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Concrete Beam Design: Pouring the Foundation to Engineering in T&E Classrooms

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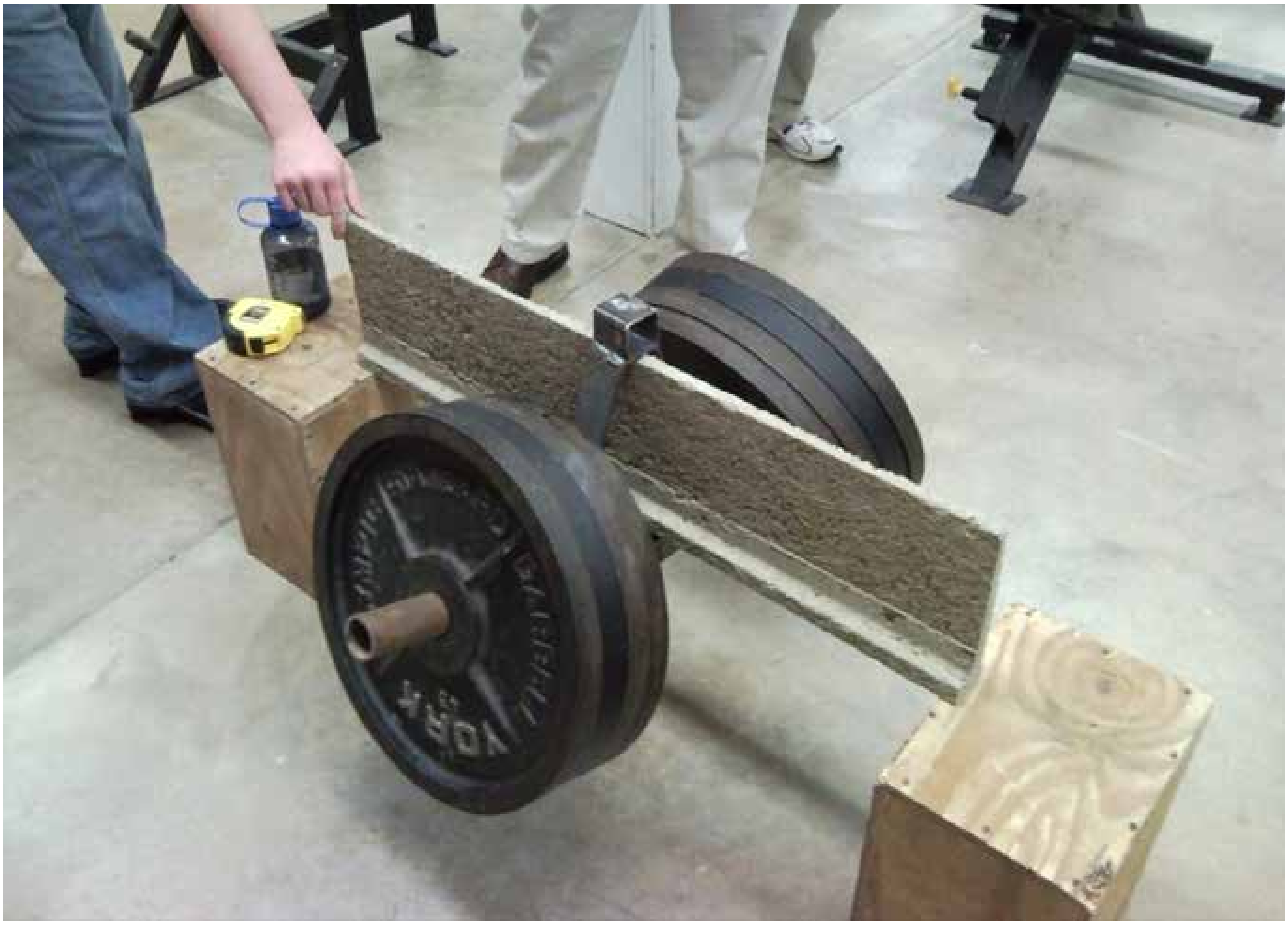


concrete beam design:

pouring the foundation to engineering in T&E classrooms

The concepts and skills learned will lead your students into concrete beam and form design and fabrication as well as the ability to precisely predict the amount of weight a concrete beam will hold during testing.

by
Andrew J. Hughes and Chris Merrill

Ask a middle or high school student if they could design a concrete beam that weighs only 20 pounds and is 36" long but must hold 600 pounds without failing. What is the student likely to say? What if the student was told that, with some optimized decision making based on relatively straightforward mathematics, their beam could hold 2400 pounds or more? The focus of this article is not on concrete beam design, it is rather an introduction to engineering principles in beam design using a lab activity. The concepts and skills learned in this article will lead students into concrete beam and form design and fabrication as well as the ability to precisely predict the amount of weight a concrete beam will hold during testing. An integral process of producing a concrete beam with a precisely predicted load causing failure is the emphasis of this and a subsequent article through a technical, hands-on activity involving the application of math, science, and engineering principles in the design, fabrication, and testing.

Technology and Engineering Education (T&EE) teachers are always looking for new standards-based lessons that focus on improving students' STEM-based skills and hands-on capabilities. In this article, the authors present an introduction to beam design through a hands-on lab. The lab focuses on the teaching and learning of engineering principles involved in beam design.

The standards and benchmarks to be utilized in this concrete beam activity are:

Standards for Technological Literacy:

- *Standard 9.* Students will develop an understanding of engineering design.
  - *Benchmark H.* Modeling, testing, evaluating, and modifying are used to transform ideas into practical solutions.
  - *Benchmark I.* Established design principles are used to evaluate existing designs, to collect data, and to guide the design process.

Next Generation Science Standards:

- Engineering Design
  - *MS-ETS1-4.* Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.
  - *HS-ETS1-2.* Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.
- Forces and Interactions
  - *MS-PS2-2.* Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.
  - *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.

Beams

Structural members (i.e., beams, columns, and trusses) are designed to support external loads. External loading results in the structural member experiencing internal reactions. With no additional axial forces, a beam's internal reactions include shear and bending (both compression and tension) stresses. For purposes of the engineering design challenge, which will be covered in a future article, all beams will be considered to have external forces that produce only pure bending (no axial or shear forces). A beam can be either *statically determinate* or *statically indeterminate*. Statically determinate beams are simple, overhanging, and cantilever with external reactions that can be determined using equilibrium conditions; statically indeterminate beams are beyond the scope of this article and overall content of the engineering design challenge (Figure 1). Note: For further explanation of statics, especially other related concepts to structural members, teachers may consider obtaining a textbook on statics, which is a core subject within engineering.

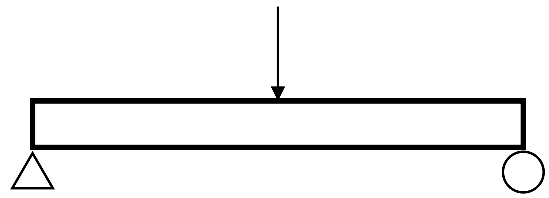


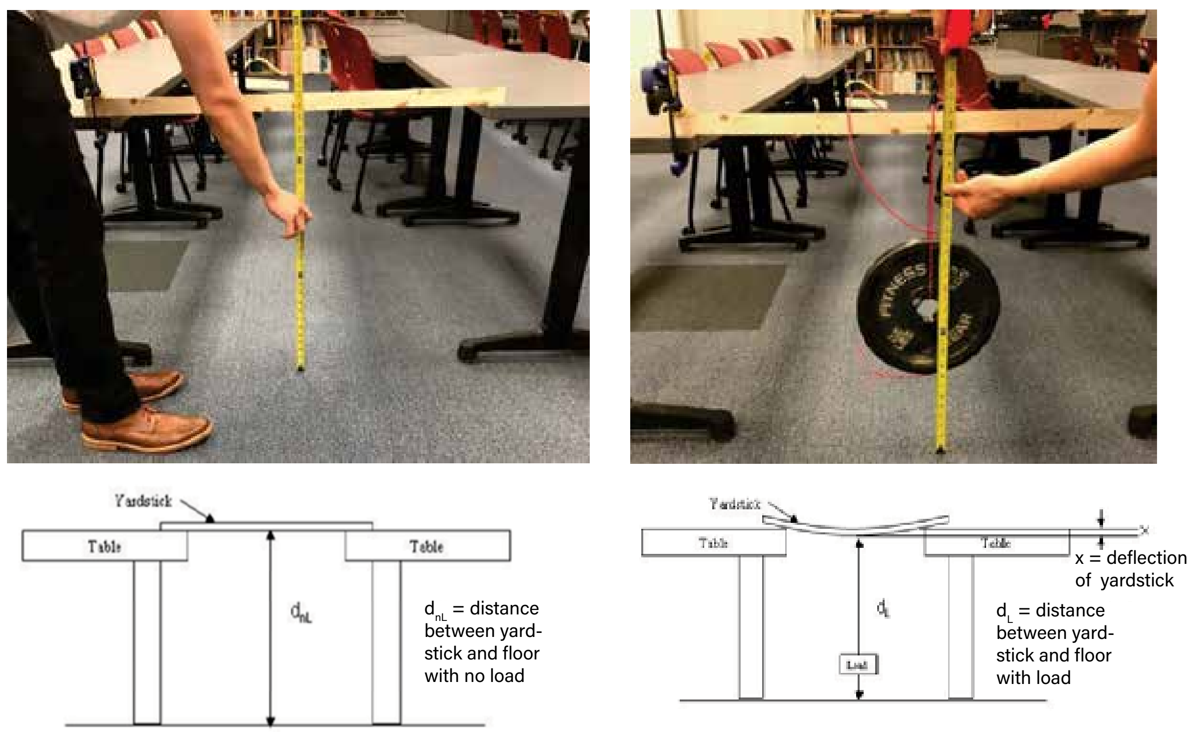
Figure 1. Simple Beam.

Classifying a Beam

There are three basic ways to classify a beam: (a) the type or style of supports; (b) the type of external loading on the beam; and (c) the shape and size of the beam. Based on the first classification, a simply supported beam is supported on both ends; one end has a pinned (fixed) support, meaning it can support an external force on both x and y axes, while the other has a roller support, meaning it can only support an external force on the y-axis. Based on the second classification, the three types of possible external loading on a beam are concentrated, uniform, and linearly varying. Additionally, it is possible to have any combination of these three different load types on a beam. In the case of uniform and linearly varying externals loads, a resultant load is calculated and acts as a concentrated load. In the third classification, an I-beam is the most common shape and C-channel is generally the second most common. There are two primary reasons that steel beams are shaped in an I: (a) steel's tensile and compression strength are similar; and (b) the I-shape makes for beam size and shape standards that allow for easier usage in various industries. Using a material that has a considerable difference between tension and compression (i.e., concrete) to make a beam changes the ideal cross-sectional shape. Basically, the ideal cross-sectional shape for a beam made from only concrete is not a traditional I. The three main parts to a standard I-beam are the lower flange, upper flange, and the web. When designing a beam, there may not be a need for all three parts. However, each part of a beam serves a purpose and as such should be considered during beam design. The main purpose of the flanges are to withstand external loads and resulting internal pressures trying to induce bending. The main purpose of the web is to separate the flanges to increase the beam's moment of inertia (i.e., resistance to bending).

Vocabulary, Phrases, and Theories in Beam Design

While students learn the background information required to



$$deflection\ (\%) = \frac{d_{nL} - d_{L}}{d_{nL}} \times 100$$

Figure 2. Deflection Percentage.

design a beam, it is a good idea to make them aware of common vocabulary, phrases, and theories associated with beams, beam design, and the design problem. Examples of these include: moment of inertia, Newton's Laws, bending, compression, tension, pressure, neutral axis, neutral surface, reference axis, free body diagram, cross-sectional area, deflection, centroid, centroidal axes, Young's modulus (also known as elastic modulus), Hooke's Law for distribution of bending stress, bending stress formula or flexure formula, moment, and load. Additionally, teachers may want to cover concepts that include: type of beams (i.e., simple, cantilever), beam supports (pinned, roller), types of loading (i.e., concentrated, uniform, and linearly varying), and size and shape standards for I-beams and C-channel. The vocabulary, phrases, and concepts should be separated into stages during the learning process so as to not overwhelm students.

Moment of Inertia

A beam's strength is determined using calculations to indicate its rigidity or resistance to bending (i.e., moment of inertia). The moment of inertia is frequently used in mechanics to calculate the stresses and deflections of beams, columns, and shafts, and moment of inertia is always computed with respect to an axis. The quantity of a moment of inertia is affected by the distribution of the area and mass relative to an axis. An object's moment-of-inertia quantity expresses that shape's tendency to resist rotation (or bending in this case) in relation to the specified axis. Understanding moment of inertia is essential for understanding the design and function of structural members, mechanical systems, and devices. Students will be adjusting the distribution of area in relation to the specified axis to modify their beam's moment-of-inertia quantity, and ultimately their beam's resistance to bending.

Learning to Control Moment of Inertia

For students to understand and "see" the moment of inertia, the authors' developed a deflection lab. It is recommended that students complete the lab with the specified materials in the process explained in the sections. During the lab, students should be provided with just-in-time teaching to help refine and conceptualize what they are experiencing during the lab. The purpose of the first lab is for students to learn about moment of inertia by comparing the impact of the cross-sectional area and that area's orientation on bending (deflection). During the different lab portions, students should be given 40" long strips of 2 x 4 framing lumber cut to specified widths and heights. Students suspend each wooden strip between two desks/tables 36" apart (needs to remain consistent). Clamp one end of the stock to the desk for testing deflection. By clamping one end of the wooden strip in place, the students create a *simply supported beam*. Students will measure the distance from the floor to the middle of the bottom of the wood strip. Students then load a weight on the middle of the strip (usually 10 pounds when laying flat or 25 pounds when standing on edge) and again measure the distance from the floor to the middle of the bottom of the wood strip. Students then calculate *the deflection percentage* (Figure 2). Based on the orientation, cross-sectional area, width, and height of the wooden strip, the wood with a higher moment of inertia will have less deflection than the wood with a lower moment of inertia using the same load and spanning the same distance.

Moment of Inertia Lab

The first strip of cut framing lumber given to the students for testing is .25″ x 1.5″ x 40″. The students test the strip standing up on edge (i.e., height measurement perpendicular to supports) with 25 pounds and laying down flat (i.e., width measurement perpendicular to supports) with 10 pounds and record the results of the deflections (Table 1). In this case, there is no change to the cross-sectional area, only the orientation. The students will see that there is relatively no deflection of the wood strip when standing up on edge, but there is a deflection when laying down flat. The students begin to recognize that the change in height (due to change in orientation) is the reason for the difference in deflection. While height is an important factor, it is only one variable in calculating the moment of inertia. It is also worth explaining to the students that the cross-sectional area remained consistent between these two initial tests, highlighting that the height and distribution of the cross-sectional area play a role in deflection.

In the second part of the same activity, students compare three wooden strips, all standing up on edge, with different heights, different cross-sectional areas, but the same width. The cut framing lumber given to the students are (a) .25″ x 1.5″ x 40″, (b) .25″ x 1″ x 40″, and (c) .25″ x .5″ x 40″. The students will record and then graph the deflection amounts (Figure 3). The students will see that there is a nonlinear increase in deflection as the height of the wooden strip decreases; this helps reinforce the idea that height is important. It should be pointed out to students that a linear decrease in height results in a nonlinear increase in deflection. Additionally, students will begin to think that height and cross-sectional area are both important. It is interesting to note that at this point in the lab, students often overlook the relationship between height, width, and cross-sectional area.

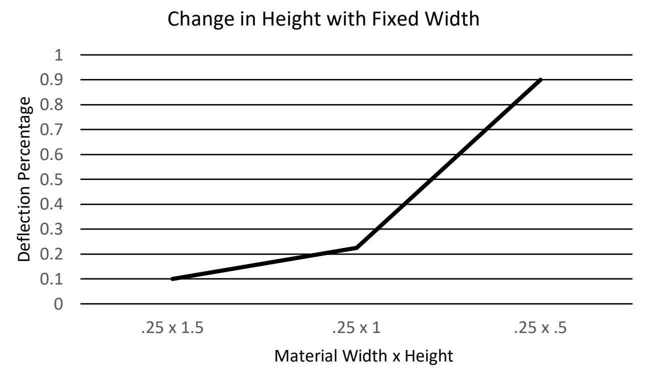


Figure 3. Example of Graphed Data.

In the third part of the same activity, students compare three wooden strips standing up on edge with different widths, different cross-sectional areas, but the same height. The cut framing lumber given to the students are: (a) .375″ x .5″ x 40″; (b) .3125″ x .5″ x 40″; and (c) .25″ x .5″ x 40″. The students record and graph the deflection amounts (Figure 4). The students see that there is a linear increase in deflection as the width of the wooden piece decreases. Students are prompted through questioning to begin thinking about the relationship between height, width, and area, as well as the results in Steps 2 and 3. This is an opportunity to ask the students why there is a nonlinear change in deflection when height is linearly changed and a linear change in deflection when width is changed. The students often will indicate that height is more important than width when determining moment of inertia based on their experience with each part of this lab.

In the fourth step of the same activity, students will do more testing to help determine the best use of a given amount of material. The students should be prompted to think about how much more

Figure 4. Example of Graphed Data.

Table 1. Table for Data Recording.

Orientation	Dimensions with Sketch	No Load Distance	Load	Load Distance	Deflection (%)
Flat			10 pounds		
Edge			25 pounds		

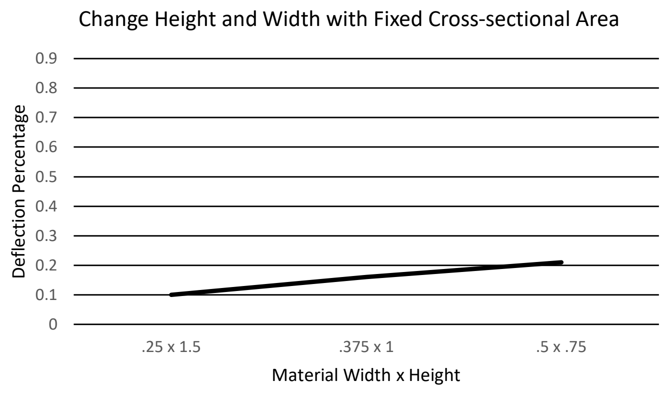


Figure 5. Example of Graphed Data.

important height is than width when determining moment of inertia. The students will compare the amount of deflection in three different wooden strips standing up on edge all with the same cross-sectional area but different heights and widths. The three framing lumber pieces are sized (a) .25″ x 1.5″ x 40″, (b) .375″ x 1″ x 40″, and (c) .5″ x .75″ x 40″. The students record and graph the deflection amounts (Figure 5). The students are going to see that as the height of the strip decreases but width increases, the deflection amount increases. At this point, when given the constraint of a fixed cross-sectional area, students should be able to determine the dimensions of a wooden strip that would have the least deflection.

The students should be able to describe that increasing height of a simply supported beam with a rectangular cross section decreases deflection nonlinearly. Deflection actually decreases exponentially; however, this is difficult for students to conceptualize based on a three-beam sample size. The students should also be able to describe that increasing width of a simply supported beam with a rectangular cross section decreases deflection linearly. The students are basically defining the moment of inertia and describing how to control it. The students may still have trouble understanding the role of area. They may still believe that increased cross-sectional area means decreased deflection.

In the fifth step, students compare a wooden strip that has an increased cross-sectional area from increased width, but decreased height. The final wooden strip given to the students for testing is .4375″ x 1.25″ x 40″. The students test the strip standing up on edge, record the results of the deflection, and compare the results to the original .25″ x 1.5″ x 40″ strip standing up on edge. The students will see that there is no difference in deflection when comparing both the .4375″ x 1.25″ x 40″ and .25″ x 1.5″ x 40″ strips when standing up on edge. The students will see that the wooden strips had similar deflections, and the .4375″ x 1.25″ x 40″ strip had less height and used more material. Students comprehend that increasing area (material used) does not necessarily decrease deflection. Through questioning about concepts seen during the lab, the students begin to realize that there must be an equation that is used to determine the moment of inertia and generally the equation's structure. A moment-of-inertia equation's structure is based on the shape of the cross section as well as linear changes to height and width, resulting in both nonlinear and linear changes to the beam's resistance to bending. In the equation for the moment of inertia about the x-centroidal axis of a rectangular cross section ($\bar{I}_{x'}$), height is exponentially more important than width. This means that increasing height linearly will increase $\bar{I}_{x'}$ nonlinearly. The moment of inertia equations for other cross-sectional shapes (areas) are shared with the students at the end of the lab (Figure 6).

Note: The centroid is denoted as 'C.' $\bar{I}_{x'}$ is the moment of inertia about the x-centroidal axis. $\bar{I}_{y'}$ is the moment of inertia about the y-centroidal axis. I_x is the moment of inertia about the x-reference axis. I_y is the moment of inertia about the y-reference axis.

Conclusion

At the conclusion, students should be able to describe how the height, width, and area impact a beam's moment of inertia (i.e., the beam's resistance to bending). In mechanics, the moment of inertia represents the second type of moment for an area. Now that students have learned about the moment of inertia, an article appearing in the February issue ot *TET* will cover the first type of moment for an area; which is the location of the centroid. Both this and the upcoming articles are intended for a teacher to follow a process resulting in their students' ability to design and optimize a beam, precisely predicting a load-causing failure, using woodworking equipment to fabricate a form to cast the concrete beam design, and to test the beam verifying the predicted load-causing failure. This assertation is based on the authors' experience teaching beam design for over 12 years.

NOTE: Supplemental materials include the Concrete Beam Design Challenge worksheet, Controlling Moment of Inertia lab worksheet, and TSA Structural Engineering Competition and are available in the online article at: www.iteea.org/TETJan20Concrete1.aspx

References

Cheng, F. H. (1997). *Statics and strength of materials* (2nd ed). Westerville, OH: Glencoe/McGraw-Hill.

International Technology Education Association (ITEA/ITEEA). (2000/2002/2007). *Standards for technological literacy: Content for the study of technology.* Reston, VA: Author.

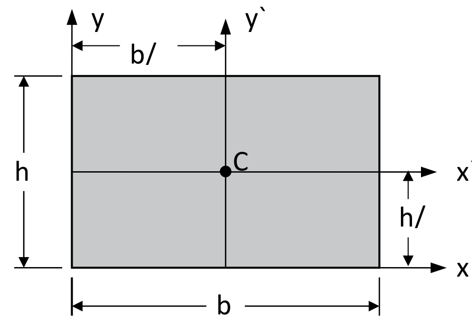
Morrow, H. W., Kokernak, R. P., & Morrow, H. W. (2011). *Statics and strength of materials* (7th ed.). Pearson Prentice Hall.

NGSS Lead States. (2013). *Next generation science standards: For states, by states.* Washington, DC: The National Academies Press.

Rectangle:

moment of inertia about centroidal axis	moment of inertia about reference axis
$\bar{I}_{x'} = \frac{1}{12}bh^3$	$I_x = \frac{1}{3}bh^3$
$\bar{I}_{y'} = \frac{1}{12}b^3h$	$I_y = \frac{1}{3}b^3h$

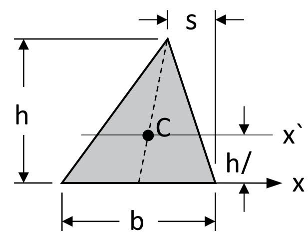
Area = bh



Triangle:

moment of inertia about centroidal axis	moment of inertia about reference axis
$\bar{I}_{x'} = \frac{1}{36}bh^3$	$I_x = \frac{1}{12}bh^3$

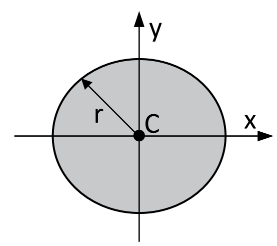
$$Area = \frac{1}{2}bh$$



Circle:

moment of inertia about centroidal axis
$\bar{I}_x = \bar{I}_y = \frac{1}{4}\pi r^4$

$$Area = \pi r^2$$



moment of inertia about centroidal axis	moment of inertia about reference axis
$\bar{I}_{x'} = \frac{h^3(a^2+4ab+b^2)}{36(a+b)}$	$I_x = \frac{h^3(3a+b)}{12}$
$\bar{I}_{y'} = \frac{h(a+b)(a^2+b^2)}{48}$	$I_y = \frac{h(a+b)(a^2+7b^2)}{48}$

$$Area = \frac{h}{2}(a+b)$$

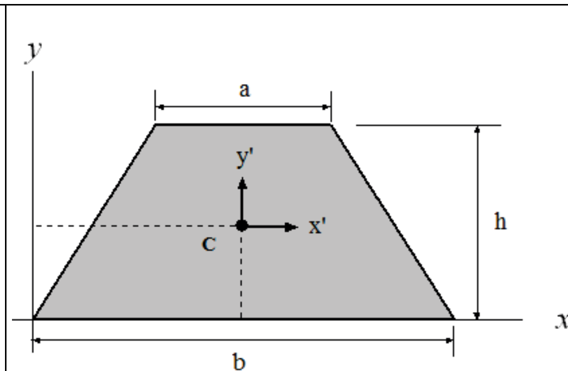
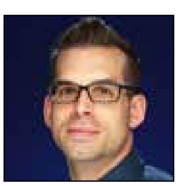


Figure 6. Moment of Inertia Equations.



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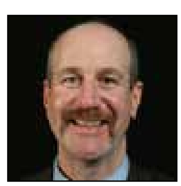

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