Structural Analysis: Skills for Practice

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Contents

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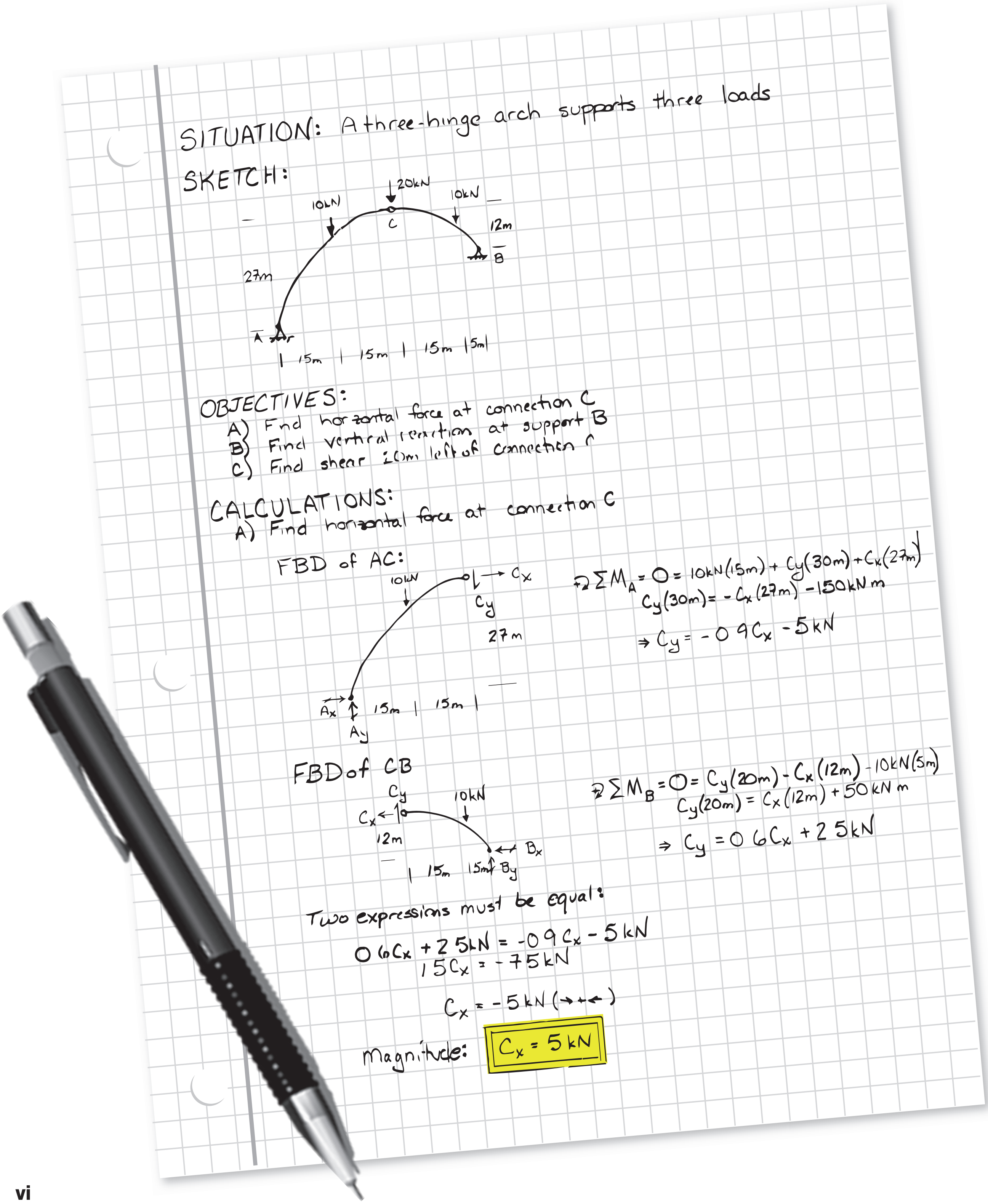

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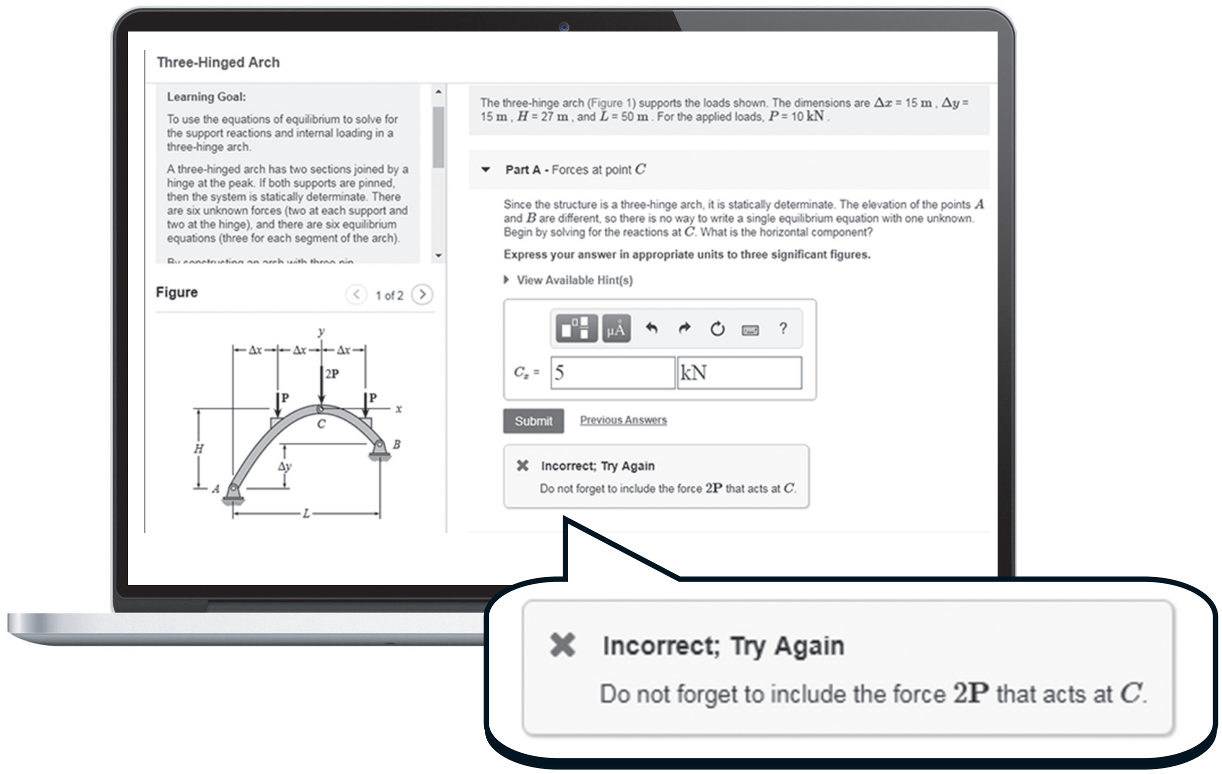

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PREFACE

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™ 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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- 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.

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.

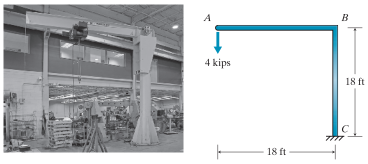


Figure 5.45

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.

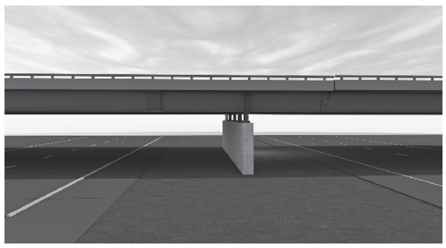
Examples

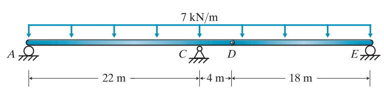
The text emphasizes developing intuition for reasonable answers and cultivating the habit of predicting results.

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.

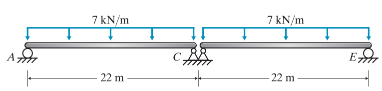
Homework Problems

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).

Homework Problems

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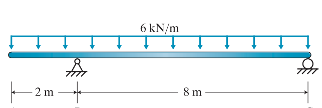

Prob. 2.7

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.

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:

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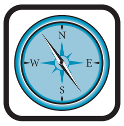
Recommendation:
If the crane manufacturer wants to reduce the vertical displacement, our results indicate that increasing the moment of inertia of the mast would be most effective. If that does not provide a sufficient reduction, the manufacturer should increase the moment of inertia of the arm as well. 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