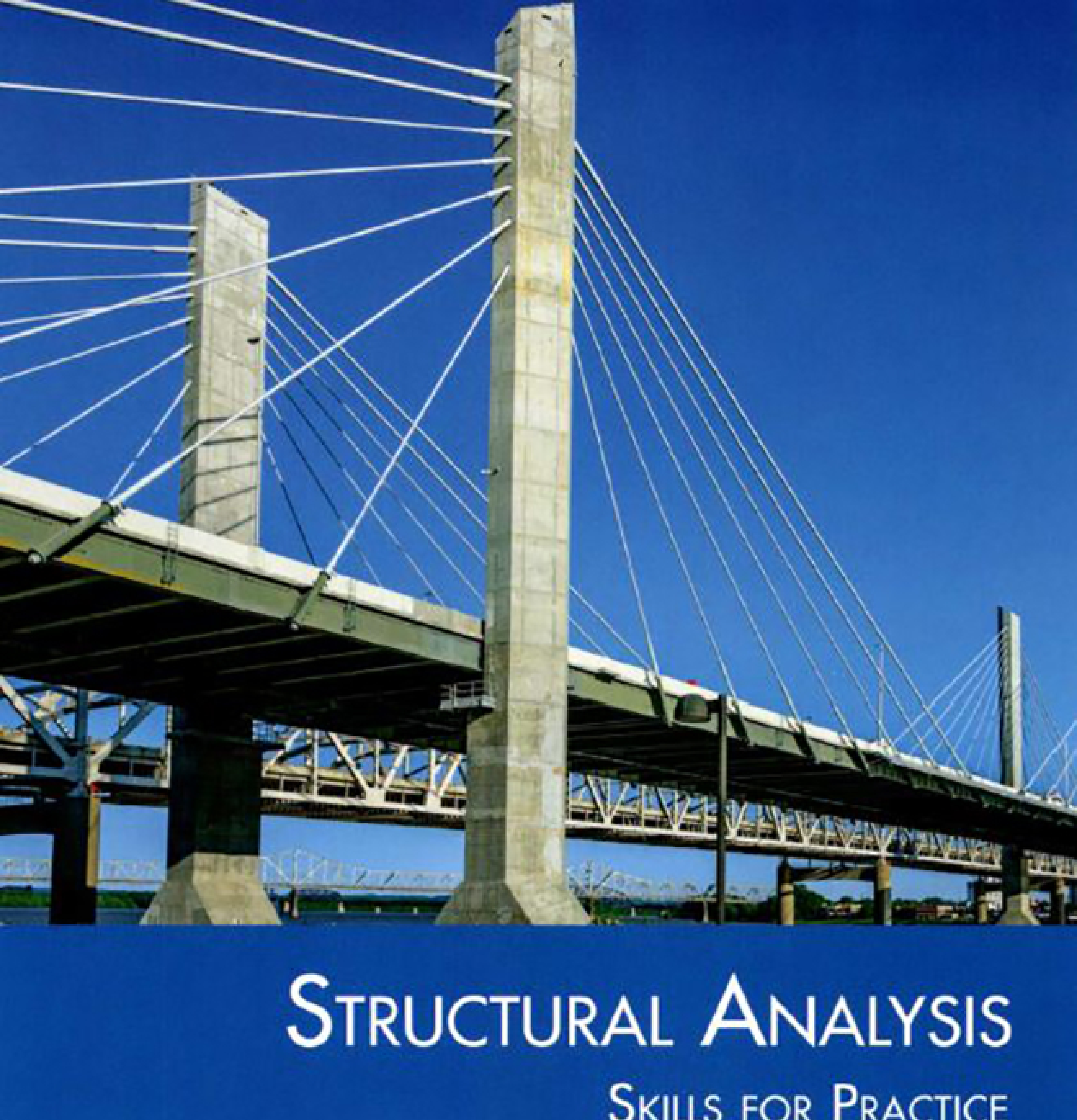
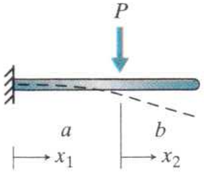
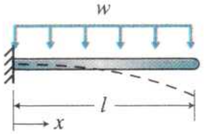
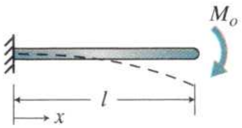
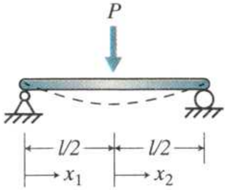
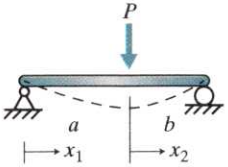
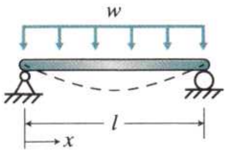


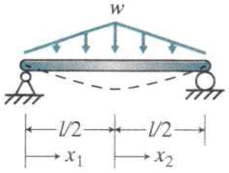
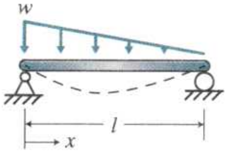
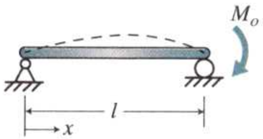
STRUCTURAL ANALYSIS

SKILLS FOR PRACTICE

Pearson

JAMES H. HANSON

Situation	θ_L	(∡+) θ_R	$\Delta(x)$ $(+\uparrow)$	**Location of** $\Delta_{\max}$	$\Delta_{\max}$ $(+\uparrow)$
	0	$-\dfrac{Pa^2}{2EI}$	$\Delta(x_1) = -\dfrac{P}{6EI}(-x_1^3 + 3ax_1^2)$ $\Delta(x_2) = -\dfrac{P}{6EI}(3a^2x_2 + 2a^3)$	$x_2 = b$	$-\dfrac{P}{6EI}(3a^2b + 2a^3)$
	0	$-\dfrac{wl^3}{6EI}$	$\Delta(x) = -\dfrac{w}{24EI}(x^4 - 4lx^3 + 6l^2x^2)$	$x = l$	$-\dfrac{wl^4}{8EI}$
	0	$-\dfrac{M_o l}{EI}$	$\Delta(x) = -\dfrac{M_o x^2}{2EI}$	$x = l$	$-\dfrac{M_o l^2}{2EI}$
	$-\dfrac{Pl^2}{16EI}$	$\dfrac{Pl^2}{16EI}$	$\Delta(x_1) = -\dfrac{P}{48EI}(-4x_1^3 + 3l^2x_1)$ $\Delta(x_2) = -\dfrac{P}{48EI}(4x_2^3 - 6lx_2^2 + l^3)$	$x_1 = \dfrac{l}{2},$ $x_2 = 0$	$-\dfrac{Pl^3}{48EI}$
	$-\dfrac{Pab}{6EIl}(l + b)$	$\dfrac{Pab}{6EIl}(l + a)$	$\Delta(x_1) = -\dfrac{Pb}{6EIl}[-x_1^3 + (a^2 + 2ab)x_1]$ $\Delta(x_2) = -\dfrac{Pa}{6EIl}[x_2^3 - 3bx_2^2 + 2(b^2 - ab)x_2 + 2ab^2]$	If $a \geq b$, $x_1 = \sqrt{\dfrac{a^2}{3} + \dfrac{2ab}{3}}$	If $a \geq b$, $-\dfrac{Pab}{27EIl}(a + 2b)\sqrt{3a^2 + 6ab}$
	$-\dfrac{wl^3}{24EI}$	$\dfrac{wl^3}{24EI}$	$\Delta(x) = -\dfrac{w}{24EI}(x^4 - 2lx^3 + l^3x)$	$x = \dfrac{l}{2}$	$-\dfrac{5wl^4}{384EI}$

 	$-\frac{5wl^3}{192EI}$	$\frac{5wl^3}{192EI}$	$\Delta(x_1) = -\frac{w}{960EI}\left(\frac{16}{l}x_1^5 - 40lx_1^3 + 25l^3x_1\right)$ $\Delta(x_2) = -\frac{w}{960EI}\left(-\frac{16}{l}x_2^5 + 40x_2^4 - 40l^2x_2^2 + 8l^4\right)$	$x_1 = \frac{l}{2},$ $x_2 = 0$	$-\frac{wl^4}{120EI}$
 	$-\frac{8wl^3}{360EI}$	$\frac{7wl^3}{360EI}$	$\Delta(x) = -\frac{w}{360EI}\left(-\frac{3x^5}{l} + 15x^4 - 20lx^3 + 8l^3x\right)$	$x = 0.481l$	$-\frac{0.00652wl^4}{EI}$
 	$\frac{M_ol}{6EI}$	$-\frac{M_ol}{3EI}$	$\Delta(x) = \frac{M_o}{6EIl}(-x^3 + l^2x)$	$x = \frac{l}{\sqrt{3}}$	$\frac{M_ol^2}{9\sqrt{3}EI}$

STRUCTURAL ANALYSIS: SKILLS FOR PRACTICE

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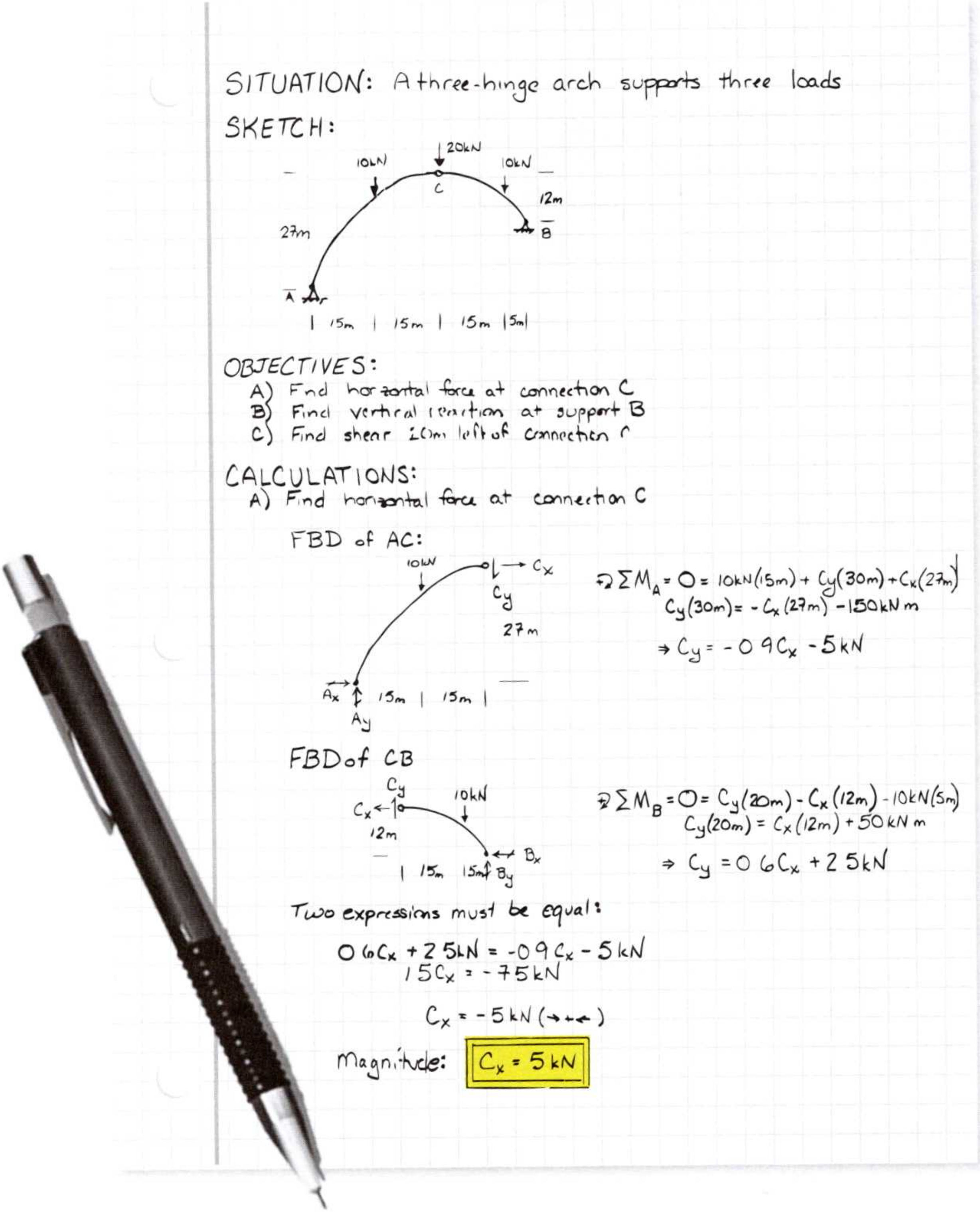

SITUATION: A three-hinge arch supports three loads

SKETCH:

OBJECTIVES:

A) Find horizontal force at connection C
B) Find vertical reaction at support B
C) Find shear 20m left of connection C

CALCULATIONS:

A) Find horizontal force at connection C

FBD of AC:

$$\curvearrowleft \Sigma M_A = 0 = 10kN(15m) + C_y(30m) + C_x(27m)$$
$$C_y(30m) = -C_x(27m) - 150kN\,m$$
$$\Rightarrow C_y = -0\ 9C_x - 5kN$$

FBD of CB

$$\curvearrowleft \Sigma M_B = 0 = C_y(20m) - C_x(12m) - 10kN(5m)$$
$$C_y(20m) = C_x(12m) + 50kN\,m$$
$$\Rightarrow C_y = 0\ 6C_x + 2\ 5kN$$

Two expressions must be equal:

$$0\ 6C_x + 2\ 5kN = -0\ 9C_x - 5kN$$
$$1\ 5C_x = -7\ 5kN$$

$$C_x = -5kN\ (\rightarrow\leftarrow)$$

Magnitude: $\boxed{C_x = 5kN}$

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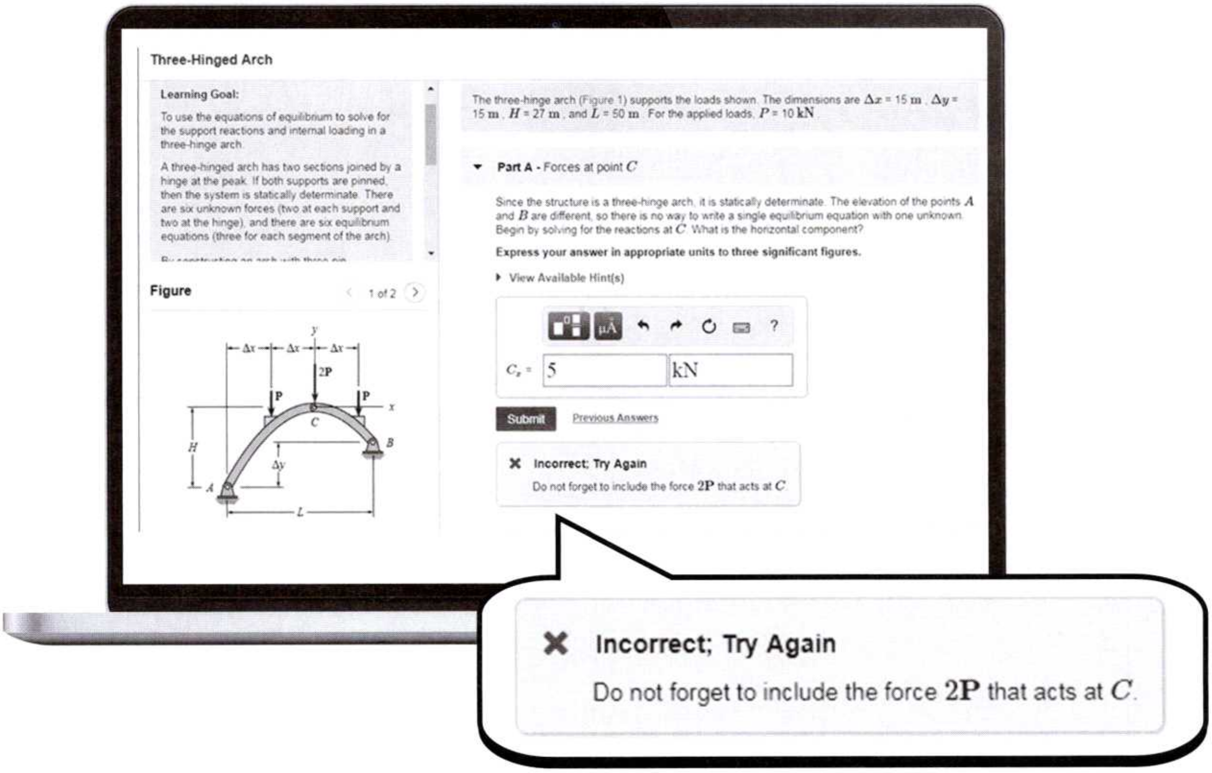

Three-Hinged Arch

Learning Goal:

To use the equations of equilibrium to solve for the support reactions and internal loading in a three-hinge arch.

A three-hinged arch has two sections joined by a hinge at the peak. If both supports are pinned, then the system is statically determinate. There are six unknown forces (two at each support and two at the hinge), and there are six equilibrium equations (three for each segment of the arch).

The three-hinge arch (Figure 1) supports the loads shown. The dimensions are Δx = 15 m , Δy = 15 m , H = 27 m , and L = 50 m . For the applied loads, P = 10 kN .

Part A - Forces at point C

Since the structure is a three-hinge arch, it is statically determinate. The elevation of the points A and B are different, so there is no way to write a single equilibrium equation with one unknown. Begin by solving for the reactions at C. What is the horizontal component?

Express your answer in appropriate units to three significant figures.

View Available Hint(s)

C_x = 5 kN

✖ **Incorrect; Try Again**

Do not forget to include the force $\mathbf{2P}$ that acts at C.

✖ **Incorrect; Try Again**

Do not forget to include the force $\mathbf{2P}$ that acts at C.

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PREFACE

Motivation for a New Text

Let's be realistic, most structural analysis performed in practice is done on a computer. So why do we need another text on how to perform analysis by hand? Because most structural analysis is performed using a computer. That might sound like circular logic, but think about it for a moment. A text on hand methods for structural analysis should be focused on skills needed to complement computer aided analysis, and I couldn't find one of those.

If you ask experienced engineers, there are three practical reasons for performing hand calculations: 1) some problems are faster to solve by hand than by computer, 2) hand methods can be more efficient in the preliminary design phase where we don't yet know the member properties, and 3) hand methods make up many of the tools practitioners use for evaluating detailed analysis results. The topics in this text were carefully chosen to support these three purposes. That meant developing several chapters dedicated to skills used by experienced engineers but not found in other textbooks (e.g., approximate analysis of braced frames, approximating drift, analysis of rigid diaphragms).

Yes, computers have made it possible for us to design structures that could not have been designed before. Nevertheless, even today most structures could still be designed by hand. It is the increase in efficiency that makes computers indispensable in the modern design process. With that increased efficiency, however, also comes the ability to make errors faster than ever before. Therefore, it is especially important that new engineers learn the skills for and develop the habit of evaluating the reasonableness of structural analysis results.

The evaluation skills presented in this text are the result of a ten year project to gather experience from practicing structural engineers and incorporate it in the classroom based on principles from cognitive science. Students following a traditional curriculum and practitioners both took an exam to measure their ability to identify the most reasonable answer and explain why. As expected, practitioners outperformed the students. With the curriculum presented in this text, however, students performed much better on the exam than students following the traditional curriculum. In fact, they cut the gap with practitioners in half.

The curriculum in this text emphasizes developing intuition for reasonable answers and cultivating the habit of predicting results. Intuition allows experienced practitioners to know if a result is not reasonable without giving it conscious thought. The fastest way to develop intuition is to practice evaluation skills routinely and to reflect on the thought process we used. That reflection is called metacognition and is fostered in most of the homework problems in this text. Expert evaluators of results will tell you that they start by predicting results. There are important reasons from cognitive psychology for why it should be in that order, so predicting results before performing detailed analysis is a routine part of the homework and example problems in this text. These skills and habits are valuable not only for students going on to practice structural engineering, but for our students going into any field of engineering.

So while developing a new text, why not address other issues students bring up about their structural analysis textbooks and courses. One such issue is not seeing how the theory connects with the real world. It is difficult for someone new to structural engineering to make the connection between stick figures on a page and real structures they see in the world. To help students make this connection, every example and homework problem is based on a real-world structure with a scenario motivating the requested analysis.

Another issue is the amount of detail in the examples. Students learn a lot by reviewing worked examples and reflecting on why each step is taken. To help in that learning, the examples in this text carry units throughout all calculations and the examples don't skip steps. In addition, the calculations are augmented with comments explaining why different steps were performed and what the results mean.

Organization

Each chapter begins with Motivation: a brief description of why the topics in that chapter are important to practice structural engineering. Most of the sections within the chapters are organized with the following format: Introduction, How-To, Section Highlights (boxed and shaded for easy identification), and Example Problems (boxed for easy identification). The homework problems are grouped at the end of each chapter and are easily identified by a ribbon down the side of the page.

Homework Problems and Example Structure

The homework format is another product of the ten year study. The homework problems are structured to achieve three goals: 1) develop intuition, 2) practice the concept, and 3) accurately evaluate results.

Most homework problems begin with students making a guess about some part of the solution in order to promote development of intuition. It is important to the development process that students make a **guess** without fear of being wrong. Therefore, this part should be graded based on whether it was done or not. If students believe that the quality of the guess will impact their score, they will wait until after they have generated a solution before writing down their guess.

The middle part of each homework problem emphasizes application of the concepts covered in that section of the text. This is the traditional hand calculation portion.

Since many of the hand methods in this text are useful for evaluating computer analysis results, homework problems for about half of the chapters also require that the student calculate the result using structural analysis software. The student is asked to verify fundamental principles for their result (i.e., all equations of equilibrium are satisfied) and features of the graphical solution (e.g., segment of constant shear diagram value where there is no applied load).

The student is then asked to make a comprehensive argument that the computer analysis results are reasonable. For full credit, the student should use all of the previous parts of the homework problem (except the guess) to demonstrate that the computer results are reasonable: hand solution(s), verification of fundamental principles, and verification of features of the graphical solution. In this argument the hand solution part of the homework might have used an approximate analysis method. In those cases, the student should recognize that the hand and computer solutions should not match perfectly. The student will need to decide whether the difference is acceptable or not.

Grading Advice

Each problem that starts with an initial guess ends with reflection on that guess. The student is asked to compare the initial guess with the computer results and reflect on why the two are similar or different. Again, if the instructor wants to successfully promote development of intuition, the students must feel that there is no disadvantage to having an initial guess that does not match the computer result. An example rubric that can be used to score this reflection is shown in the following table:

	Full Credit (10)	**Adequate (7)**	**Marginal (5)**	**Unacceptable (0)**
If the guess and solution generally match:	Explains how previous experience and/or fundamental principles led to a guess that matched.	Identifies previous experienced and/or fundamental principles that guided the guess.	Attempts to explain why the guess matched the solution, but shows little understanding of pertinent fundamental principles and/or features of the solution.	No demonstration of understanding of why the guess matched the solution.
If the guess and solution generally *do not* match:	Explains why guess does not match based on previous experience and/or fundamental principles.	Identifies fundamental principles and/or features of the solution that could be used to explain the difference.	Attempts to explain the difference, but shows little understanding of pertinent fundamental principles and/or features of the solution.	No demonstration of understanding of why the guess did not match the solution.

Examples of how to apply the rubric to score student reflections are also available.

Using Structural Analysis Software

This text is not based on the use of a specific structural analysis software program. Any structural analysis program that can model 2D trusses and frames will be sufficient. Note that in order to model braced frames, the program must allow specification of pinned connections in an otherwise rigid frame.

If students do not already have access to structural analysis software, they can obtain free software via the internet. For example, basic use of the program MASTAN2 can be taught in a single lecture. The program is available for free download from the following website:

www.mastan2.com

Instructor Resources

The single objective of this text is to prepare your students with skills and habits for the practice of engineering, regardless of the specialty. Trust the process. Do all the steps. The organization of the example and homework problems is based on how experienced engineers approach analysis and is supported by cognitive science.

All instructor resources are available for download at www.pearsonhighered.com. If you are in need of a login and password for this site, please contact your local Pearson representative.

Mastering Engineering

This online tutorial and assessment program allows you to integrate dynamic homework with automated grading of the calculation parts of problems and personalized feedback. Mastering^{TM} Engineering allows you to easily track the performance of your entire class on an assignment-by-assignment basis, or the detailed work of an individual student. For more information visit www.masteringengineering.com.

Instructor Solutions Manual

Fully worked-out solutions to the homework problems.

PowerPoint Lecture Images

All figures from the text are available in PowerPoint for your lecture needs. These are used to give students real visual examples of the phenomena.

Learning Catalytics

This "bring your own device" student engagement, assessment and classroom intelligence system enables you to measure student learning during class, and adjust your lectures accordingly. A wide variety of question and answer types allows you to author your own questions, or you can use questions already authored into the system. For more information visit www.learningcatalytics.com or click on the Learning Catalytics link inside Mastering Engineering.

Prerequisite Courses

This text is constructed assuming that students have already completed statics and mechanics of materials courses; therefore, topics such as determinate truss analysis have been omitted.

Acknowledgments

I am blessed to be able to share this approach to teaching structural analysis with you. The old phrase "It takes a village" is so true. All of my students over the years have inspired me and helped me in creating this text. I greatly appreciate their hard work and feedback. My colleagues in Civil and Environmental Engineering at Rose-Hulman have been extremely supportive of me as I focused on making this available to you. There is nothing we won't do for each other to provide a better student experience.

The approach to structural analysis and verification of results unique to this text is a direct result of what I learned from interviews with dozens of experienced structural engineers. Their passion and input really made this text about skills for practice.

The team that Pearson assembled to help me in this process has been stellar. Their unified focus has been to bring my vision to life in order to help you. Part of that team is faculty reviewers, and their feedback made this text so much better. Some of them want to remain anonymous, but others agreed to allow me to thank them publicly:

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- Tomasz Arciszewski, George Mason University
- Mikhail Gershfeld, California State Polytechnic University
- Thomas H. Miller, Oregon State University
- Gokhan Pekcan, University of Nevada – Reno
- Hayder A. Rasheed, Kansas State University
- Hung-Liang (Roger) Chen, West Virginia University
- Husam Najm, Rutgers University
- Steven Vukazich, San Jose State University

This text doesn't happen without the support of my friends and family, especially the love of my life Diane. Because they believe in sharing my passion with you, they sacrificed and encouraged me. For example, all of the photos in this text were taken by me. That means my family endured many stops and detours during our travels in order to hunt for those images.

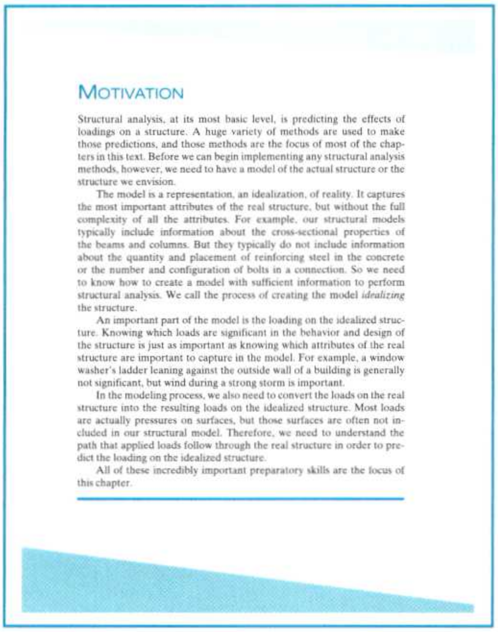
The words "thank you" don't seem adequate, but it is so important for me to thank all these people for joining into the vision for this text. The impact of their contributions permeates every page. Each and every person has my sincere thanks and gratitude!

How You Can Help

This text is meant to help you, both instructor and student. If you see an opportunity to do that better please let me know. As I said, it takes a village.

Thanks!
Prof. Jim Hanson
james.hanson@rose-hulman.edu

VISUAL WALKTHROUGH



MOTIVATION

Structural analysis, at its most basic level, is predicting the effects of loadings on a structure. A huge variety of methods are used to make those predictions, and those methods are the focus of most of the chapters in this text. Before we can begin implementing any structural analysis methods, however, we need to have a model of the actual structure or the structure we envision.

The model is a representation, an idealization, of reality. It captures the most important attributes of the real structure, but without the full complexity of all the attributes. For example, our structural models typically include information about the cross-sectional properties of the beams and columns. But they typically do not include information about the quantity and placement of reinforcing steel in the concrete or the number and configuration of bolts in a connection. So we need to know how to create a model with sufficient information to perform structural analysis. We call the process of creating the model *idealizing* the structure.

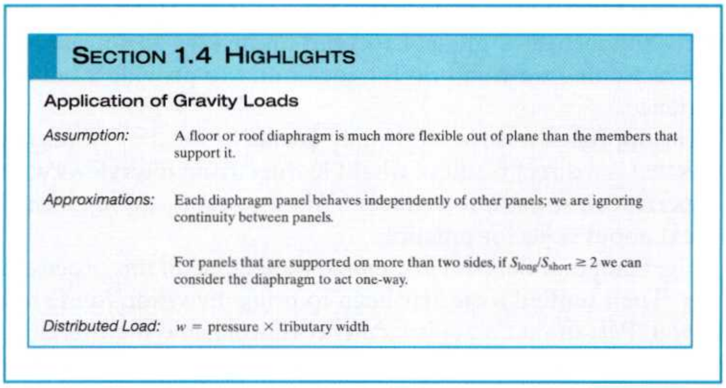
An important part of the model is the loading on the idealized structure. Knowing which loads are significant in the behavior and design of the structure is just as important as knowing which attributes of the real structure are important to capture in the model. For example, a window washer's ladder leaning against the outside wall of a building is generally not significant, but wind during a strong storm is important.

In the modeling process, we also need to convert the loads on the real structure into the resulting loads on the idealized structure. Most loads are actually pressures on surfaces, but those surfaces are often not included in our structural model. Therefore, we need to understand the path that applied loads follow through the real structure in order to predict the loading on the idealized structure.

All of these incredibly important preparatory skills are the focus of this chapter.

Motivations

Motivations start each chapter to provide justification and real world context for what students will be learning about in the chapter and why it's important.



SECTION 1.4 HIGHLIGHTS

Application of Gravity Loads

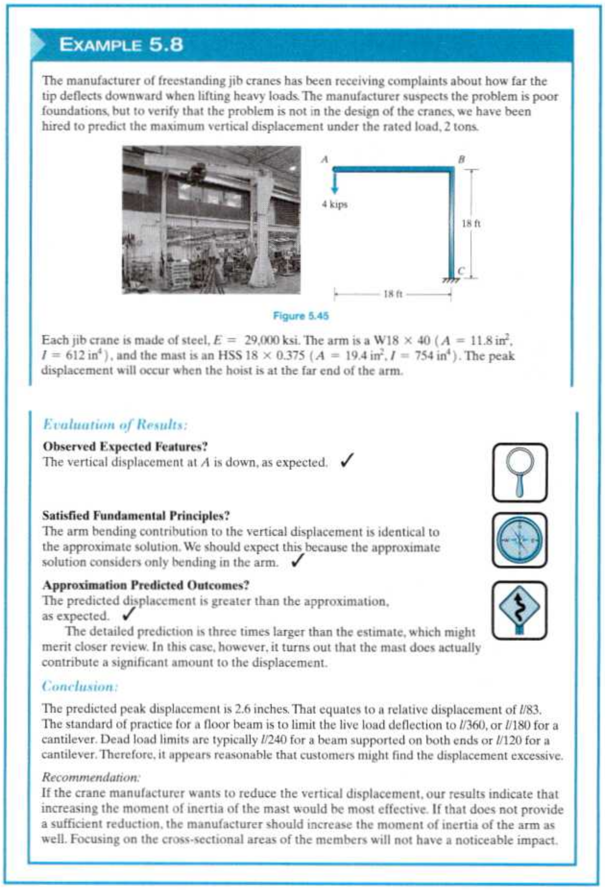
Assumption:	A floor or roof diaphragm is much more flexible out of plane than the members that support it.
Approximations:	Each diaphragm panel behaves independently of other panels; we are ignoring continuity between panels.
	For panels that are supported on more than two sides, if $S_{long}/S_{short} \geq 2$ we can consider the diaphragm to act one-way.
Distributed Load:	w = pressure × tributary width

Section Highlights

Section Highlights are boxed and highlighted for easy identification.

Examples

The text emphasizes developing intuition for reasonable answers and cultivating the habit of predicting results. *Evaluation of Results* within the Example Problems include icons and headings reinforcing the importance of evaluating results via Observations of Expected Features, Satisfaction of Fundamental Principles, and confirmation that the Approximations Predicted the Outcomes.



EXAMPLE 5.8

The manufacturer of freestanding jib cranes has been receiving complaints about how far the tip deflects downward when lifting heavy loads. The manufacturer suspects the problem is poor foundations, but to verify that the problem is not in the design of the cranes, we have been hired to predict the maximum vertical displacement under the rated load, 2 tons.

Figure 5.45

Each jib crane is made of steel, $E = 29{,}000$ ksi. The arm is a W18 × 40 ($A = 11.8\ \text{in}^2$, $I = 612\ \text{in}^4$), and the mast is an HSS 18 × 0.375 ($A = 19.4\ \text{in}^2$, $I = 754\ \text{in}^4$). The peak displacement will occur when the hoist is at the far end of the arm.

Evaluation of Results:

Observed Expected Features?
The vertical displacement at A is down, as expected. ✓

Satisfied Fundamental Principles?
The arm bending contribution to the vertical displacement is identical to the approximate solution. We should expect this because the approximate solution considers only bending in the arm. ✓

Approximation Predicted Outcomes?
The predicted displacement is greater than the approximation, as expected. ✓

The detailed prediction is three times larger than the estimate, which might merit closer review. In this case, however, it turns out that the mast does actually contribute a significant amount to the displacement.

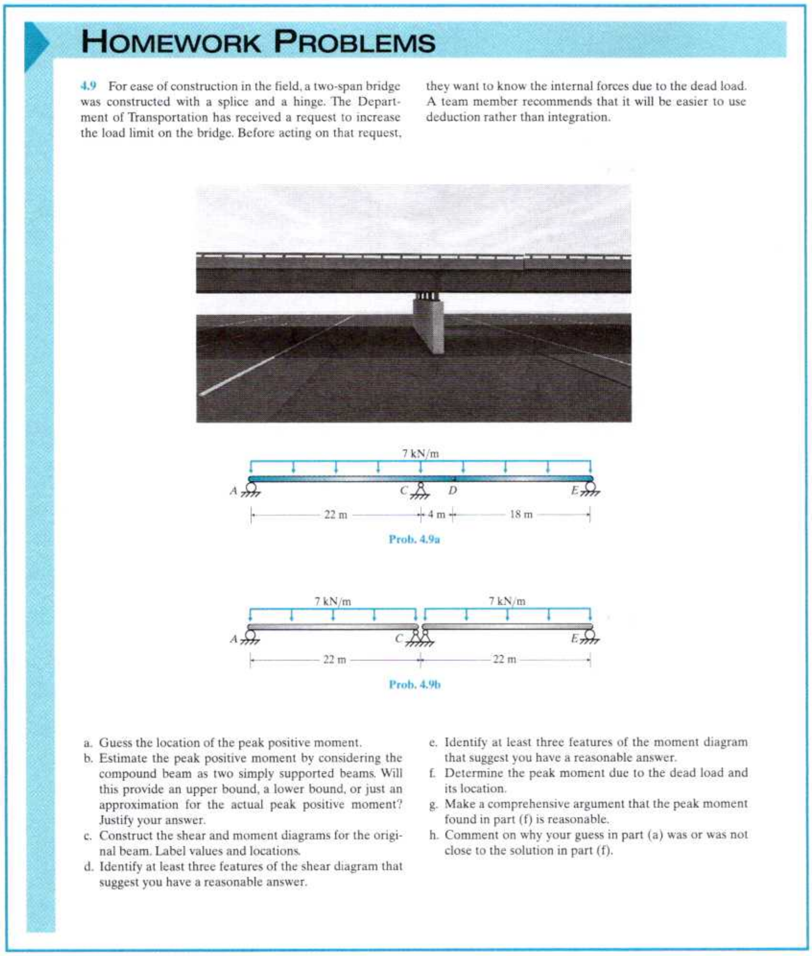
Conclusion:

The predicted peak displacement is 2.6 inches. That equates to a relative displacement of $l/83$. The standard of practice for a floor beam is to limit the live load deflection to $l/360$, or $l/180$ for a cantilever. Dead load limits are typically $l/240$ for a beam supported on both ends or $l/120$ for a cantilever. Therefore, it appears reasonable that customers might find the displacement excessive.

Recommendation:
If the crane manufacturer wants to reduce the vertical displacement, our results indicate that increasing the moment of inertia of the mast would be most effective. If that does not provide a sufficient reduction, the manufacturer should increase the moment of inertia of the arm as well. Focusing on the cross-sectional areas of the members will not have a noticeable impact.

Homework Problems

The homework problems are structured to achieve three goals: 1) develop intuition, 2) practice the concept, and 3) accurately evaluate results. Most homework problems and examples begin with students making a guess about some part of the solution in order to promote development of intuition. Each problem that starts with an initial guess ends with a reflection on that guess.



HOMEWORK PROBLEMS

4.9 For ease of construction in the field, a two-span bridge was constructed with a splice and a hinge. The Department of Transportation has received a request to increase the load limit on the bridge. Before acting on that request, they want to know the internal forces due to the dead load. A team member recommends that it will be easier to use deduction rather than integration.

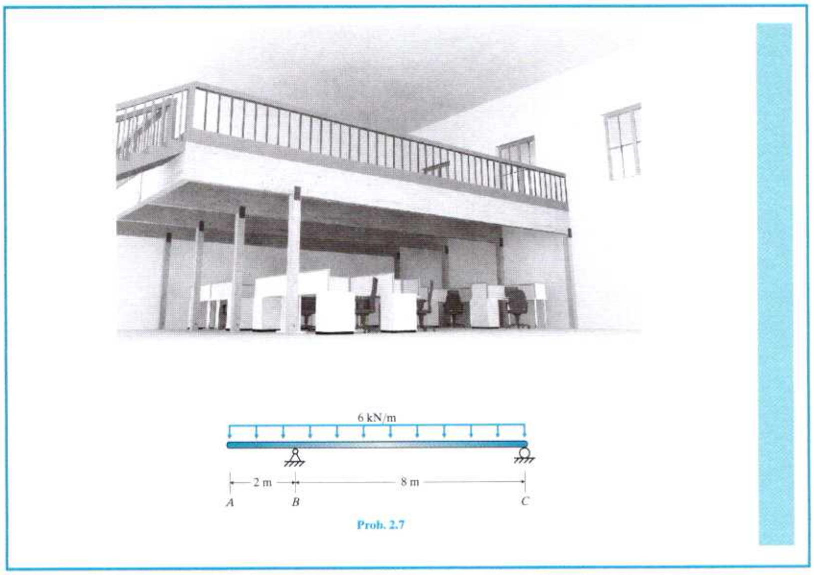
Prob. 4.9a

Prob. 4.9b

a. Guess the location of the peak positive moment.
b. Estimate the peak positive moment by considering the compound beam as two simply supported beams. Will this provide an upper bound, a lower bound, or just an approximation for the actual peak positive moment? Justify your answer.
c. Construct the shear and moment diagrams for the original beam. Label values and locations.
d. Identify at least three features of the shear diagram that suggest you have a reasonable answer.
e. Identify at least three features of the moment diagram that suggest you have a reasonable answer.
f. Determine the peak moment due to the dead load and its location.
g. Make a comprehensive argument that the peak moment found in part (f) is reasonable.
h. Comment on why your guess in part (a) was or was not close to the solution in part (f).

Real-World Connection

Each example and homework problem starts with a real-world scenario to show how the analysis skills apply to practice. With that scenario is a photo or highly detailed photorealistic rendering of the structure to connect the idealization to reality.

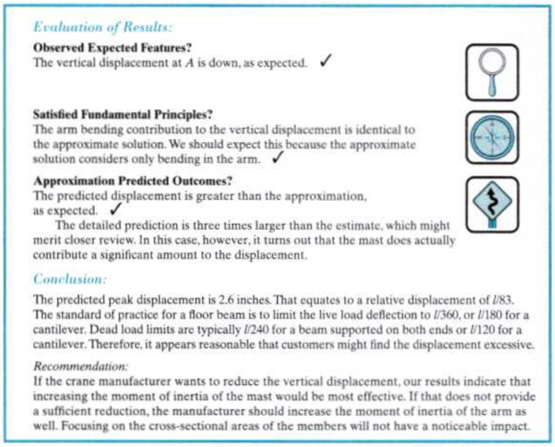


Prob. 2.7

CHAPTER 0

EVALUATING RESULTS

The reality is that in the practice of structural engineering we typically rely on complex structural analyses to finalize our designs. Our obligation to hold paramount the safety, health and welfare of the public[1] means that we must *always* evaluate the reasonableness of our results. Practitioners use a wide variety of tools to evaluate their analysis and design results. If we focus specifically on how experienced practitioners evaluate structural analysis results, their tools can be organized into three categories: features of the solution, fundamental principles, and approximations.



Evaluation of Results:

Observed Expected Features?
The vertical displacement at A is down, as expected. ✓

Satisfied Fundamental Principles?
The arm bending contribution to the vertical displacement is identical to the approximate solution. We should expect this because the approximate solution considers only bending in the arm. ✓

Approximation Predicted Outcomes?
The predicted displacement is greater than the approximation, as expected. ✓

The detailed prediction is three times larger than the estimate, which might merit closer review. In this case, however, it turns out that the mast does actually contribute a significant amount to the displacement.

Conclusion:

The predicted peak displacement is 2.6 inches. That equates to a relative displacement of $l/83$. The standard of practice for a floor beam is to limit the live load deflection to $l/360$, or $l/180$ for a cantilever. Dead load limits are typically $l/240$ for a beam supported on both ends or $l/120$ for a cantilever. Therefore, it appears reasonable that customers might find the displacement excessive.

Recommendation:

If the crane manufacturer wants to reduce the vertical displacement, our results indicate that increasing the moment of inertia of the mast would be most effective. If that does not provide a sufficient reduction, the manufacturer should increase the moment of inertia of the arm as well. Focusing on the cross-sectional areas of the members will not have a noticeable impact.

Observed Expected Features?

Based on our understanding of mechanics principles and the situation, we expect to see certain features in the results of our analysis. For example, we expect a beam to have a smooth deflected shape as long as there is no internal hinge. Similarly, when we look in the mirror we expect to see certain attributes. Therefore, whenever we have compared features of the solution in the example problems, we have put a small mirror.

Satisfied Fundamental Principles?

Fundamental principles such as equilibrium and compatibility must be satisfied at all times. Just as a compass always points north, these fundamental principles always apply. We typically learn these principles in our statics and mechanics of materials courses. Now we will rely on them to help verify that our results are reasonable. To help you recognize where we used fundamental principles to verify our results in an example problem, we have put a small compass with the check.

Approximations Predicted Outcomes?

We make approximations in order to obtain a solution quickly and with reduced likelihood of error. Approximations are like making a curved road straight; it is not the same journey, but you finish in a similar place. Practitioners use approximations extensively, so we will cover many different approximation tools. We have put a small road sign with each approximation used to verify results.

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[1] Part of First Fundamental Cannon from the ASCE Code of Ethics, and similar to part of the Code of Professional Conduct of the European Council of Civil Engineers

CHAPTER 1

LOADS AND STRUCTURE IDEALIZATION

In order to convert reality into something we can analyze, we create idealized versions of the structure and loading.

MOTIVATION

Structural analysis, at its most basic level, is predicting the effects of loadings on a structure. A huge variety of methods are used to make those predictions, and those methods are the focus of most of the chapters in this text. Before we can begin implementing any structural analysis methods, however, we need to have a model of the actual structure or the structure we envision.

The model is a representation, an idealization, of reality. It captures the most important attributes of the real structure, but without the full complexity of all the attributes. For example, our structural models typically include information about the cross-sectional properties of the beams and columns. But they typically do not include information about the quantity and placement of reinforcing steel in the concrete or the number and configuration of bolts in a connection. So we need to know how to create a model with sufficient information to perform structural analysis. We call the process of creating the model *idealizing* the structure.

An important part of the model is the loading on the idealized structure. Knowing which loads are significant in the behavior and design of the structure is just as important as knowing which attributes of the real structure are important to capture in the model. For example, a window washer's ladder leaning against the outside wall of a building is generally not significant, but wind during a strong storm is important.

In the modeling process, we also need to convert the loads on the real structure into the resulting loads on the idealized structure. Most loads are actually pressures on surfaces, but those surfaces are often not included in our structural model. Therefore, we need to understand the path that applied loads follow through the real structure in order to predict the loading on the idealized structure.

All of these incredibly important preparatory skills are the focus of this chapter.

1.1 Loads

Introduction

When analyzing and designing a structure, we consider the types of loads that could reasonably act on the structure during its lifetime. For example, it is very unlikely that a structure built on the earth's surface will experience the load of an asteroid impact. Therefore, asteroids are typically not on the list of loads we consider in design. A very strong wind, however, is a reasonable possibility, so we design for that.

The reasonably likely values of load for which we should design are often identified in standards like *Minimum Design Loads for Buildings and Other Structures* (ASCE 2017) or codes like the *AASHTO LRFD Bridge Design Specifications* (AASHTO 2012) and the Eurocode *EN 1991: Actions on Structures* (CEN 2002–2006). In some situations, we anticipate loads that require us to search other resources (e.g., floating ice pushing on a marine structure). In all cases, we can increase the magnitude of loads and add types of loads if, in our judgment, such a change more accurately reflects the risk.

How the load acts on a structure depends on the type of load.

How-To

Dead (D)

Dead load is the self-weight of a structure. The dead load typically includes everything fixed in place, even nonstructural items such as flooring, plumbing, and hand rails. Dead load is considered a gravity load because it acts vertically (due to the effect of gravity).

The self-weight of nonstructural items is often called *superimposed dead load* because the effect is added to the self-weight of the structural members. Examples of superimposed dead load include the self-weights of electrical conduit, light fixtures, air ducts, carpeting, and ceiling tiles.

The total dead load is the product of the density of the material and the volume of the material. Table 1.1 shows typical densities of some common construction materials. For materials with specified or common thicknesses, the dead load is often presented as weight per unit of surface area (Table 1.2). Multiplying the density by the cross-sectional area gives a distributed load that acts along the length of the structure (Figure 1.1).

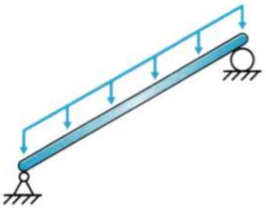


Figure 1.1 Load acting on an inclined structure.

Live (L)

We consider loads associated with the use or occupancy of a structure as live loads. Examples include people, vehicles, furniture, books, merchandise, and partition walls (interior, nonstructural walls that are reasonably likely to be moved over the life of the structure). The two common exceptions are stored liquids and bulk materials (e.g., corn, sand) because those are given their own categories. Live load is also a gravity load, so it acts vertically.

Unlike dead load, live load can act everywhere, somewhere, or nowhere. By this we mean that the full floor space might be used (everywhere), only some of the floor space might be used (somewhere), or at times none of the floor space will have live load (nowhere). We must consider all three possibilities to find the most extreme design case for a structural member.

Table 1.1 Densities of Common Construction Materials (Based on ASCE 2017)

Material	**pcf**	**kN/m^3**
Concrete, Reinforced:		
Cinder	111	17.4
Stone	150	23.6
Glass	160	25.1
Masonry, Brick (solid parts of hollow masonry):		
Hard	130	20.4
Soft	100	15.7
Masonry, Concrete (solid parts of hollow masonry):		
Lightweight units	105	16.5
Normal weight units	135	21.2
Plywood	36	5.7
Steel, Cold-Drawn	492	77.3
Wood, Seasoned:		
Ash, commercial white	41	6.4
Fir, Douglas, coast region	34	5.3
Oak, commercial reds and whites	47	7.4
Pine, southern yellow	37	5.8
Redwood	28	4.4

Table 1.2 Dead Load Pressures of Common Construction Materials (Based on ASCE 2017)

Component	**psf**	**kN/m^2**
Ceilings:		
Acoustical fiberboard	1	0.05
Mechanical duct allowance	4	0.19
Suspended steel channel system	2	0.10
Coverings, Roof, and Wall Composition:		
Three-ply ready roofing	1	0.05
Four-ply felt and gravel	5.5	0.26
Deck, metal, 18 gauge	3	0.14

(continued)

Table 1.2 (Continued)

Component	psf	kN/m^2
Insulation, roof boards (per inch or mm thickness):		
Fiberboard	1.5	0.0028
Perlite	0.8	0.0015
Polystyrene foam	0.2	0.004
Urethane foam with skin	0.5	0.009
Waterproofing membranes:		
Bituminous, gravel-covered	5.5	0.26
Liquid applied	1	0.05
Single-ply, sheet	0.7	0.03
Floors and Floor Finishes:		
Ceramic or quarry tile (3/4-in.) on 1/2-in. mortar bed	16	0.77
Hardwood flooring, 7/8-in.	4	0.19
Linoleum or asphalt tile, 1/4-in.	1	0.05
Frame Partitions:		
Movable steel partitions	4	0.19
Wood or steel studs, 1/2-in. gypsum board each side	8	0.38

The magnitude of the live load we expect, and therefore use in design, depends on the use of the area. Table 1.3 lists live load pressures for a variety of building uses. Live load for bridges is typically a uniform lane load typically a uniform lane load and a single point load that represents the design truck. Note that for most building occupancy categories it is extremely unlikely that large areas are experiencing the full live load simultaneously. Therefore, the codes allow us to reduce the average magnitude of the live load based on the total area being supported by a member. This process is called *live load reduction* and is outside the scope of this text.

Most areas that experience live load are flat. But sometimes we deal with inclined areas such as ramps or theater seating. In those cases, we consider the live load to act on the *horizontal projection* (Figure 1.2). The horizontal projection is the area seen from above, the plan view. We do this because a steeper ramp has more surface area but does not hold more people. The number of people who can push together is limited by the length and width as seen from above.

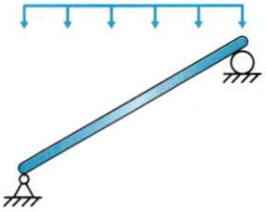


Figure 1.2 Load acting on the horizontal projection of an inclined structure.

Snow (S)

Snow is another gravity load, thus acting down. The amount of snow that falls from the sky onto a given area is not dependent on the surface area but on the length and width as seen from above; therefore, snow acts on the horizontal projection just like live load. Because snow is an environmental load, the weight of snow that accumulates on the ground depends on the geographic region. We modify the ground snow load to account for terrain effects around the structure, thermal behavior of the structure, and potential impact of failure.

Table 1.3 Live Load Pressures (Based on ASCE 2017)

Occupancy or Use	psf	kN/m^2
Assembly Areas and Theaters: [a]		
Fixed seats (fastened to floor)	60	2.87
Lobbies	100	4.79
Movable seats	100	4.79
Platforms (assembly)	100	4.79
Stage floors	150	7.18
Balconies and decks [b]	≤ 100	≤ 4.79
Corridors:		
First floor	100	4.79
Other floors [c]		
Dining Rooms and Restaurants [a]	100	4.79
Libraries:		
Reading rooms	60	2.87
Stack rooms [a]	150	7.18
Corridors above first floor	80	3.83
Manufacturing and Storage Warehouses: [a, d]		
Light	125	6.00
Heavy	250	11.97
Office Buildings: [e]		
Lobbies and first-floor corridors	100	4.79
Offices	50	2.40
Corridors above first floor	80	3.83
Roofs:		
Ordinary flat, pitched, and curved roofs	20	0.96
Roofs used for roof gardens	100	4.79

[a] Live load reduction for these uses is not permitted.

[b] Requirement is 1.5 times the live load for the occupancy served. Need not exceed the values shown.

[c] Same as occupancy served except as indicated.

[d] Shall be designed for heavier loads if required for anticipated storage. Live load reduction for these uses is not permitted.

[e] Shall also be designed for a single point load of 2000 lb or 8.90 kN without the pressure.

Because snow can be moved by wind and might slide on sloped roofs, we typically consider partial loading, unbalanced loading, drifting, and rain-on-snow surcharge. We demonstrate some of these in examples throughout this text.

Wind (W)

Wind is an environmental load that depends on many factors. The wind pressures we use in design are based on geographic location, terrain effects around the structure, shape of the structure, potential impact of failure, and height above the ground surface. The peak wind velocity increases with distance from the ground; therefore, wind pressure on a structure is higher at the top than at the bottom.

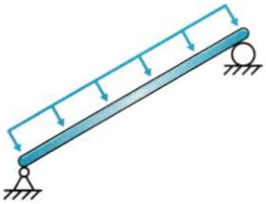


Figure 1.3 Load acting normal to the surface of an inclined structure.

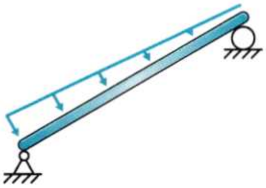


Figure 1.4 Load acting normal to the surface and increasing with depth on an inclined structure.

The wind pressures all act normal to the structure surfaces (Figure 1.3). Therefore, wind load tends to have vertical and lateral components. On the windward side (upwind side), wind typically creates pressure on the surface; on the leeward side (downwind side), it typically creates suction.

Fluid (F) and Soil (H)

In some cases, structures hold fluids in quantities large enough that we need to consider the load (e.g., swimming pool, cistern, chemical vat). Fluids stored in the structure tend to be static. Therefore, the pressure on the structure is hydrostatic and acts normal to the surface. Because the pressure is generated by gravity, the magnitude of the pressure increases with depth (Figure 1.4).

Soil has a similar effect on a structure. If the structure does not move relative to the soil, the at-rest condition, then the soil creates pressure that increases with depth and acts normal to the surface. If the structure moves toward the soil (passive condition) or away from the soil (active condition), there might also be friction stress parallel to the surface.

Because both fluid and soil pressures act normal to surfaces, they might have horizontal and vertical components.

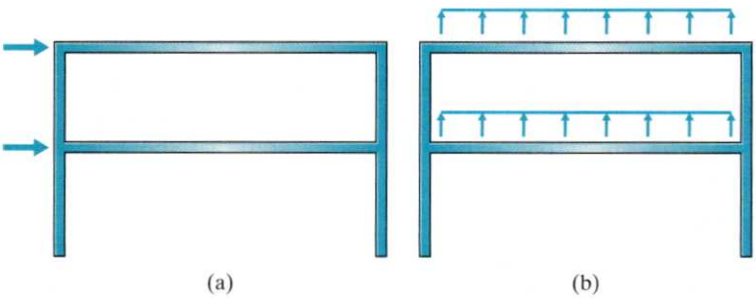
Earthquake (E)

Earthquake loads are fundamentally different from the other loads. All of the other loads are forces that act on the structure. In an earthquake, however, the ground moves underneath the structure. The resulting acceleration of the structural mass has an effect similar to an applied force.

Except for extreme cases, we approximate the dynamic effect on the structure with an equivalent static force. That force is dispersed throughout the structure wherever the largest concentrations of mass are. Therefore, we typically idealize earthquake load as forces applied laterally at the floor and roof levels (Figure 1.5a). Under some circumstances, we also consider the vertical effect. In those cases, we idealize the vertical component of the earthquake load as distributed along the floor and roof levels just like dead load (Figure 1.5b).

Units

Loads act on structures as pressures (e.g., kPa = kN/m^2 or psf = lb/ft^2). The conversion of those pressures to distributed loads on members is covered in Sections 1.4 and 1.5. The units of distributed loads are force/length (e.g., kN/m or plf = lb/ft). Because of the large magnitude of forces used in structural engineering, we often use a unit of force uncommon in other disciplines of engineering: the kip, k. A kip is 1000 lb. In SI units, we typically measure force in kilonewtons, kN.



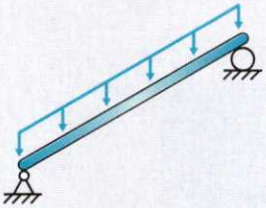
(a) (b)

Figure 1.5 Earthquake idealized as equivalent static forces at the levels with the most concentrated mass: the floor and roof; (a) Lateral forces for horizontal seismic effects; (b) Distributed loads for vertical seismic effects.

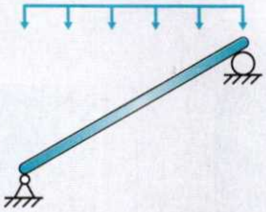
SECTION 1.1 HIGHLIGHTS

Loads

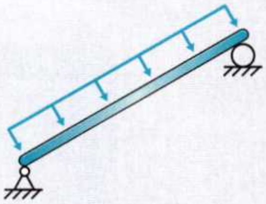
Application of loads by type:



Along member: *Dead*



Along horizontal projection: *Live, Snow*



Normal to surface: *Fluid, Soil, Wind*

EXAMPLE 1.1

Find the dead load pressure for the flooring cross-section shown.

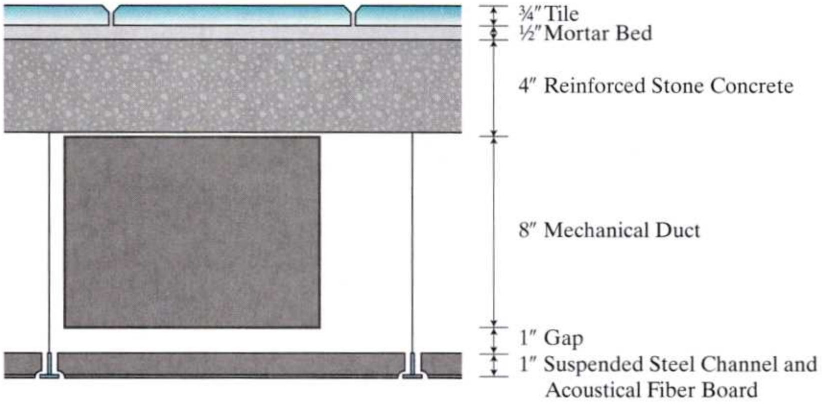


Figure 1.6

Detailed Solution:

From Table 1.2:	
Tile on mortar bed	16 psf
Mechanical duct allowance	4 psf
Suspended steel channel system	2 psf
Acoustical fiberboard	1 psf
From Table 1.1:	
Reinforced stone concrete 150 pcf (4 in.)/(12 in./ft) =	50 psf
Total:	73 psf

EXAMPLE 1.2

Find the soil pressure along a 1-meter-wide strip of the inclined back of the retaining wall. The soil is a sand-gravel mix. For this type of soil, the typical pressure of the soil on the wall is 5.50 kN/m^2 per meter of depth.

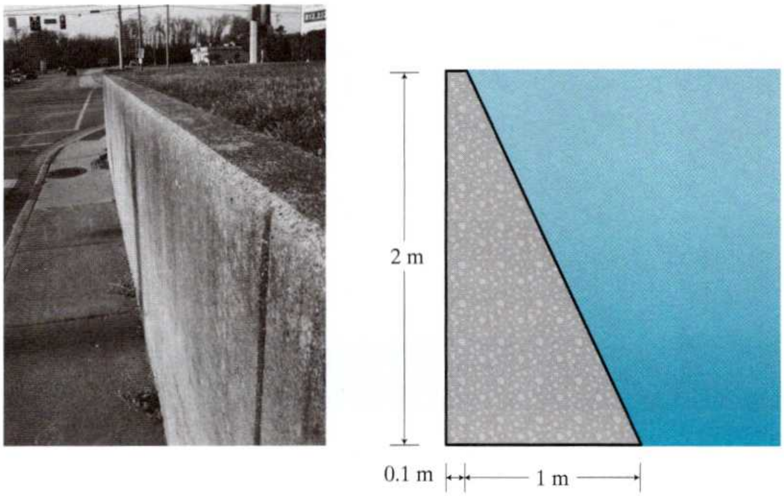


Figure 1.7

Detailed Analysis:

Pressure for a 1-m-strip of wall:	5.50 kN/m per m depth	$= 5.50$ kN/m^2
Pressure at top:	(5.50 kN/m^2)(0 m)	= 0 kN/m
Pressure at bottom:	(5.50 kN/m^2)(2 m)	= 11 kN/m
Angle:	$\tan^{-1}$(1 m/2 m)	= 26.6°

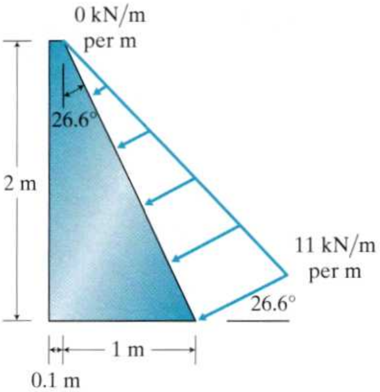


Figure 1.8

1.2 Load Combinations

Introduction

One of the primary goals of structural design is public safety. To have a safe design, we need structural analysis results sufficiently large that there is only a very small probability that the actual loading will exceed those results. To rationally develop those analysis results, we typically amplify the effects of the maximum likely load. The amount of amplification depends on the type of load because the peak magnitude of some types of load is more variable than for others.

Another consideration is that different types of loads often act simultaneously. It would be dangerous to consider the effects of only one load at a time. Therefore, we consider the effects of reasonably likely combinations of loads with load factors. To ensure public safety, we design for the structural analysis results based on the factored and combined effects.

How-To

In Section 1.1, we introduced the concept of maximum likely loads. But the peak load that a structure experiences actually has a probability distribution like the one shown in Figure 1.9. The magnitude that has an acceptably low probability of being exceeded is what we call the *maximum likely load*. The shape of the probability distribution is roughly the same for all types of loads, but the spread of the distribution changes for different types of loads (Figure 1.10).

In Figure 1.10, both distributions lead to the same maximum likely load magnitude, but the range of peak load magnitudes beyond the maximum likely value is much bigger for the dark blue graph. This means that

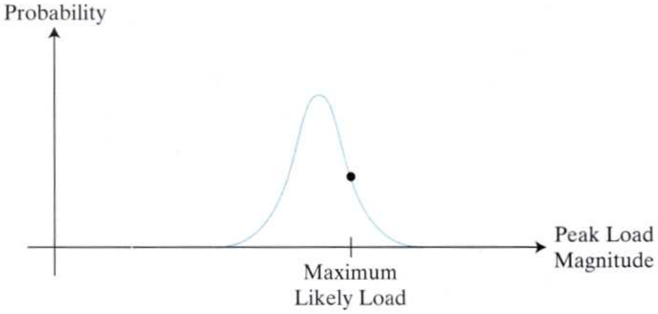


Figure 1.9 Probability distribution of the peak load that a structure experiences in its lifetime.

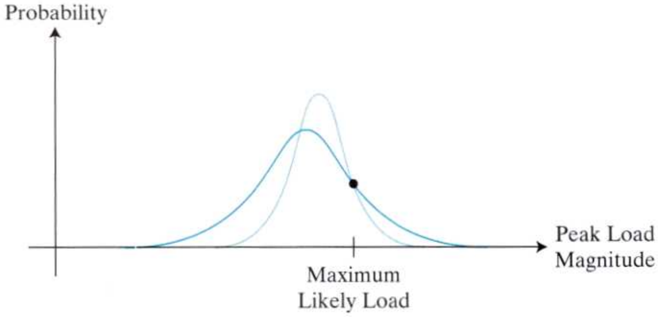


Figure 1.10 Probability distribution of the peak load for two different types of loads with exactly the same maximum likely peak load.

if the maximum likely value is exceeded with the dark blue load, it might reach a much larger value than would the light blue load.

In order to protect the safety, health, and welfare of the public, we use load factors to increase the maximum likely load effects in case the actual peak load exceeds the maximum likely value. We use different load factor values based on the spread of the probability distributions like the ones shown in Figure 1.10. For example, dead load has a narrower distribution, like the light blue curve, so we tend to know the maximum likely self-weight of a structure pretty well. Therefore, we give dead load a load factor of 1.2 in many of the load combinations from ASCE 7. Live load has a broader distribution, like the dark blue curve, so we give live load a load factor of 1.6 in many of the combinations.

The most extreme effect on a structure typically occurs when multiple loads act simultaneously. Therefore, we consider the combined effects of loads, as shown in Table 1.4. The factored and combined effect is called the *design value* (e.g., design moment, design reaction) because that is the value for which we must design the structure. We also call this the *ultimate value*.

The different combinations represent the likelihood of different types of loads reaching their peak simultaneously. For example, it is extremely unlikely that wind and earthquake will reach their maximum likely values at the same moment; therefore, none of the combinations have both wind and earthquake terms.

The combinations use some load factors less than 1 for the same reason. For example, consider combination 3. It is highly unlikely that a structure will experience an extreme live load at the same time as the worst snowstorm in years. People stay home during bad storms like that, but it is reasonable to expect some live load during the snowstorm. Therefore, combination 3 uses a factor of 0.5 on live load effects and a factor of 1.6 on snow effects.

It is important to use judgment with these load factors and combinations. If the effect of a type of load diminishes the effect of another type of load, we must consider the possibility that one or more of the loads does not act at all, a load factor of 0. The only exception is loads that will always act, such as dead. We see from the combinations that it is reasonable to reduce the load factor to 0.9 for a permanent load *if* that would increase the overall effect.

Table 1.4 Load Combinations with Load Factors (Based on ASCE 2017)

ID	Combination
1.	$1.4(D + F)$
2.	$1.2(D + F) + 1.6(L + H) + 0.5S$
3.	$1.2(D + F) + 1.6(S + H) + (0.5L \text{ or } 0.5W)^{a,b}$
4.	$1.2(D + F) + 1.0W + 1.6H + 0.5L + 0.5S^{a}$
5.	$0.9D + 1.0W + 1.6H$
6.	$1.2(D + F) + 1.0E + 1.6H + 0.5L + 0.2S^{a,c}$
7.	$0.9(D + F) + 1.0E + 1.6H^{c}$

[a] For all occupancies with live load pressure greater than 100 psf or classified as "assembly" (Table 1.3), the factor on L is 1.0 rather than 0.5.

[b] The "or" means that only the larger of the two effects need be considered.

[c] When considering vertical seismic load effect, E_v, consider upward or downward to maximize the effect.

SECTION 1.2 HIGHLIGHTS

Load Combinations

- Consider all relevant combinations.
- Permanent loads can have a load factor ranging from 0.9 to the maximum shown in the combinations.
- All other loads can have a load factor ranging from 0 to the maximum shown.

EXAMPLE 1.3

Our firm is designing timber roof trusses over the lobby at a new resort. To properly design the members and connections, our team needs to know the design tension and design compression for each member. We have been assigned two members: *AB* and *AF*.

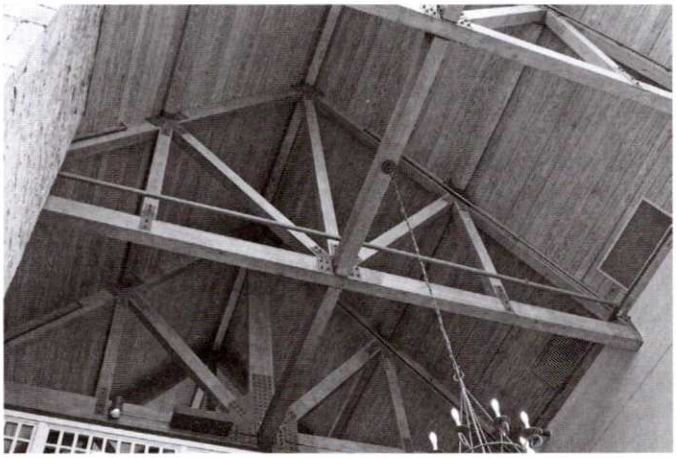


Figure 1.11

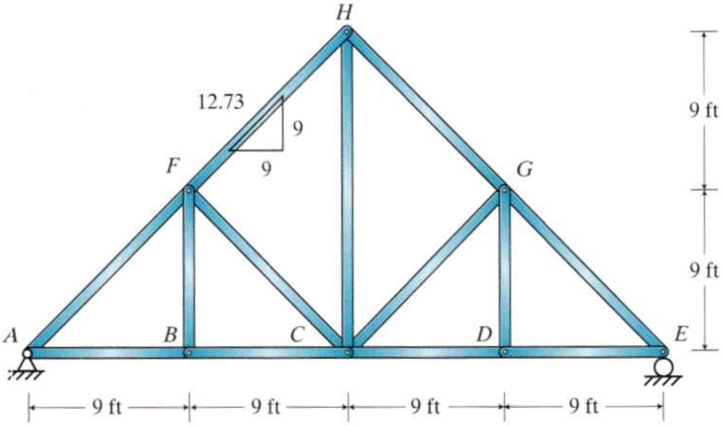


Figure 1.12