HS-PS2-3. Apply scientific principles of motion and momentum to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.<br><br>HS-PS2-10 (MA). Use free-body force diagrams, algebraic expressions, and Newton's laws of motion to predict changes to velocity and acceleration for an object moving in one dimension in various situations. | $Stress_{cr} = \frac{\pi^2 E}{\left(\frac{L}{R}\right)^2}$<br><br>• The terms Moment of Inertia and Elasticity/Elastic Modulus (See Experiment #5, Flexure/3-Point Bend)<br>• Slenderness ratio is a ratio that helps engineers to calculate the effect a structure's width and height have on the possibility that the structure will buckle. | • Apply mathematical computations to mathematical model(s) to calculate various outcomes<br>• Interpret graphs to draw conclusions<br>• Use computer software to collect data and model the deflection in an object as it relates to the support span<br>• Apply the scientific method in an experiment |

## Evidence

### Assessment Evidence

PERFORMANCE TASK(S):

1. Students will use the MSET device to conduct an experiment to plot the force placed on a sampling of columns while being compressed. The plots will help students to determine critical load. Using Euler's formula, students will then calculate the critical load and determine optimal length, etc. of a column for various loads. Students will use this procedure to designing a structure in future lessons.

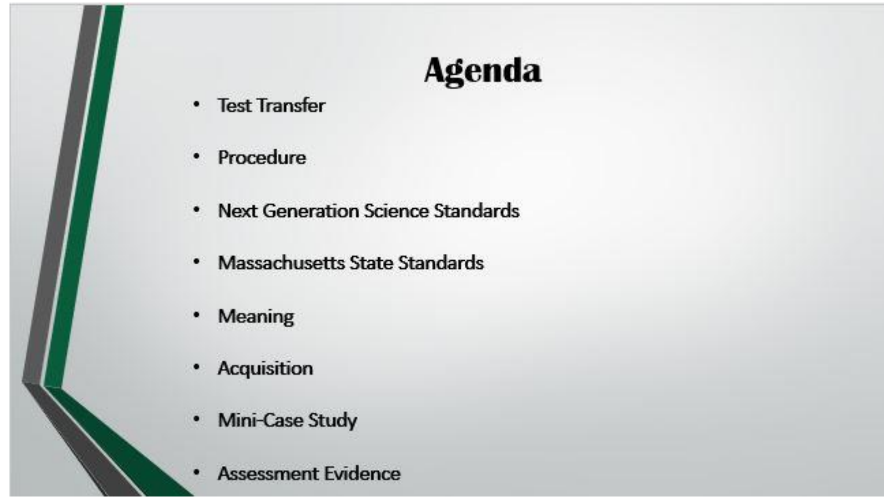
OTHER EVIDENCE:
The essential questions will be used as an entrance/exit slip to determine growth in understanding.

## Stage 3 – Learning Plan

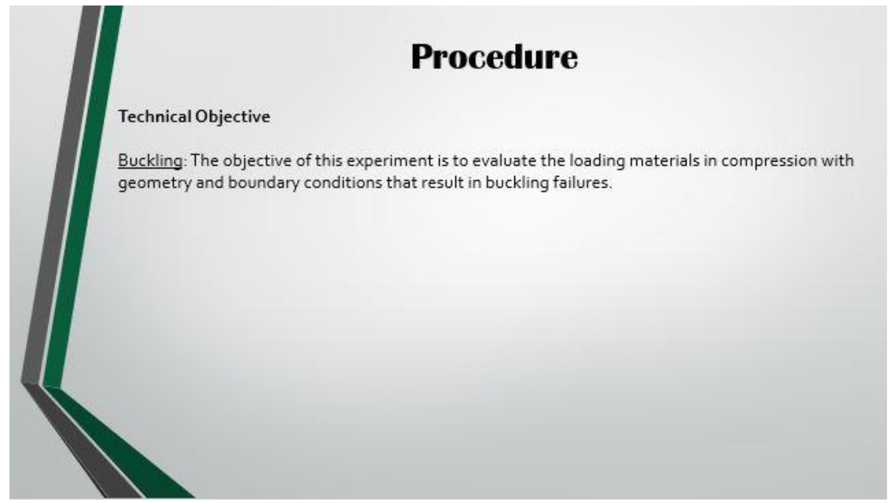
*Summary of Key Learning Events and Instruction*

**See outline of Buckling experiment summary included.**

# PowerPoint Template for Instruction – Buckling





## Procedure

**Approach**

Buckling: In this experiment varying lengths of garolite rods with 1/16″ diameters will be tested under the hinged-hinged condition. Samples will be loaded until they buckle and the critical load recorded. The theoretical critical load will then be compared to the experimental load.

## Standards/Established Goals

### Next Generation Science Standards

**Engineering Design:**

- HS-ETS1-4 Use a computer simulation to model the impact of proposed solutions to a complex real-world problem.

**Forces and Interactions:**

- HHS-PS2-1 Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.

## Standards/Established Goals

### Massachusetts State Standards

**Technology and Engineering:**

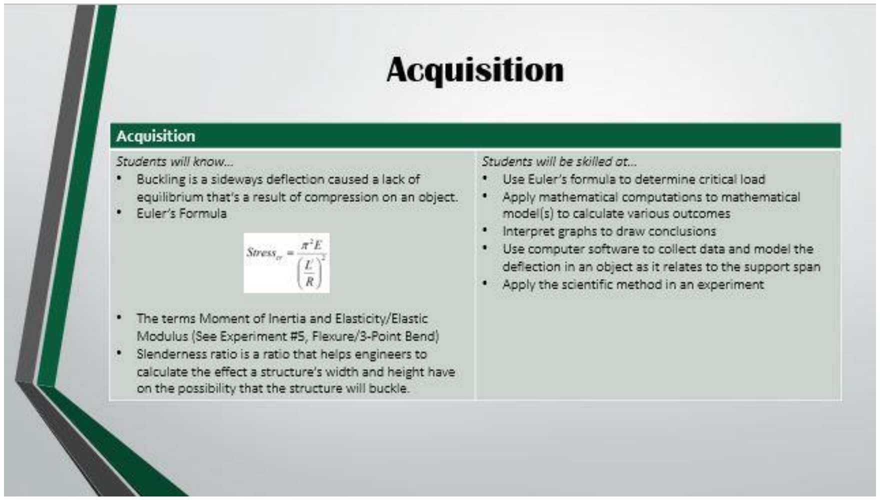
- HSHS-ETS1-4. Use a computer simulation to model the impact of a proposed solution to a complex real-world problem.
- HS-ETS3-4(MA). Use a model to illustrate how the forces of tension, compression, torsion, and shear affect the performance of a structure. Analyze situations that involve these forces and justify the selection of materials for the given situation based on their properties.

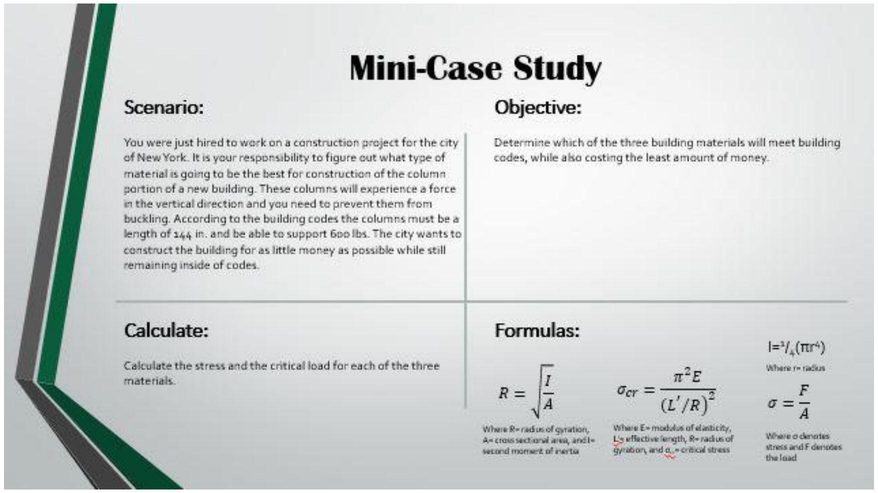
**Introductory Physics:**

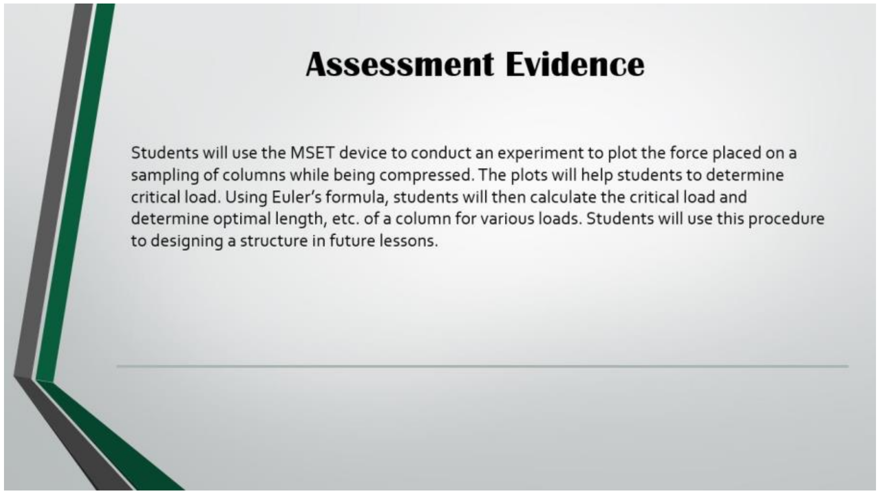
- HS-PS2-1. Analyze data to support the claim that Newton's second law of motion is a mathematical model describing change in motion (the acceleration) of objects when acted on by a net force.
- HS-PS2-3. Apply scientific principles of motion and momentum to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.
- HS-PS2-10 (MA). Use free-body force diagrams, algebraic expressions, and Newton's laws of motion to predict changes to velocity and acceleration for an object moving in one dimension in various situations.

## Meaning

| Meaning | |
|---|---|
| UNDERSTANDINGS:<br>*Students will understand that…*<br>1. The amount of force compressing a column without buckling or failure is relevant to designing structures, such as buildings and equipment.<br>2. Critical load of a column depends on elasticity, moment of inertia, and length/slenderness ratio. In order to increase stability, one must either increase its moment of inertia, shortening the column, or using material with more elasticity.<br>3. Euler's formula is used to calculate the critical load of a column, and that formula utilizes all the factors mentioned in Understanding #2. | ESSENTIAL QUESTIONS:<br>1. How can determining critical load on a column help engineers to design structures?<br>2. How can a column be made to be more stable and less likely to buckle or fail?<br>3. How can one calculate critical load of a column and what adjustments can be made to assure stability.<br>4. How is buckling related to experiments (Experiment #5) that analyze the support span of an object and its effect on deformation of said object? |


Acquisition
Acquisition
Students will know…
• Buckling is a sideways deflection caused a lack of equilibrium that's a result of compression on an object.
• Euler's Formula
$Stress_{cr} = \frac{\pi^2 E}{\left(\frac{L}{R}\right)^2}$
• The terms Moment of Inertia and Elasticity/Elastic Modulus (See Experiment #5, Flexure/3-Point Bend)
• Slenderness ratio is a ratio that helps engineers to calculate the effect a structure's width and height have on the possibility that the structure will buckle.
Students will be skilled at…
• Use Euler's formula to determine critical load
• Apply mathematical computations to mathematical model(s) to calculate various outcomes
• Interpret graphs to draw conclusions
• Use computer software to collect data and model the deflection in an object as it relates to the support span
• Apply the scientific method in an experiment


Mini-Case Study
Scenario:
You were just hired to work on a construction project for the city of New York. It is your responsibility to figure out what type of material is going to be the best for construction of the column portion of a new building. These columns will experience a force in the vertical direction and you need to prevent them from buckling. According to the building codes the columns must be a length of 144 in. and be able to support 600 lbs. The city wants to construct the building for as little money as possible while still remaining inside of codes.
Objective:
Determine which of the three building materials will meet building codes, while also costing the least amount of money.
Calculate:
Calculate the stress and the critical load for each of the three materials.
Formulas:
$R = \sqrt{\frac{I}{A}}$
Where R= radius of gyration, A= cross sectional area, and I= second moment of inertia
$\sigma_{cr} = \frac{\pi^2 E}{(L'/R)^2}$
Where E= modulus of elasticity, L'= effective length, R= radius of gyration, and $\sigma_{cr}$ = critical stress
$I = \frac{1}{4}(\pi r^4)$
Where r= radius
$\sigma = \frac{F}{A}$
Where σ denotes stress and F denotes the load


Assessment Evidence
Students will use the MSET device to conduct an experiment to plot the force placed on a sampling of columns while being compressed. The plots will help students to determine critical load. Using Euler's formula, students will then calculate the critical load and determine optimal length, etc. of a column for various loads. Students will use this procedure to designing a structure in future lessons.

**MSET Experiment Procedure– Buckling**

## Technical objective

The objective of this experiment is to evaluate the effects of loading materials in compression with geometry and boundary conditions that result in buckling failures. Samples of identical properties will be tested at various lengths. As compressive forces are applied, visual inspection of the straightness of each sample will be examined until the sample buckles.

## Background

Materials with an applied compressive load will decrease in size in the direction of the applied load while expanding in cross sectional area as is shown in Figure 1. Although reverse and identical to tensile loading, the amount of force required to cause material failure can be greatly less than that of a tensile loaded specimen. Materials loaded in compression that experience significant lateral deformation (perpendicular to the applied load) are said to have buckled. This is shown in Figure 2.

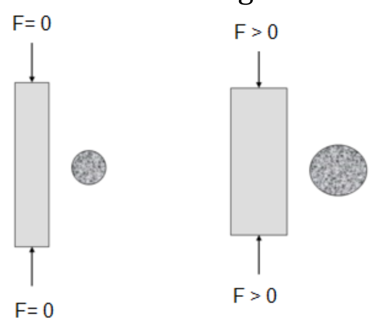



*Figure 1 - Material before and after compressive force is applied*

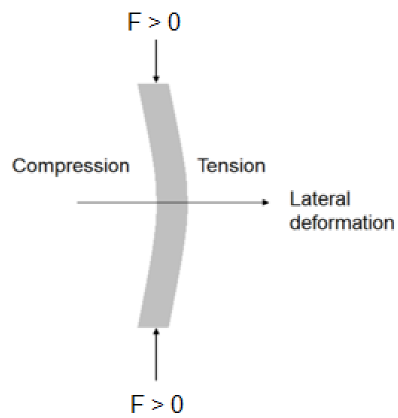



*Figure 2 - Buckling Failure*

As the material is loaded, it is stressed by a magnitude proportional to the force "F" applied and inversely proportional to cross-sectional area "A".

$$\text{Stress} = F / A \qquad \text{eq. (1)}$$

The stress calculated using equation #1 may be accurate for low loads, however the magnitude of stress induced at failure is also a function of boundary conditions, and specimen geometry.

$$Stress_{cr} = \frac{\pi^2 E}{\left(\frac{L'}{R}\right)^2} \qquad \text{eq. (2)}$$

where: E = modulus of elasticity

$\frac{L'}{R}$ = slenderness ratio

Note the "cr" subscript which reflects the fact that relatively slender samples or geometries will experience a stress which will result in a critical failure if reached. The stiffness or modulus of elasticity is a significant factor in the material's ability not to buckle, but as can be seen in equation #2, the slenderness ratio has a major impact on the load carrying capability.

The slenderness ratio can be calculated by determining the effective length which is equal to the specimen's length multiplied by a correction factor. The correction compensates for how the material is mounted at each end. A few correction factors are listed below in Table 1.

| Boundary | Effective Length |
|---|---|
| Clamped - Clamped | 0.5 (L) |
| Clamped - Hinged | 0.7 (L) |
| Hinged - Hinged | L |

*Table 1 - Effective length correction factors*

The term "*R*" is the radius of gyration and is calculated by taking the square root of the moment of inertia "*I*" divided by the cross sectional area "*A*" defined in equation #3.

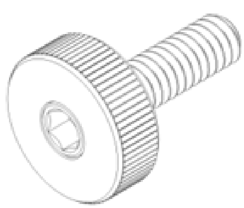
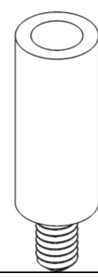
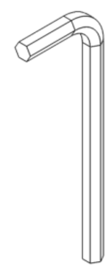
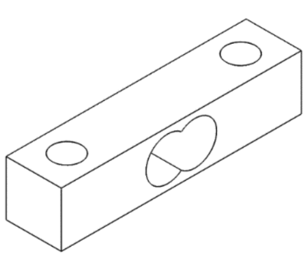
$$R = \sqrt{\frac{I}{A}} \quad \text{eq. (3)}$$

## Approach

In this experiment varying lengths of garolite rods with 1/16” diameters will be tested under the hinged-hinged condition. Samples will be loaded until they buckle and the critical load recorded. The theoretical critical load will then be compared to the experimental load.

## Experiment Setup

1. Gather the following components:

| | | |
|---|---|---|
| ¾” Thumbscrew  | Bucking Cup 2x  | 4mm Hex Wrench  |
| Sample 1  | Sample 2  | Sample 3  |
| 5kg Load Cell  | | |

2. Attach the tower to the base plate as shown in the Quick Setup Guide. **Safety shield must be used for this experiment; it has been omitted from the following illustrations for clarity purposes.**
3. Use the 4mm hex wrench to attach the 5kg load cell to the carriage with the arrow pointing up.

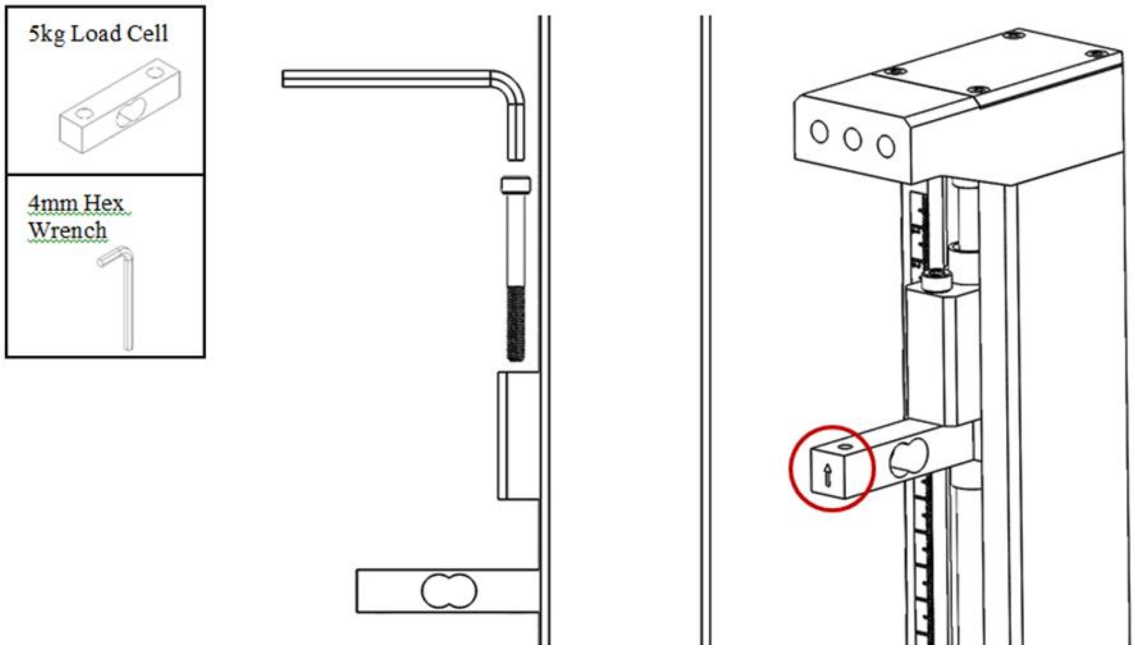



*Figure 3: Load Cell Orientation*

4. Plug the load cell into port 1 at the back of the SIM.

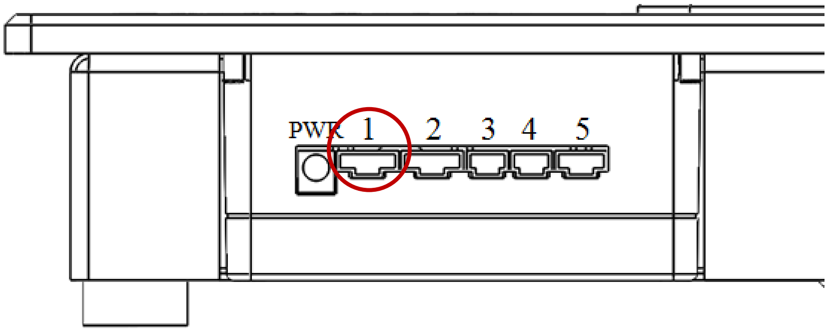



*Figure 4: Port 1 on SIM*

5. Attach one of the buckling cups to the baseplate as shown in Figure 5.

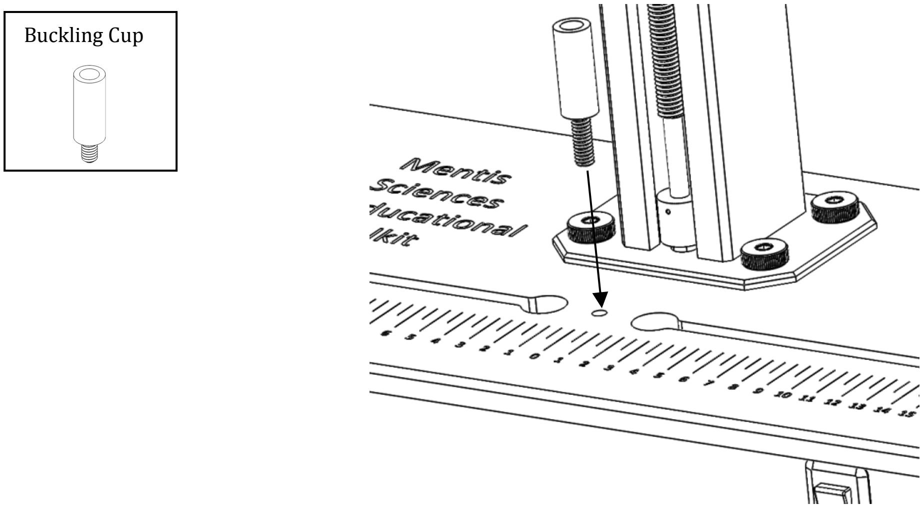



*Figure 5: Placement of Bucking Cup 1*

6. Attach the other buckling cup to the load cell.

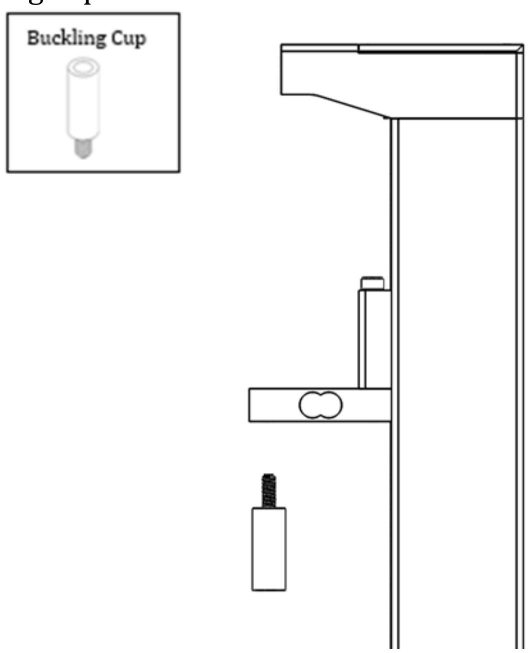
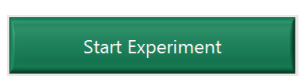



*Figure 6: Placement of Buckling Cup 2*

## Experimental Procedure

1. Put on safety glasses.
2. In the MSET software, click "Buckling" then 

to launch the buckling experiment.

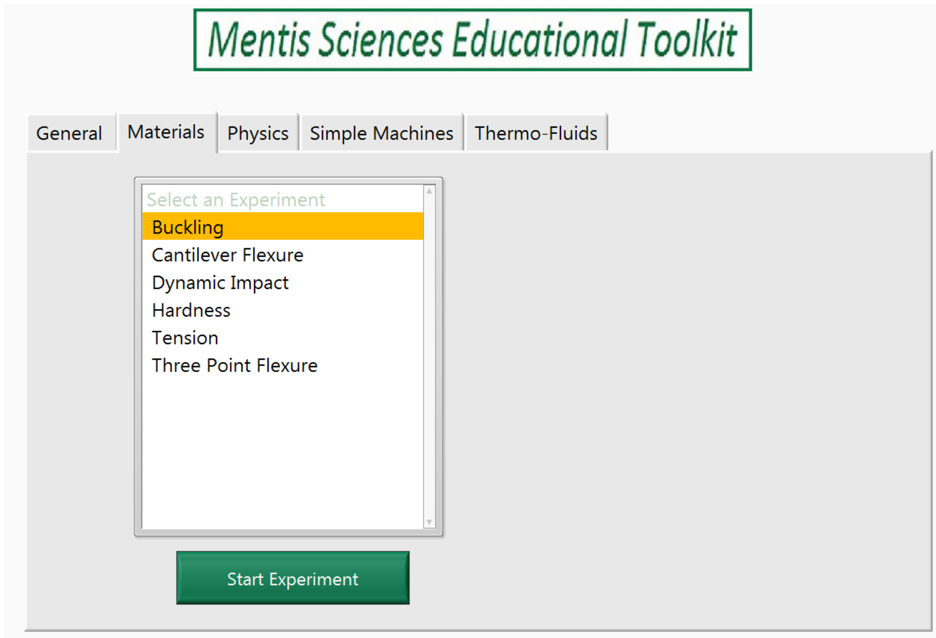



*Figure 7: Location of Bucking Experiment*

3. Choose the 5kg loadcell option on the following screen.

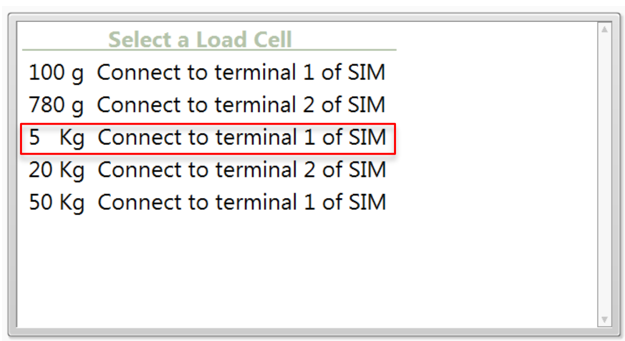



*Figure 8. Loadcell Selection Window*

4. Wait for the program to finish initializing.
5. Set the "Update Time" to 250ms.

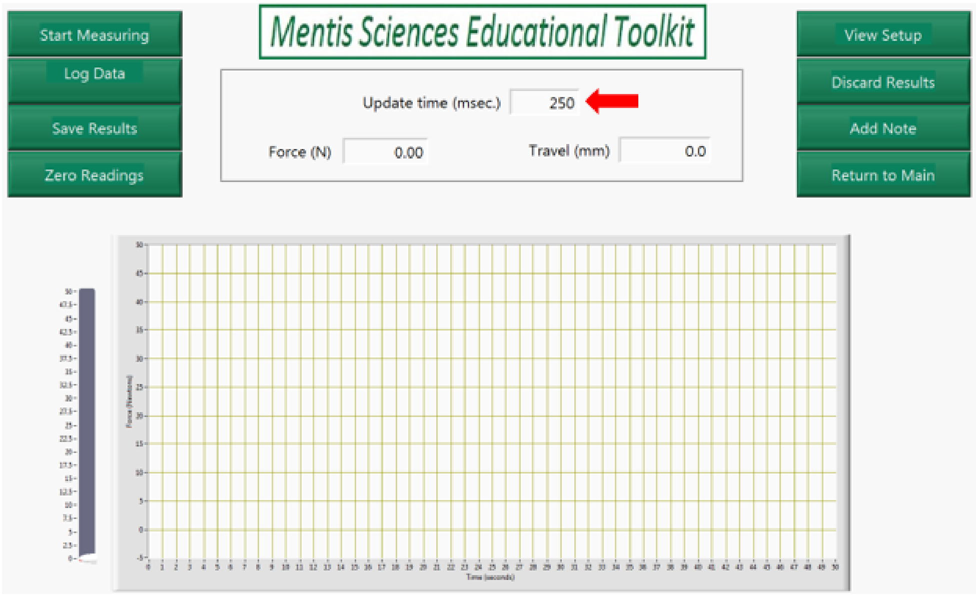



*Figure 9. Buckling Experiment Window*

6. Position the carriage such that its top is level with the 3.5cm mark on the tower scale.

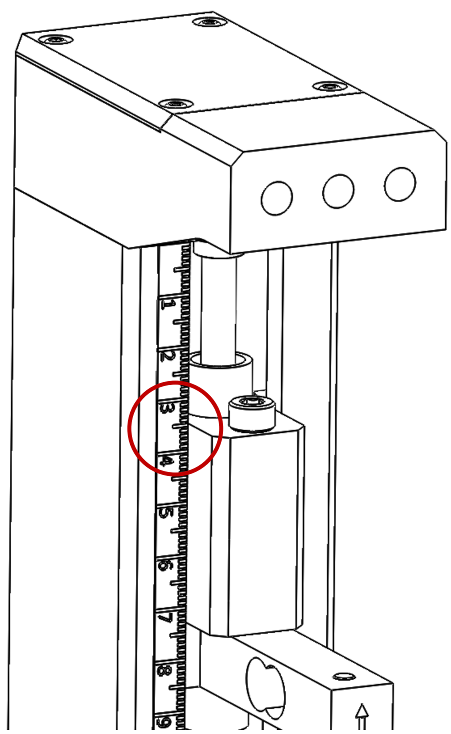


*Figure 10:Carriage Alignment*

7. Place sample 1 in the base buckling cup.
8. With the speed control set to its slowest setting and making sure to guide the top of the sample into the load cell buckling cup, lower the carriage until the top is level with the 5 cm mark to capture the sample in the cups.

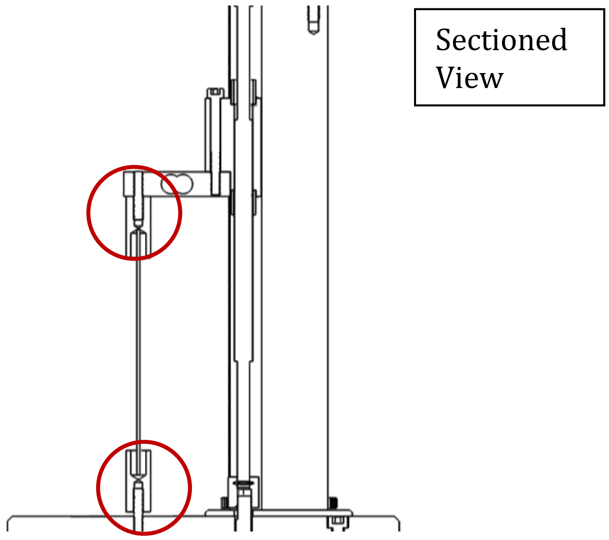
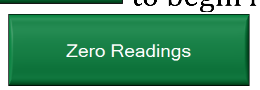
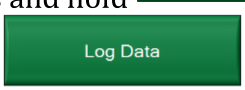
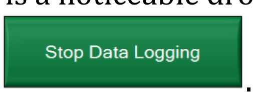



*Figure 11: Buckling Sample Captured in Cups*

9. Click 

to begin reading the sensors.
10. Press and hold 

on the MSET program to zero the load readout.
11. Click 

to begin collecting data.
12. While monitoring the real-time plot, slowly and smoothly begin turning buckling cup 1 located on the baseplte counterclockwise to apply load to the sample until there is a noticeable drop in force.
13. Click 

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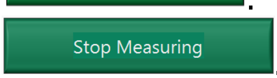
14. Click 

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15. Determine the critical load for the sample by identifying the highest load before the force drops off. See Figure 12 for an example. Record this value in the table at the end of this section.
16. Turn the bucking cup on the baseplate clockwise until it is in contact with the baseplate.
17. Remove sample 1 by raising the carriage until the sample is free.
18. Place sample 2 into the base plate cup.
19. Lower the carriage until its top is level with the 8.5cm mark on the tower scale.

20. With the speed control set to its slowest setting and making sure to guide the top of the sample into the buckling cup, lower the carriage until the top is level with the 10 cm mark.
21. Click **Start Measuring** to begin reading the sensors.
22. Click **Zero Readings** on the MSET program to zero the load readout.
23. Click **Log Data** to begin collecting data
24. While monitoring the real-time plot, slowly and smoothly begin turning buckling cup 1 counterclockwise to apply load to the sample until there is a noticeable drop in force.
25. Click **Stop Data Logging**.
26. Click **Stop Measuring**.
27. Determine the critical load for the sample by identifying the highest load before the force drops off. See Figure 12 for an example. Record this value in the table at the end of this section.
28. Turn bucking cup 1 clockwise until it is in contact with the baseplate.
29. Remove sample 2 by raising the carriage until the sample is free.
30. Lower the carriage until its top is level with the 11.5cm mark on the tower scale.
31. Place sample 3 in the base plate buckling cup.
32. With the speed control set to its slowest setting and making sure to guide the top of the sample into the buckling cup, lower the carriage until the top is level with the 12.8 cm mark.
33. Click **Start Measuring** to begin reading the sensors.
34. Click **Zero Readings** on the MSET program to zero the load readout.
35. Click **Log Data** to begin collecting data.
36. While monitoring the real-time plot, slowly and smoothly begin turning buckling cup 1 counterclockwise to apply load to the sample until there is a noticeable drop in force.
37. Click **Stop Data Logging**.
38. Click **Stop Measuring**.

    Determine the critical load for the sample by identifying the highest load before the force drops off. See Figure 12 for an example. Record this value in the table at the end of this section.

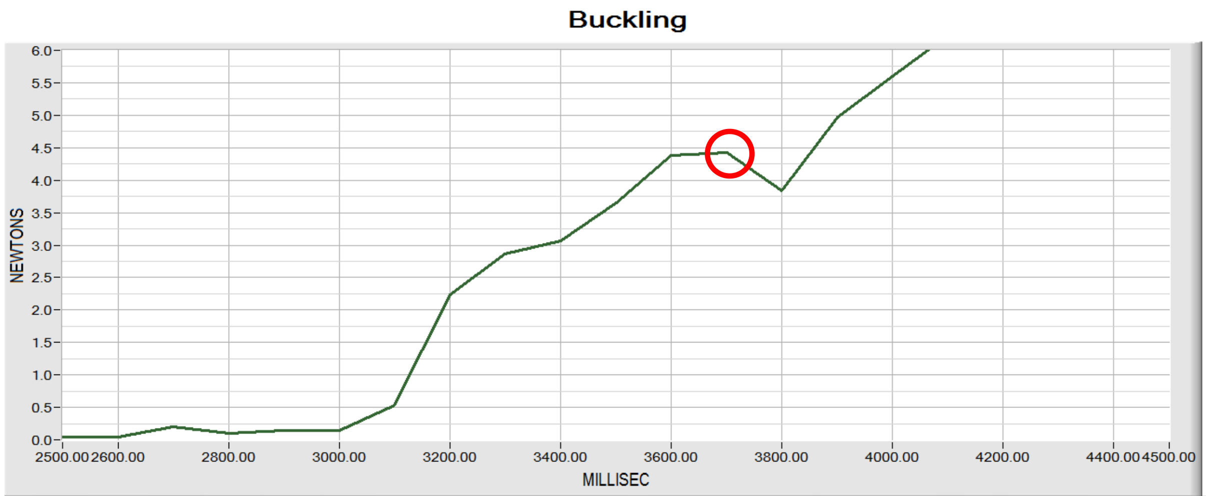



*Figure 12: Identifying Critical Load*

| Sample | Critical Load |
|---|---|
| 1 | |
| 2 | |
| 3 | |

32. The data collection portion of this experiment is now complete.

## Data Analysis

1. Determine the effective lengths used during the experiment.

| Sample | Effective Length |
|---|---|
| 1 | |
| 2 | |
| 3 | |

2. Calculate the theoretical critical buckling load (show a sample calculation).
3. Compare experimental buckling stress to theoretical results including percent differences.
4. Plot buckling stress vs. slenderness ratio on one graph for each boundary condition.
5. Generate a mathematical relationship for the results plotted (ie., perform a regression analysis of the plotted data).

# MSET - BUCKLING

## Purpose

Examine the effects of loading materials in compression with a length and diameter that causes buckling

## Columns

Columns are structural components used in engineered projects to support vertical loads. A building for example is fabricated with columns to support the weight of the entire structure built on top it. If columns are not properly sized the structure can collapse by buckling upon itself.

## Theory

The critical load "F" that causes a column to buckle, or fail can be calculated with a known stiffness "E", moment of inertia "I", length "L", and correction factor "C".

$$F = \frac{\pi^2 EI}{(LC)^2}$$

The equation can be generalized for different geometries by calculating stress "S"

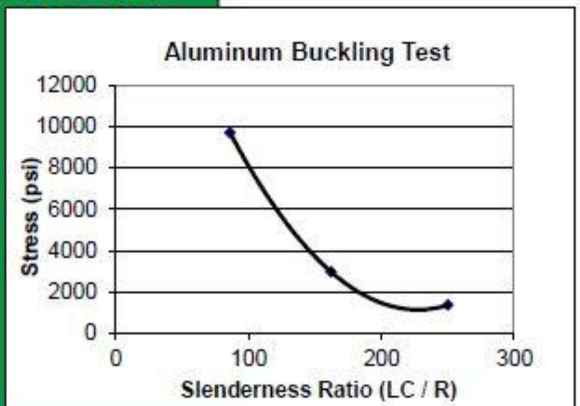
$$S = \frac{\pi^2 E}{(LC/R)^2}$$

The denominator (LC/R) is known as the slenderness ratio and is calculated with "R" the radius of gyration, and "A" the cross sectional area

$$R = \sqrt{\frac{I}{A}}$$

## Setup

## Results




Results will show longer and smaller cross sectional area columns will fail at lower loads, and that the relationship is nonlinear

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## Inquiry-Based Mini Project – Buckling

You were just hired to work on a construction project for the city of New York. It is your responsibility to figure out what type of material is going to be the best for construction of the column portion of a new building. These columns will experience a force in the vertical direction and you need to prevent them from buckling. According to the building codes the columns must be a length of 144 in. and be able to support 600 lbs.. The city wants to construct the building for as little money as possible while still remaining inside of codes.

Calculate the stress and the critical load for each of the three materials and determine which one will meet building codes, while also costing the least amount of money.

**Given:**

| Material | Modulus of elasticity, E (x 10^6 psi) | Length (in) | Radius (in) | Cost ($) | Critical Load (lb.) |
|---|---|---|---|---|---|
| Nickel 200 | 29.6 | 144 | 3 | 140 | |
| Copper Alloy C22000 | 16.7 | 144 | 3 | 100 | |
| Aluminum | 10 | 144 | 3 | 25 | |

**Formula(s):**

$$R = \sqrt{\frac{I}{A}}$$

Where R= radius of gyration, A= cross sectional area, and I= second moment of inertia

$$\sigma_{cr} = \frac{\pi^2 E}{(L'/R)^2}$$

Where E= modulus of elasticity, $L^l$= effective length, R= radius of gyration, and $\sigma_{cr}$= critical stress

$$I = {}^1/_4(\pi r^4)$$

Where r= radius

$$\sigma = \frac{F}{A}$$

Where σ denotes stress and F denotes the load

## Teacher Solution Key - Buckling

**Calculated Stress of each Material**:

$$\sigma_{cr\ Nickel\ 200} = \frac{(\pi^2 * (2.96 * 10^7 psi)}{\left[\left(\frac{144in}{\sqrt{\frac{(0.25)*(\pi*3^4)in^4}{(\pi*3^2)in^2}}}\right)\right]^2} = 3.17 * 10^4 psi$$

$$\sigma_{cr\ Copper\ Alloy\ C22000} = \frac{(\pi^2 * (1.67 * 10^7 psi)}{\left[\left(\frac{144in}{\sqrt{\frac{(0.25)*(\pi*3^4)in^4}{(\pi*3^2)in^2}}}\right)\right]^2} = 1.78 * 10^4 psi$$

$$\sigma_{cr\ Aluminum} = \frac{(\pi^2 * (1.00 * 10^7 psi)}{\left[\left(\frac{144in}{\sqrt{\frac{(0.25)*(\pi*3^4)in^4}{(\pi*3^2)in^2}}}\right)\right]^2} = 1.07 * 10^4 psi$$

**Calculated Critical Load:**

$$F_{cr\ Nickel\ 200} = \frac{\sigma_{cr\ Nickel\ 200}}{A} = \frac{3.17 * 10^4 psi}{(\pi * 3^2)in^2} = 1121\ lbs$$

$$F_{cr\ Copper\ Alloy\ C22000} = \frac{\sigma_{cr\ Copper\ Alloy\ C22000}}{A} = \frac{1.78 * 10^4 psi}{(\pi * 3^2)in^2} = 632\ lbs$$

$$F_{cr\ Nickel\ 200} = \frac{\sigma_{cr\ Nickel\ 200}}{A} = \frac{1.07 * 10^4 psi}{(\pi * 3^2)in^2} = 379\ lbs$$

| Material | E (psi) | Length (in) | Radius (in) | Area (in^2) | I (in^4) | Stress Critical (psi) | Force (lbf) |
|---|---|---|---|---|---|---|---|
| Nickel | 29600000 | 144 | 3 | 28.27433388 | 63.61725124 | 31699.25025 | 1121.131638 |
| Copper | 16700000 | 144 | 3 | 28.27433388 | 63.61725124 | 17884.37429 | 632.5303496 |
| Aluminum | 10000000 | 144 | 3 | 28.27433388 | 63.61725124 | 10709.20616 | 378.7606884 |

**Filled in Graph of Calculated Work:**

| Material | Modulus of elasticity, E (x 10^6 psi) | Length (in) | Radius (in) | Cost ($) | Critical Load (lb.) |
|---|---|---|---|---|---|
| Nickel 200 | 29.6 | 144 | 3 | 14,000,000 | 1121 |
| Copper Alloy C22000 | 16.7 | 144 | 3 | 10,000,000 | 633 |
| Aluminum | 10 | 144 | 3 | 9,000,000 | 379 |

Copper Alloy C22000 is able to meet the building safety codes. The required load is 600 pounds and the critical buckling load is 633 pounds for this material, while costing the city the least amount of money. Nickel 200 is stronger yet more expensive, and aluminum is cheaper, but weaker.

A follow on question for the students is to determine the minimum diameter of the Aluminum column that will satisfy the load. What is the price of the aluminum column as compared with the copper alloy?

**Inquiry-Based Mini Project Rubric – Buckling**

| | 3 | 2 | 1 | 0 | Score |
|---|---|---|---|---|---|
| **Proper Use of Equipment** | Used the MSET to determine the critical load of various structures as well as plot buckling stress and slenderness ratio. | Struggled with using the MSET and getting accurate data. Was able to use the equipment and determine critical load of various structures and materials as well as plot buckling stress and slenderness ratio with some assistance. | Even at the end of the experiment, struggled with the use of the MSET and could not accurately determine critical load of various structures and materials as well as plot buckling stress and slenderness ratio. | Didn't use the MSET | |
| **Accuracy of Use of Terminology** | Used all terms accurately including, critical load, moment of inertia, elasticity/elastic modulus, Euler's formula, buckling stress, and slenderness ratio. | May have used all of the terms but one or two were not used accurately. | Used some of the terms but not all of them, or the terms were used but not used accurately. | Didn't use any of the terms in the explanation of the solution to the mini-project | |
| **Rationale for Solution** | Provided a detailed rationale for the choices made in their solution. Explanation included how Euler's | Provided a rationale for their solution, but could only briefly explain how Euler's formula played a | Provided a rationale, but explanation was lacking the proper connections between buckling stress and | Didn't provide a rationale for their solution. | |

| | | | | | |
|---|---|---|---|---|---|
| | formula helped them determine their solution and how buckling stress and critical load were determined for each possible solution as well as a break down of costs for each material. A logical explanation for the use of chosen material is given along with why it is most cost effective. | part and how buckling stress and critical load were determined or how they factored in to the final solution. An explanation for the use of the chosen material was given along with a cost break down but supporting evidence lacked detail. | critical load and the various calculations completed. The rationale for the choice of material was not clear and lacked evidence. The solution may have been incorrect and/or based on some incorrect calculations. | | |
| **Use of Mathematical Computations** | Accurately completed all calculations to determine critical load and plotted buckling stress and slenderness ratio accurately. Calculations were used to explain why a particular material was chosen in their final solution to the mini-project. | May have accurately plotted buckling stress and slenderness ratio and accurately determined critical load, however could not use it to explain why a specific material was chosen in the final solution of the mini-project. | Attempted to calculate critical load and plot buckling stress and slenderness ratio, but included some miscalculations. | Did not complete or include proper calculations for experiment. | |