MSET

3-Point Bend/Flexure

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.

3-Point Bend/Flexure Introduction

In this unit students will explore the flexure properties of beams of various geometric shapes and materials and apply engineering practices to determine the relationship between strength, stiffness, and deflection. Students will synthesize data to examine stiffness as it relates to support span and change in load. 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. Understand the difference between Mass and Weight, Force and Load; where mass is a measure of the amount of material in an object; weight is the gravitational force acting on a body; force is a measure of the interaction between two bodies; and load is the force exerted on a body or object, which refers to an applied force, commonly in units of pound force (lbf) or newtons (N).
2. Understand the concept of a "linear" response.
3. Have basic mechanical skills to configure the MSET based on written and visual instruction.
4. Be capable of drawing conclusions about the concept being studied by interpreting data from multiple experiments.
5. Have basic algebra knowledge.

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UbD Chart – 3-Point Bend/Flexure

<table>
<tr><th colspan="3">Desired Results</th></tr>
<tr><td rowspan="6">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:
3-PS2-1: Plan and conduct and investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.

3PS2-2: Make observations and/or measurements of an objects motion to provide evidence that a pattern can be used to predict future motion.

MS-PS2-2: Plan and investigation to provide evidence that the change in an objects motion depends on the sum of the forces and the mass of the object

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:</td><td colspan="2">Transfer</td></tr>
<tr><td colspan="2">Students will be able to independently use their learning of moment of inertia, elastic modulus, and Newton’s Laws of Motion to determine the potential load an object can withstand without deformity and therefore make relevant decisions when building a structure.</td></tr>
<tr><td colspan="2">Meaning</td></tr>
<tr><td>UNDERSTANDINGS
Students will understand that…
1. As the support span of an object is reduced (shortened), stiffness increases…the inverse is also true.
2. The load that an object can withstand without deflection is proportional to the length of the support span.
3. The elastic modulus deals with the ratio between the force exerted on an object to the resultant deformation.
4. Newton’s First Law is the theoretical basis for determining the elastic modulus for an object
5. Newton’s First Law and the Euler-Bernoulli Beam Theory Equations of Linear Elasticity provide the means of calculating the load-carrying and deflection characteristics of beams</td><td>ESSENTIAL QUESTIONS

1. How does the length of an object (support span) affect the load that the object can withstand without deflection and object stiffness?
2. How can the elastic modulus and the area moment of inertia help one to determine the stiffness of an object?
3. How do Newton’s Laws of Motion and Euler-Bernoulli’s equations help to explain how support span, change in load, deflection, and object stiffness are related to one another?</td></tr>
<tr><td colspan="2">Acquisition</td></tr>
<tr><td>Students will know…
● Newton’s laws of motion
● The definitions of mass, weight, and force.
● The terms, inertia, moment of inertia, and elastic modulus</td><td>Students will be skilled at…
● Apply mathematical computations to mathematical model(s) to calculate various outcomes
● Interpret graphs to draw conclusions</td></tr>
</table>

HS-ETS-1-2: Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering. HS-ETS-1-3: Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts. 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 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.		• 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

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.		

Evidence

Assessment Evidence

PERFORMANCE TASK(S):

1. Students will use the MSET device to conduct an experiment to measure beam stiffness as it relates to support span and change in load. Students will use 2 different methods to determine the object stiffness and consider the effect the support span has on the stiffness. Differences in the 2 calculations will be analyzed as well. The MSET device will be used to plot load and displacement values, and students will use these values to calculate stiffness. Students will use this procedure to design a structure in future lessons.

2. As a final performance assessment, students will complete the Inquiry-Based Mini-Project (see page 22), where they will need to make decisions about what length the beams for a new building should be in order to build the safest structure. The students will use the MSET and mathematical calculations to do comparisons and then make a final decision and write a proposal in favor of a particular length. Student understanding will be evaluated using the mini-project rubric (see page 28).

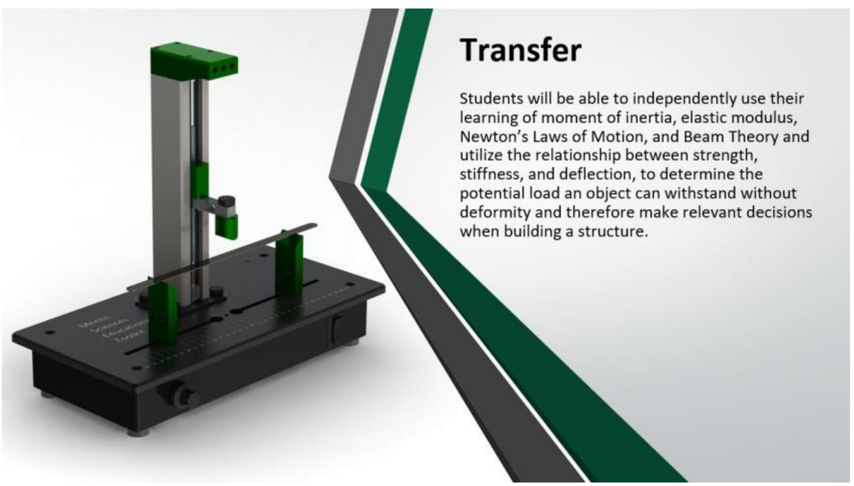
OTHER EVIDENCE:
The essential questions will be used as an entrance/exit slip to determine growth in understanding.

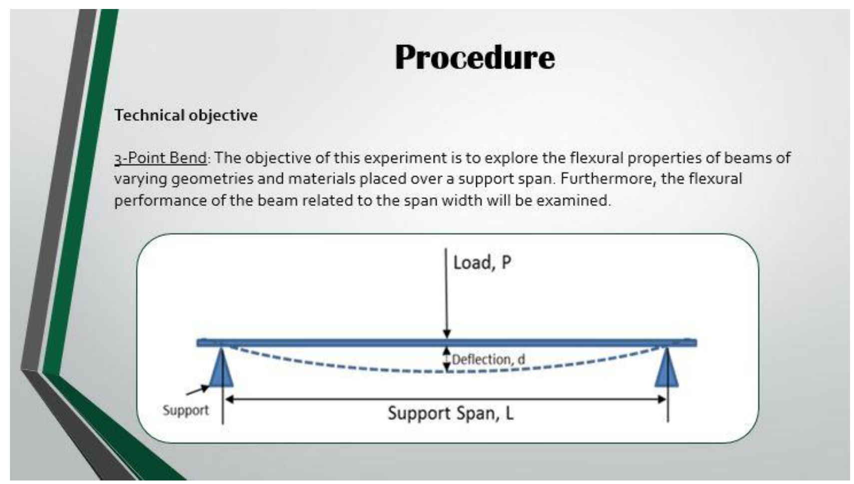
Stage 3 – Learning Plan

Summary of Key Learning Events and Instruction

See outline of 3-Point Bend/Flexure experiment summary included.

PowerPoint Template for Instruction





Procedure

Approach

3-Point Bend: In this experiment an aluminum beam will be tested with three different support spans. At each support span the beam will be loaded to a prescribed force. The force and deflection of the beam will be recorded and the beam stiffness will be calculated. The stiffness for identical beams with various support spans will be evaluated for the effect of the support span and compared to the relationship given in Equation #1.

$$K = \frac{P}{d} = \frac{48 \cdot E \cdot I}{L^3}$$

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:

- HS-PS2-1 Analyze data to support the claim that Newton's second law of motion
- 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

Standards/Established Goals

Massachusetts State Standards

Technology and Engineering:

HS-ETS-1-2: Design a solution to a complex real world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

HS-ETS-1-3: Evaluate a solution to a complex real world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

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): Illustrate how the forces of tension, compression, torsion, and shear affect the performance of a structure.

Introductory Physics:

3-PS2-1: Plan and conduct and investigation to provide evidence of the effects of balanced and unbalanced forces on the motion of an object.

3PS2-2: Make observations and/or measurements of an objects motion to provide evidence that a pattern can be used to predict future motion.

MS-PS2-2: Plan and investigation to provide evidence that the change in an objects motion depends on the sum of the forces and the mass of the object

- 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

Meaning

Meaning	
UNDERSTANDINGS: *Students will understand that...* 1. As the support span of an object is reduced (shortened), stiffness increases...the inverse is also true. 2. The load that an object can withstand without deflection is proportional to the length of the support span. 3. The elastic modulus deals with the ratio between the force exerted on an object to the resultant deformation. 4. Newton's First Law is the theoretical basis for determining the elastic modulus for an object. 5. Newton's First Law and the Euler-Bernoulli Beam Theory Equations of Linear Elasticity provide the means of calculating the load-carrying and deflection characteristics of beams.	ESSENTIAL QUESTIONS: 1. How does the length of an object (support span) affect the load that the object can withstand without deflection and object stiffness? 2. How can the elastic modulus and the area moment of inertia help one to determine the stiffness of an object? 3. How do Newton's Laws of Motion and Euler-Bernoulli equations help to explain how support span, change in load, deflection, and object stiffness are related to one another?

Acquisition

Acquisition	
Students will know… • Newton's laws of motion • The definitions of mass, weight, and force. • The terms, inertia, moment of inertia, and elastic modulus	*Students will be skilled at…* • 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 are an intern at an engineering firm. The firm has been hired to design and help build a new school, which will use steel beams in the ceiling. As one of your first jobs as an intern, you are tasked with determining the stiffness of the beams so that the firm can make decisions about the support span. The National Building Codes stipulate the allowable deformation in the beam must be less than L / 915, where L is the length of the beam measured in centimeters. The mass of each of the beams is 20 Kg per linear meter.

Objective:

Each beam must support its own weight and will be supported by columns at each end, which will be bolted to a concrete floor. The maximum allowable bearing stress (force per unit area) the floor can safely support is 200 kg / cm^2.

There is an opportunity to change from steel beams I-beams, to steel trusses with an equivalent section modulus. Steel trusses weigh 5 Kg / linear meter, but cost 35% more than steel I-beams; steel columns cost $100 / cm^2.

Metrics:

Three lengths of beams are needed in the school: 10, 16, and 20 meters. Use your knowledge of the MSET 3-Point-Bend experiment, and apply the following scale factors to determine the allowable load for each beam, where:

Load: 1 gram = 1000 Kilograms
Span: 1 cm = 1 meter
Deflection: 1 mm = 1 cm

Calculate:

Calculate the following for each case:

1. Length of the beam in cm
2. Maximum allowable deflection for each beam
3. Weight of each beam
4. Maximum allowable load for each beam
5. Maximum force on each support column
6. Minimum bearing area for each column
7. Determine the cost per cm^2 for each case
8. Recommend the optimum construction for each beam

Mini-Case Study

Conclusion:

Write up a proposal supporting your calculations and present your results to the firm. Use appropriate formulas and calculations as support for your decision as well as an explanation about why your choice will contribute to a safe structure. Be sure to use the appropriate terminology in your explanation including mass, force, deflection, stress, moment of inertia, and elastic modulus.

Assessment Evidence

Students will use the MSET device to conduct an experiment to measure beam stiffness as it relates to support span and change in load. Students will use 2 different methods to determine the object stiffness and consider the effect the support span has on the stiffness. Differences in the 2 calculations will be analyzed as well. The MSET device will be used to plot load and displacement values, and students will use these values to calculate stiffness. Students will use this procedure to design a structure in future lessons.

As a final performance assessment, students will complete the Inquiry-Based Mini-Project (see page 22), where they will need to make decisions about what length the beams for a new building should be in order to build the safest structure. The students will use the MSET and mathematical calculations to do comparisons and then make a final decision and write a proposal in favor of a particular length. Student understanding will be evaluated using the mini-project rubric.

MSET Experiment Procedure – 3-Point Bend/Flexure

Technical objective

The objective of this experiment is to explore the flexural properties of beams of varying geometries and materials placed over a support span. Furthermore, the flexural performance of the beam related to the span width will be examined.

Background

A beam is a structural member that spans between two supports and carries a load. Beams are very common elements of a structural design from buildings and bridges to airplanes and cars.

Consider a beam supported on each end as shown in Figure 1. When a load is applied at the center of the span the beam deflects and bends in response. Similar to a load being applied to a spring the beam has a stiffness which, for small deflections, is linear. The beam stiffness is directly related to the support span, the material that the beam is made from, and the cross-sectional geometry of the beam. This experiment only focuses on the effect of the support span.

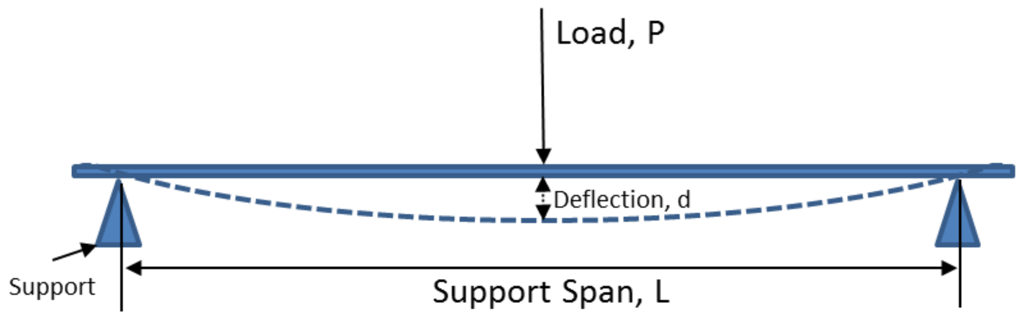


Figure 1: Simply Supported Beam Loaded in Flexure

The stiffness of a simply supported beam as shown in Figure 1 is given by Equation #1. The stiffness of the beam, "K", would be in units of force per unit displacement such as Newtons per millimeter (N/mm). The values for E and I relate to the material properties and beam geometry respectively. For this experiment these factors will be held constant. Note that the stiffness is inversely proportional to the cube of the support span. This means that as the support span is reduced the beam stiffness increases exponentially and as it grows the beam stiffness decreases exponentially.

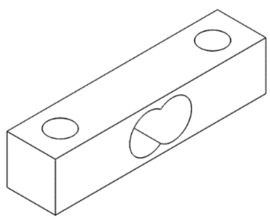
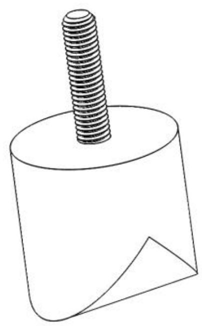
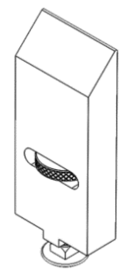
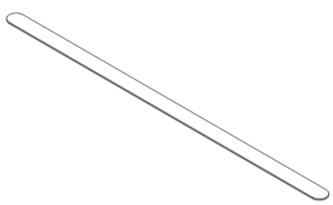
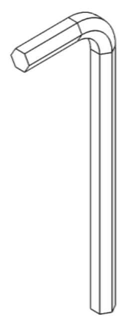
$$K = \frac{P}{d} = \frac{48 \cdot E \cdot I}{L^3} \qquad \text{Eq. (1)}$$

Approach

In this experiment an aluminum beam will be tested with three different support spans. At each support span the beam will be BOB loaded to a prescribed force. The force and deflection of the beam will be recorded and the beam stiffness will be calculated. The stiffness for identical beams with various support spans will be evaluated for the effect of the support span and compared to the relationship given in Equation #1.

Assembly

1. Gather the following components:

5kg Load Cell 	Load Nose 	Support Assembly **x2** 
Steel Sample 	4mm Hex Wrench 	

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.

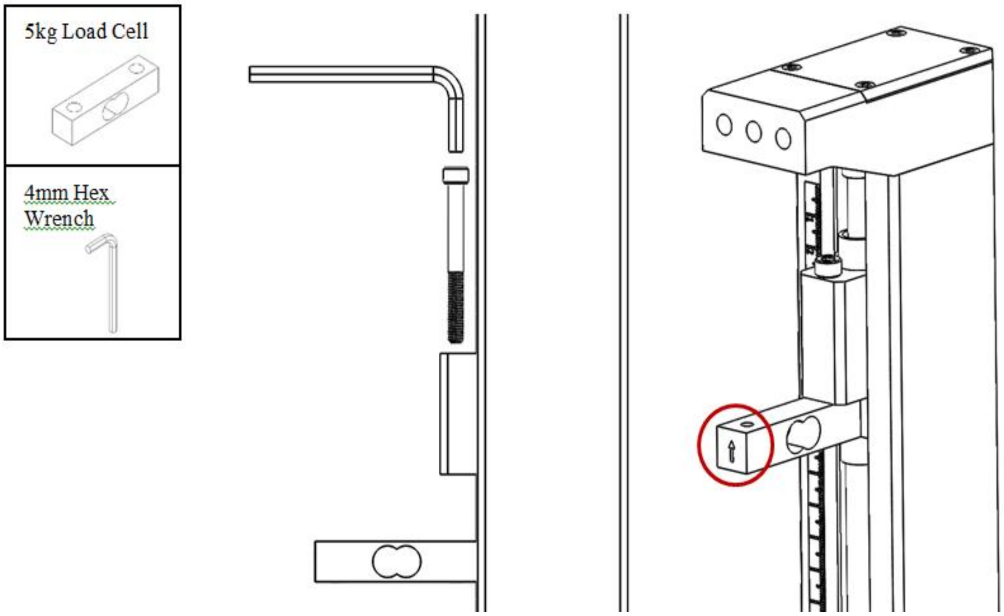


Figure 2: Load Cell Orientation

4. Plug the load cell into port 1 at the back of the SIM.
5. Thread the load nose into the load cell as shown in Figure 4. Small o-ring is located at the base of the threaded stud. Thread the load nose onto the loadcell until there is slight pressure on the o-ring and the load nose is in the proper orientation as shown in Figure 4.

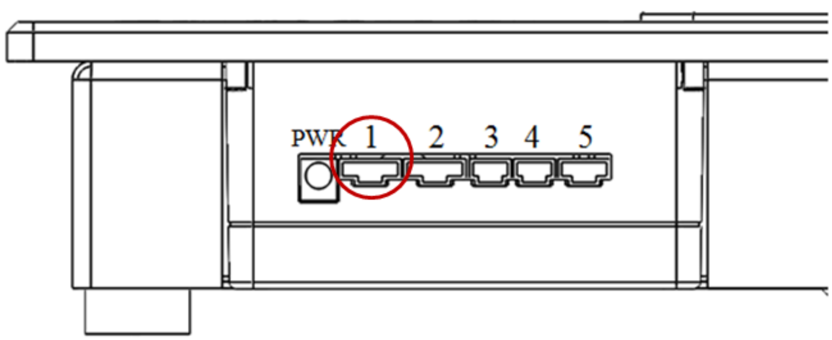


Figure 3: Port 1 on SIM

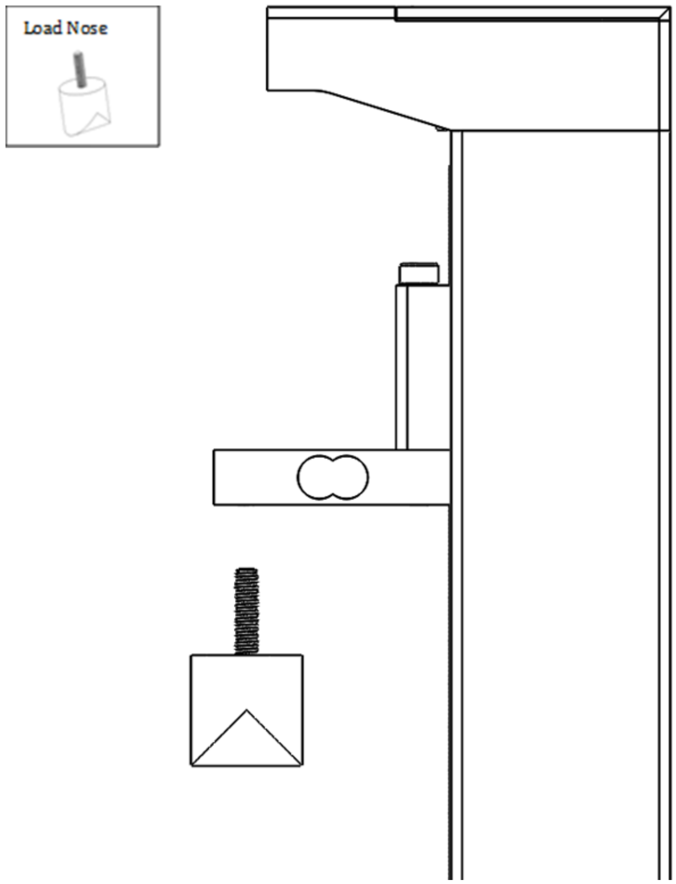


Figure 4: Load Nose Assembly

6. Attach the two support assemblies to the baseplate by first turning the thumbnut counter-clockwise to loosen the locking mechanism. Next, drop them into the openings near the center and then sliding them outward. Finally, tighten the support down by twisting the thumbnut clockwise.

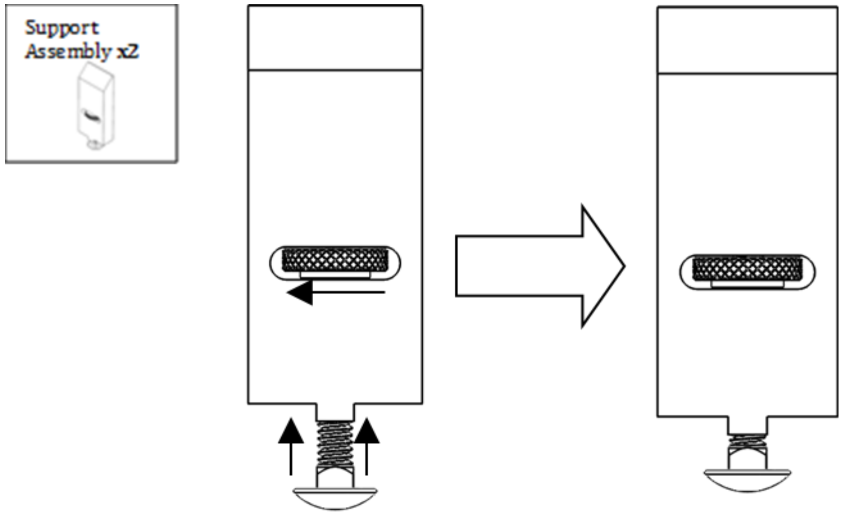


Figure 5: Support Operation

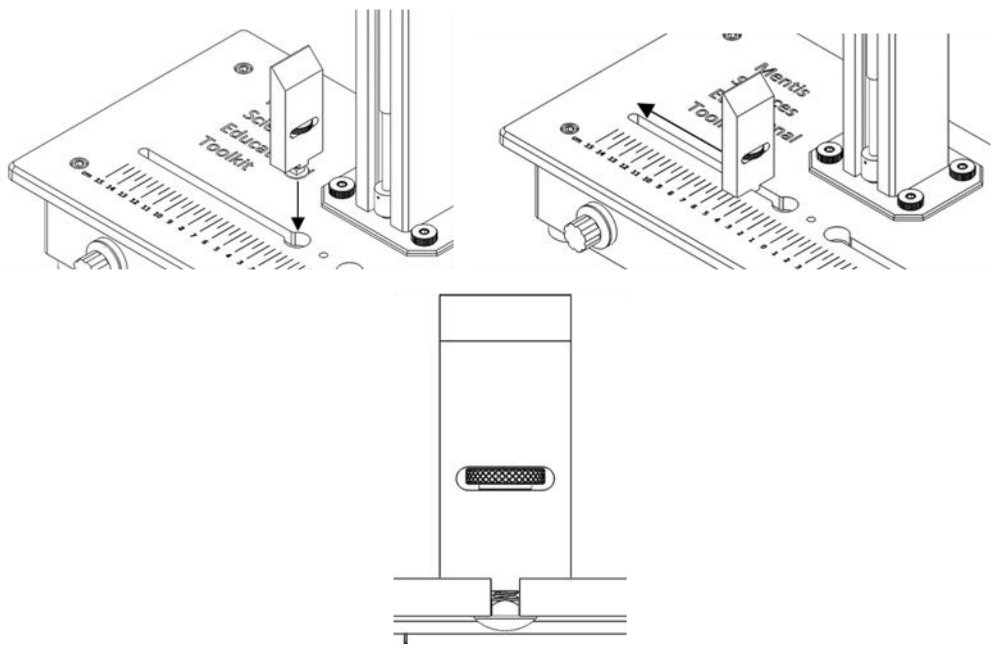
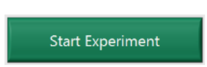


Figure 6: Installation Locations for Supports

Experimental Procedure

1. Put on safety glasses.
2. Click "3-point Flexure" then 

to launch the flexure experiment.

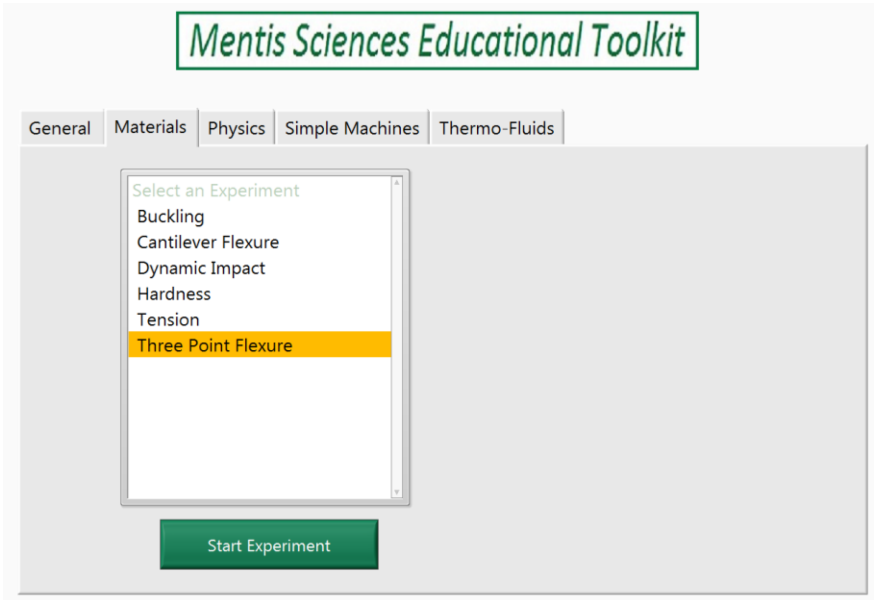


Figure 7: Location of Three Point Flexure Experiment

3. Select the 5 kg load cell from the menu options.

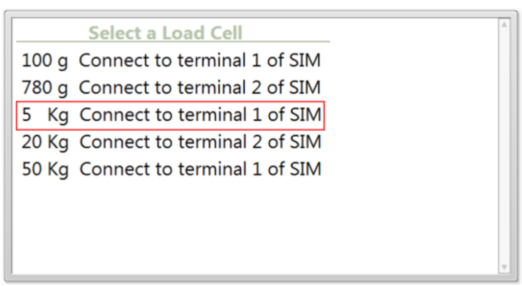


Figure 8. Load Cell Options

4. Using Table 1, set the support span to the largest value (23 cm).

Table 1: Maximum Load for Each Support Span

Support Span (cm)	23	19	15
Maximum Applied Load (N)	35	35	35

5. Place the sample on the support span.

6. Click Start Measuring to begin reading the sensors.
7. Move the carriage to a position such that the load nose just begins to contact the sample but does not display a load on the MSET program.
8. Press and hold Zero Readings on the MSET program to zero the load and displacement readouts.
9. Press Log Data to begin collecting data.
10. Begin displacing the carriage downward until the beam has been loaded to approximately 35 N (As noted as the maximum load in Table 1). **Stop the movement immediately upon reaching 35 N or else the sample may be damaged.**
11. Record the final ending load and displacement values in Table 2 in the data analysis section of this tutorial.
12. Press Stop Data Logging then Stop Measuring.
13. Press Save Results. A window will pop up notifying the user that data will be saved once Return to Main is pressed at the end of the experiment.

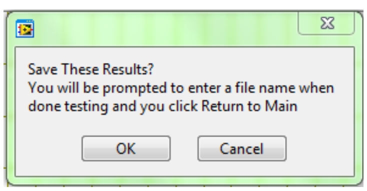


Figure 9. Save Results Prompt

14. Press "ok".
15. Repeat steps 4 to 12 for the remaining spans in Table 1.
16. Press Return to Main.
17. Enter a file name and press "ok".
18. The data collection portion of this experiment is now complete.

Data Analysis

1. Calculate the change in deflection, the change in load, and the beam stiffness and record results in the appropriate cells in Table 2. Refer to the MSET Experiment 01 – Spring Stiffness to review how to perform these calculations with the 2-point method.

Table 2: Experimental Load and Deflection Results

	23cm Support Span		**19cm Support Span**		**15cm Support Span**	
	Load (N)	Deflection (mm)	Load (N)	Deflection (mm)	Load (N)	Deflection (mm)
Final						
Change (Difference)						
Stiffness (N/mm)						

2. Access the data saved from the flexure testing. Using a data processing program, such as Microsoft Excel, plot the load deflection data for each support span and determine the slope of each plot by adding a linear trendline and its equation. Report the average stiffness in Table 3.

Table 3: Average Stiffness from Linear Trendlines

Support Span	**Stiffness (N/mm)**
23cm	
19cm	
15cm	

3. Explain how the support span affects the stiffness of the beam with identical materials and geometry. Specifically compare the change in stiffness related to the change in support span and reference Equation #1.

4. The beam stiffness was determined using 2 different methods, the 2-point method and the average method. To compare the difference in experimental results is useful to evaluate the percent difference between those results. Using Equation #2 calculate the percent difference between evaluating the results with the 2-point method vs. the average method. Record the results in Table 4.

$$\%Difference = \frac{|K_{2-Point} - K_{Average}|}{\left(\frac{K_{2-Point} + K_{Average}}{2}\right)} \times 100 \qquad \text{Eq. (2)}$$

Table 4: Percent Difference Between 2-Point and Average Calculations

Support Span	Percent Difference
23cm	
19cm	
15cm	

5. In Equation #1 the factors E and I were introduced. E is known as the Elastic Modulus which is a property of the aluminum material. I is known as the Area Moment of Inertia which is a property of the cross-section of the beam. These factors will be evaluated in future experiments but were held constant in this experiment. Using the constant values of E and I given in Table 5 and Equation #1 calculate the beam stiffness that we expected for each of the support spans.

Table 5: Beam Properties

Elastic Modulus, E	180,000 (N/mm^2)
Area Moment of Inertia, I	2.82 (mm^4)

Table 6: Calculated (Expected) Beam Stiffness for each Support Span

Support Span	Calculated (expected) Stiffness (N/mm)
23cm	
19cm	
15cm	

Using Equation#3 below, calculate the percent error between the experimentally determined stiffness' (two-point calculation and average trend line analysis) and the calculated expected spring stiffness from Table 6. Record results in Table 7. What are some potential causes for error?

$$\%Error = \frac{|K_{Experiment} - K_{Expected}|}{K_{Expected}} \times 100 \qquad \text{(eq.\#3)}$$

Table 7: Percent Error Between Experimental Stiffness and Manufactures Specifications

Support Span	Two-Point Stiffness	Average Stiffness
23cm		

19cm		
15cm		

MSET - THREE POINT BEND

Purpose

Develop an understanding of geometry, material properties, and problem formulation.

Beams

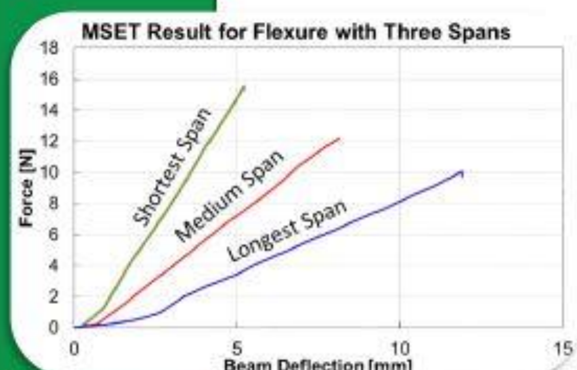
Beams are one of the fundamental components used in engineering. A bridge for example is fabricated with a number of beams configured, and sized to support vehicles.

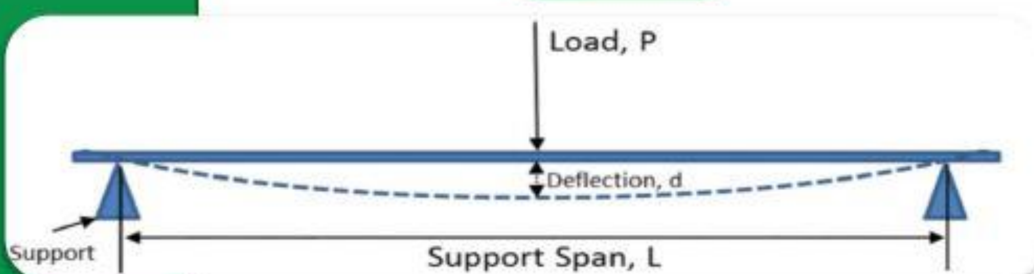
Theory

A beam loaded at its center will deflect a distance "d". The amount of deflection depends on the magnitude of force "P", beam span "L", stiffness "E", and beam combined geometric shape "I"

$$d = \frac{PL^3}{48EI}$$

Setup





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Inquiry-Based Mini Project – 3-Point Bend/Flexure

You are an intern at an engineering firm. The firm has been hired to design and help build a new school, which will use steel beams in the ceiling. As one of your first jobs as an intern, you are tasked with determining the stiffness of the beams so that the firm can make decisions about the support span. The National Building Codes stipulate the allowable deformation in the beam must be less than L / 915, where L is the length of the beam measured in centimeters. The mass of each of the beams is 20 Kg per linear meter.

Each beam must support its own weight and will be supported by columns at each end, which will be bolted to a concrete floor. The maximum allowable bearing stress (force per unit area) the floor can safely support is 2000 N / cm^2.

There is an opportunity to change from steel I-beams, to steel trusses with an equivalent section modulus. Steel trusses weigh 5 Kg / linear meter, but cost 35% more than steel I-beams; steel I-beams cost $200 per linear meter; and Steel columns cost $100/$cm^2$.

Three lengths of beams are needed in the school: 10, 16, and 20 meters. Using the MSET calculate the stiffness of steel, K, and use that value in your calculations. Provide a plot of the overlaid date with your findings. Use your knowledge of the MSET 3-Point-Bend experiment, and apply the following scale factors to determine the allowable load for each beam, where:

Load:	1 gram = 1000 Kilograms
Span:	1 cm = 1 meter
Deflection:	1 mm = 1 cm

Calculate the following for each case:

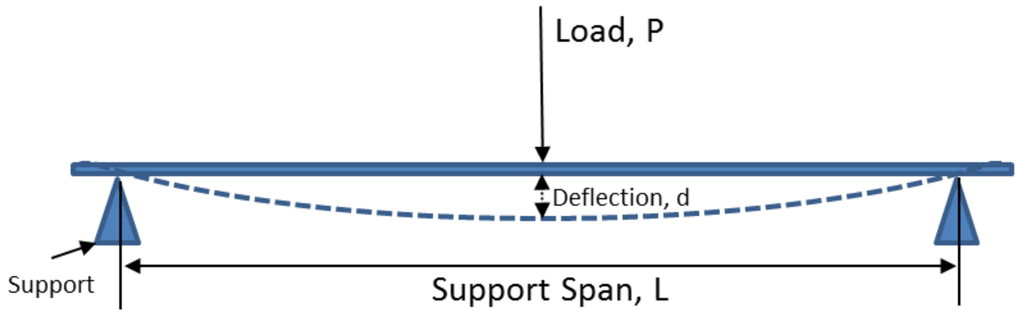
1. Length of the beam in cm
2. Maximum allowable deflection for each beam
3. Weight of each beam
4. Maximum allowable load for each beam
5. Maximum force on each support column
6. Minimum bearing area for each column
7. Determine the cost for each case

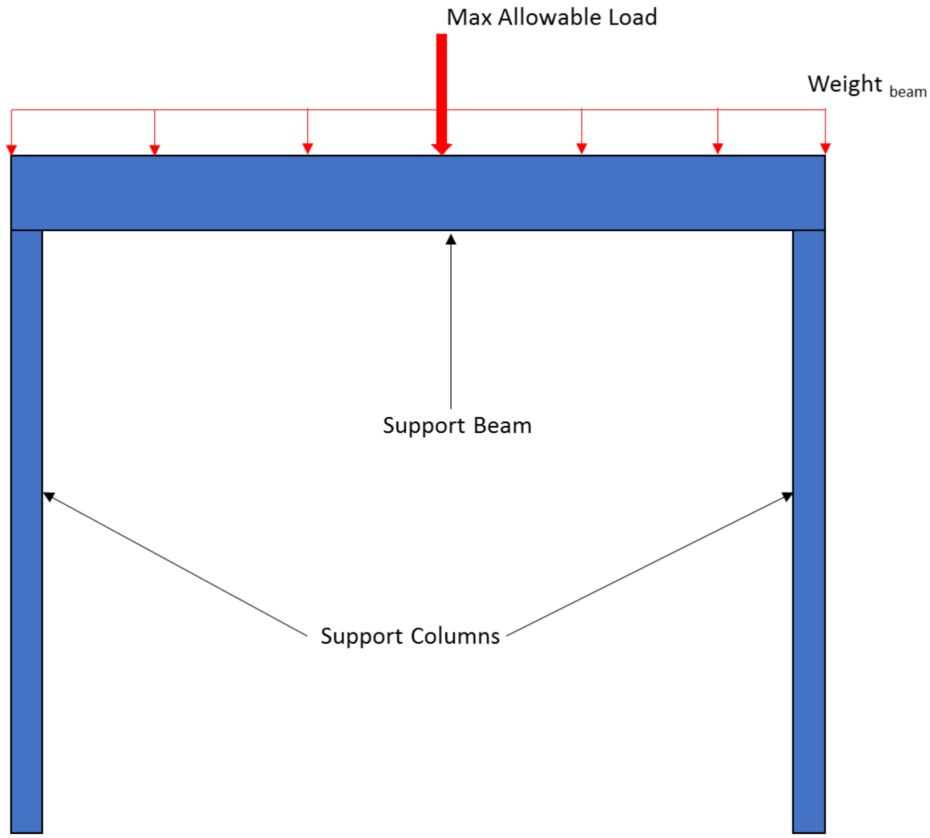
You will need to write up a proposal supporting your calculations and present your results to the firm. Use appropriate formulas and calculations as support for your decision as well as an explanation about why your choice will contribute to a safe structure. Be sure to use the appropriate terminology in your explanation including mass, force, deflection, stress, moment of inertia, and elastic modulus.

Your proposal/explanation will be evaluated using the mini-project rubric.

Teacher Solution Key – 3-Point Bend/Flexure

Free Body Diagrams:





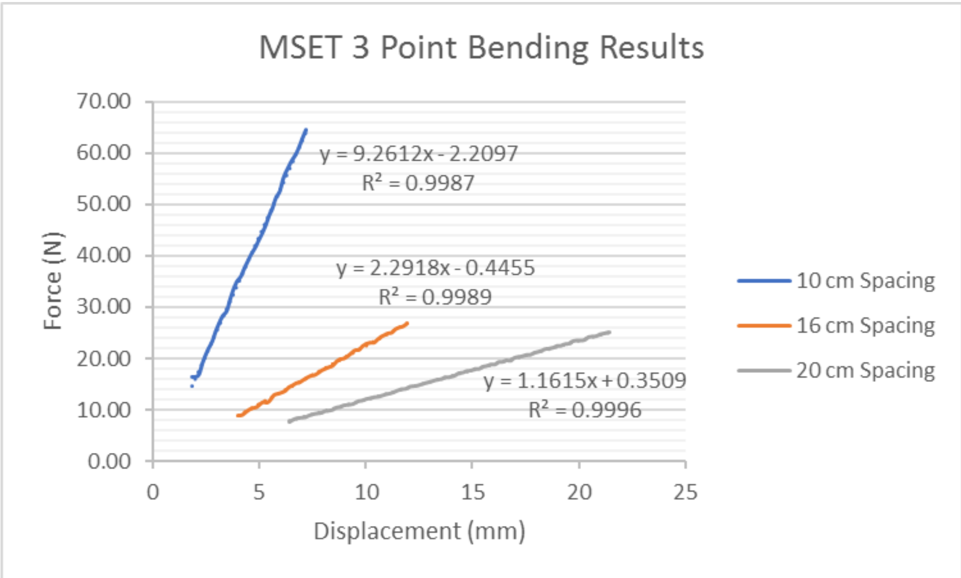
Relevant Equations:

$$F = m * g$$
$$K = \frac{P}{d} = \frac{48 \cdot E \cdot I}{L^3}$$

Where K relates to the stiffness of the beam (N/mm), P is the Load, d, is deflection in the beam, E is the Elastic modulus (N/mm^2), I is the second area moment of inertia (mm^4) and L is the length of the beam.

1) Length of beam in cm- $L\ cm = L\ m * \frac{100\ cm}{1\ m}$
   a. 1000 cm
   b. 1600 cm
   c. 2000 cm
2) Maximum allowable deflection for each beam- $d = \frac{L\ (cm)}{915}$
   a. 1.0929 cm
   b. 1.7486 cm
   c. 2.1858 cm
3) Weight of each beam- $W = L\ (m) * \frac{\lambda_m\ (kg)}{1\ (m)} * \frac{9.81\ N}{1\ kg}$
   a. $\lambda_{beam} = \frac{20\ kg}{1\ m}$
      i. 1962 N
      ii. 3139.2 N
      iii. 3924 N
   b. $\lambda_{truss} = \frac{5\ kg}{1\ m}$
      i. 490.5 N
      ii. 784.8 N
      iii. 981 N

4) In order to find the max allowable the MSET was used to calculate the stiffness of the beam with the 3 different lengths. The following plot are the resulting stiffness values.



Beam Length (cm)	Maximum Allowable Deflection (cm)	Weight Beam (kg)	Force Beam (N)	K (N/mm) no scale
1000	1.092896175	200	1962	9.2612
1600	1.74863388	320	3139.2	2.2918
2000	2.18579235	400	3924	1.1615

Since the scale factors were not implemented yet the stiffness factor from testing the MSET will change accordingly.

Load 1 gram is equivalent to 10 kg, or 10,000 grams.
Deflection 1 mm is equivalent to 1 cm.
K_{scaled} (N/cm) = 10,000 $K_{no\ scale}$ (N/mm)

$$P_{max} = K_{scaled} * d_{max}$$

Beam Length (m)	K (N/mm) no scale	K(N/cm) with Scale	Pmax (N)
10	9.32	93206.00	101864.49
16	2.28	2275.54	3979.08
20	1.17	1165.08	2546.61

5) The Maximum force seen in each column will be half the total weight of the beam added to the max load seen on the beam

$$P_{column} = \frac{P_{max}(N) + P_{weight}(N)}{2}$$

Beam Length (m)	P column (N)
10	51913.24
16	3559.14
20	3235.31

6) The Bearing Area for each beam will be found by implementing the max bearing stress seen in the concrete floor (2000N / cm^2)

$$Bearing\ Area = \frac{P_{column}}{\sigma_{column}}$$

Beam Length (m)	Bearing Area (cm^2)
10	25.96
16	10.73
20	7.35

7) The Cost for each case will also examine the cost associated with switching from steel I beams to Steel Trusses. Assuming that the columns are the same the all calculations were updated using the Trusses instead of I-Beams
8)

Beam Length (m)	Weight Truss (kg)	Force Truss (N)	P column (N)	Bearing Area (cm^2)
10	50	490.5	5338.47	26.69
16	80	784.8	2381.94	11.91
20	100	981	1763.81	8.82

The I-Beams price is per linear meter so the Truss will just cost 35% more than the I-Beam, lengths of the beams are expected to be set and are not changed by type of beam supporting it.

Beam Length (m)	Cost of Beam ($)	Cost of Truss ($)
10	2000	2700
16	3200	4320
20	4000	5400

The other factor that will contribute to the cost is the size of the column that is used in the design. The size of the column will be affected by the maximum allowable load on the support, constant in both due to same material and section modulus, and the weight of the support beam. The weights of the Truss were four times less than that of the I-Beam. Both Bearing Areas and Column costs are outlined below.

Beam Length (m)	Bearing Area I-Beam (cm^2)	Bearing Area Truss (cm^2)	Cost of Column I-Beam ($)	Cost of Column Truss ($)
10	25.96	25.59	2595.66	2558.87
16	10.73	10.14	1073.25	1014.39
20	7.35	6.61	734.75	661.18

Total Costs for each case are outlined below

Beam Length (m)	Total Cost with I-Beams ($)	Total Cost with Truss ($)
10	4595.66	5258.87
16	4273.25	5334.39
20	4734.75	6061.18

Proposal

It has been determined that depending on the size of the support spans needed that the Steel I-Beams would be the better choice. The 16 meter I-Beam support span ended up being the lowest cost any of the beams. The cost per linear meter of the 20 meter I-Beam would be the best choice since the cost is similar to the 16-meter section but is 4 meters longer. The added mass from the I-beam, when compared to the truss, is so small when comparing the maximum force that can be seen on the support span. This added weight only slightly increased the bearing area seen in the columns and would only drive the cost up slightly.

When calculating all of the parameters of the setup the stiffness at 10, 16 and 20 cm on the MSET were tested. The stiffness of each case was used as the material properties of the support span. Both the Truss and I-Beam used the same stiffness values during calculations. The stiffness of the beam was directly related to the Section Modulus, or the moment of inertia times the Elastic Modulus. Using these stiffness values, the maximum force on the span was calculated by multiplying the stiffness by the max allowable deflection.

Please review supplemental provided information to complement the provided response for choosing either the 16 or 20 meter I-Beam section. This information shows the thought process and exact calculations that were used when determining the cost and strength of each beam.

Inquiry-Based Mini Project Rubric

	3	2	1	0	Score
Proper Use of Equipment	Used the MSET to collect load and deflection data accurately	Struggled with using the MSET and getting accurate data. Was able to use it with some assistance.	Even at the end of the experiment, struggled with the used of the MSET and could not accurately collect data using the equipment.	Didn't use the MSET	
Accuracy of Use of Terminology	Used all terms accurately including, mass, acceleration, force, inertia, moment of inertia, and elastic modulus	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 design	
Rationale for Solution	Provided a detailed rationale for the choices made in their solution. Explanation included a connection to Newton's Laws of Motion and how support span affects stiffness and deflection. Ideas about how the elastic modulus and the area moment of inertia can help in determining stiffness may be included.	Provided a rationale for their solution, but could only briefly connect their solution to Newton's Laws of Motion, elastic modulus, area moment of inertia, and how the support span may affect stiffness.	Provided a rationale, but their explanation was lacking connections to Newton's Laws of Motion and/or how support span affects stiffness and deflection.	Didn't provide a rationale for their solution	
Use of Mathematical Computations	Used the given formula to calculate beam stiffness (K) accurately. Calculations were used to explain how the support span affects stiffness.	May have used the given formula to calculate beam stiffness accurately, however could not use it to explain how the support span affects stiffness	Attempted to use the given formula to calculate beam stiffness, but included some miscalculations.	Did not use the given formula for calculations.	