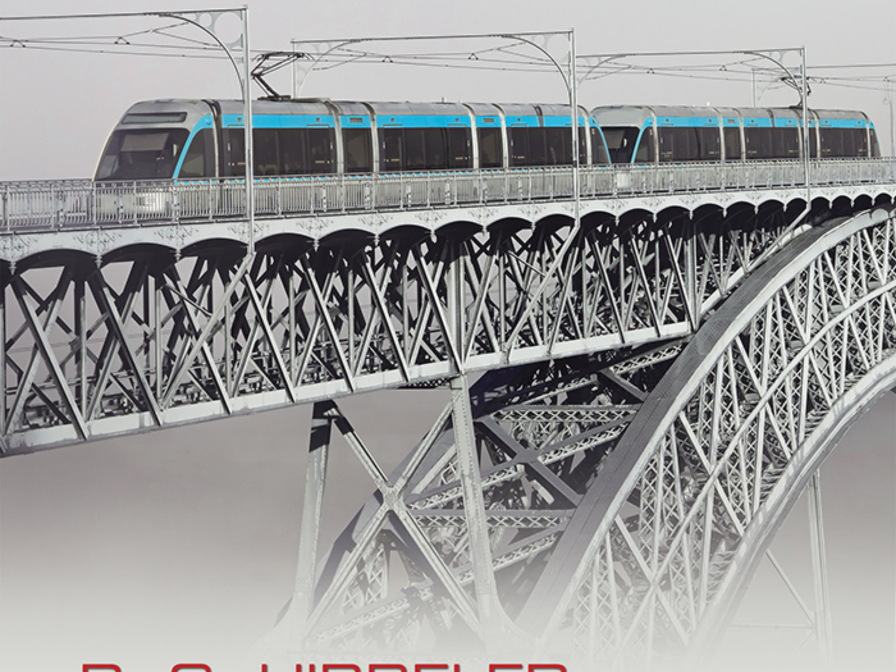
STRUCTURAL ANALYSIS

NINTH EDITION



R. C. HIBBELER

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To The Student

With the hope that this work will stimulate
an interest in Structural Analysis
and provide an acceptable guide to its understanding.

PREFACE

This book is intended to provide the student with a clear and thorough presentation of the theory and application of structural analysis as it applies to trusses, beams, and frames. Emphasis is placed on developing the student's ability to both model and analyze a structure and to provide realistic applications encountered in professional practice.

For many years now, engineers have been using matrix methods to analyze structures. Although these methods are most efficient for a structural analysis, it is the author's opinion that students taking a first course in this subject should also be well versed in some of the more important classicial methods. Practice in applying these methods will develop a deeper understanding of the basic engineering sciences of statics and mechanics of materials. Also, problem-solving skills are further developed when the various techniques are thought out and applied in a clear and orderly way. By solving problems in this way one can better grasp the way loads are transmitted through a structure and obtain a more complete understanding of the way the structure deforms under load. Finally, the classicial methods provide a means of checking computer results rather than simply relying on the generated output.

New Material and Content Revision. This edition now includes examples of the causes of structural failures, the concept of a load path, and an enhanced discussion for drawing shear and moment diagrams and the deflection of beams and frames. Chapter 17 has been added, which now provides a discussion of structural modeling concepts and a general description of how computer software is applied. Included are some structural modeling projects, along with a set of problems that require a computer analysis.

Structural Terminology. There are several places throughout the text where illustrations and discussion of additional terminology has been added, so that the student becomes familiar with the basic forms of fundamental structures and the names of their members.

Problem Arrangement. Different from the previous edition, the problems in each chapter are now placed at the end of the chapter. They are grouped with section headings for the convenience of assigning problems for homework.

New Problems. There are approximately 70% new problems in this edition. They retain a balance of easy, medium, and difficult applications. In addition, some new fundamental problems have been added that stress the importance of drawing frame moment diagrams and drawing deflected structures. Apart from the author, the problems have been checked by four other parties, namely Scott Hendricks, Karim Nora, Kurt Norlin, and Kai Beng Yap.

Additional Photos. The relevance of knowing the subject matter is reflected by the realistic applications depicted in many new and updated photos along with captions that are placed throughout the book.

Organization and Approach

The contents of each chapter are arranged into sections with specific topics categorized by title headings. Discussions relevant to a particular theory are succinct, yet thorough. In most cases, this is followed by a "procedure for analysis" guide, which provides the student with a summary of the important concepts and a systematic approach for applying the theory. The example problems are solved using this outlined method in order to clarify its numerical application. Problems are given at the end of each chapter, and are arranged to cover the material in sequential order. Moreover, for any topic they are arranged in approximate order of increasing difficulty.

Hallmark Elements

- **Photographs.** Many photographs are used throughout the book to explain how the principles of structural analysis apply to real-world situations.
- **Problems.** Most of the problems in the book depict realistic situations encountered in practice. It is hoped that this realism will both stimulate the student's interest in structural analysis and develop the skill to reduce any such problem from its physical description to a model or symbolic representation to which the appropriate theory can be applied. This modeling process is further discussed in Chapter 17. Throughout the book there is an approximate balance of problems using either SI or FPS units. The intent has been to develop problems that test the student's ability to apply the theory, keeping in mind that those problems requiring tedious calculations can be relegated to computer analysis.
- **Answers to Selected Problems.** The answers to selected problems are listed in the back of the book. Extra care has been taken in the presentation and solution of the problems, and all the problem sets have been reviewed and the solutions checked and rechecked to ensure both their clarity and numerical accuracy.
- **Example Problems.** All the example problems are presented in a concise manner and in a style that is easy to understand.
- **Illustrations.** Throughout the book, an increase in two-color art has been added, including many photorealistic illustrations that provide a strong connection to the 3-D nature of structural engineering.
- **Triple Accuracy Checking.** The edition has undergone rigorous accuracy checking and proofing of pages. Besides the author's review of all art pieces and pages, Scott Hendricks of Virginia Polytechnic Institute, Karim Nohra of the University of South Florida, and Kurt Norlin of Laurel Technical Services rechecked the page proofs and together reviewed the Solutions Manual.

- **Fundamental Problems.** These problem sets are selectively located at the end of most chapters. They offer students simple applications of the concepts and, therefore, provide them with the chance to develop their problem-solving skills before attempting to solve any of the standard problems that follow. You may consider these problems as extended examples since they *all have solutions and answers* that are given in the back of the book. Additionally, the fundamental problems offer students an excellent means of studying for exams, and they can be used at a later time to prepare for the exam necessary to obtain a professional engineering license.

Contents

This book is divided into three parts. The first part consists of seven chapters that cover the classical methods of analysis for statically determinate structures. Chapter 1 provides a discussion of the various types of structural forms and loads. Chapter 2 discusses the determination of forces at the supports and connections of statically determinate beams and frames. The analysis of various types of statically determinate trusses is given in Chapter 3, and shear and bending-moment functions and diagrams for beams and frames are presented in Chapter 4. In Chapter 5, the analysis of simple cable and arch systems is presented, and in Chapter 6 influence lines for beams, girders, and trusses are discussed. Finally, in Chapter 7 several common techniques for the approximate analysis of statically indeterminate structures are considered.

In the second part of the book, the analysis of statically indeterminate structures is covered in six chapters. Geometrical methods for calculating deflections are discussed in Chapter 8. Energy methods for finding deflections are covered in Chapter 9. Chapter 10 covers the analysis of statically indeterminate structures using the force method of analysis, in addition to a discussion of influence lines for beams. Then the displacement methods consisting of the slope-deflection method in Chapter 11 and moment distribution in Chapter 12 are discussed. Finally, beams and frames having nonprismatic members are considered in Chapter 13.

The third part of the book treats the matrix analysis of structures using the stiffness method. Trusses are discussed in Chapter 14, beams in Chapter 15, and frames in Chapter 16. Finally, Chapter 17 provides some basic ideas as to how to model a structure, and for using available software for solving problem in structural analysis. A review of matrix algebra is given in Appendix A.

Resources for Instructors

- **MasteringEngineering.** This online Tutorial Homework program allows you to integrate dynamic homework with automatic grading and adaptive tutoring. MasteringEngineering 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.
- **Instructor's Solutions Manual.** An instructor's solutions manual was prepared by the author. The manual was also checked as part of the Triple Accuracy Checking program.
- **Presentation Resources.** All art from the text is available in PowerPoint slide and JPEG format. These files are available for download from the Instructor Resource Center at www.pearsonhighered.com. If you are in need of a login and password for this site, please contact your local Pearson Prentice Hall representative.
- **Video Solutions.** Located on the Companion Website, Video Solutions offer step-by-step solution walkthroughs of representative homework problems from each chapter of the text. Make efficient use of class time and office hours by showing students the complete and concise problem solving approaches that they can access anytime and view at their own pace. The videos are designed to be a flexible resource to be used however each instructor and student prefers. A valuable tutorial resource, the videos are also helpful for student self-evaluation as students can pause the videos to check their understanding and work alongside the video. Access the videos at www.pearsonhighered.com/hibbeler and follow the links for the *Structural Analysis* text.
- **STRAN.** Developed by the author and Barry Nolan, a practicing engineer, STRAN is a downloadable program for use with Structural Analysis problems. Access STRAN on the Companion Website, www. pearsonhighered.com/hibbeler and follow the links for the *Structural Analysis* text. Complete instructions for how to use the software are included on the Companion Website.

Resources for Students

- **MasteringEngineering.** Tutorial homework problems emulate the instrutor's office-hour environment.
- **Companion Website.** The Companion Website provides practice and review materials including:
    - **Video Solutions**—Complete, step-by-step solution walkthroughs of representative homework problems from each chapter.

Videos offer:

- **Fully worked Solutions—**Showing every step of representative homework problems, to help students make vital connections between concepts.
- **Self-paced Instruction—**Students can navigate each problem and select, play, rewind, fast-forward, stop, and jump-to-sections within each problem's solution.
- **24/7 Access—**Help whenever students need it with over 20 hours of helpful review.

○ **STRAN—**A program you can use to solve two and three dimensional trusses and beams, and two dimensional frames. Instructions for downloading and how to use the program are available on the Companion Website.

An access code for the *Structural Analysis*, Ninth Edition Companion Website is included with this text. To redeem the code and gain access to the site, go to www.pearsonhighered.com/hibbeler and follow the directions on the access code card. Access can also be purchased directly from the site.

Acknowledgments

Through the years, over one hundred of my colleagues in the teaching profession and many of my students have made valuable suggestions that have helped in the development of this book, and I would like to hereby acknowledge all of their comments. I personally would like to thank the reviewers contracted by my editor for this new edition, namely:

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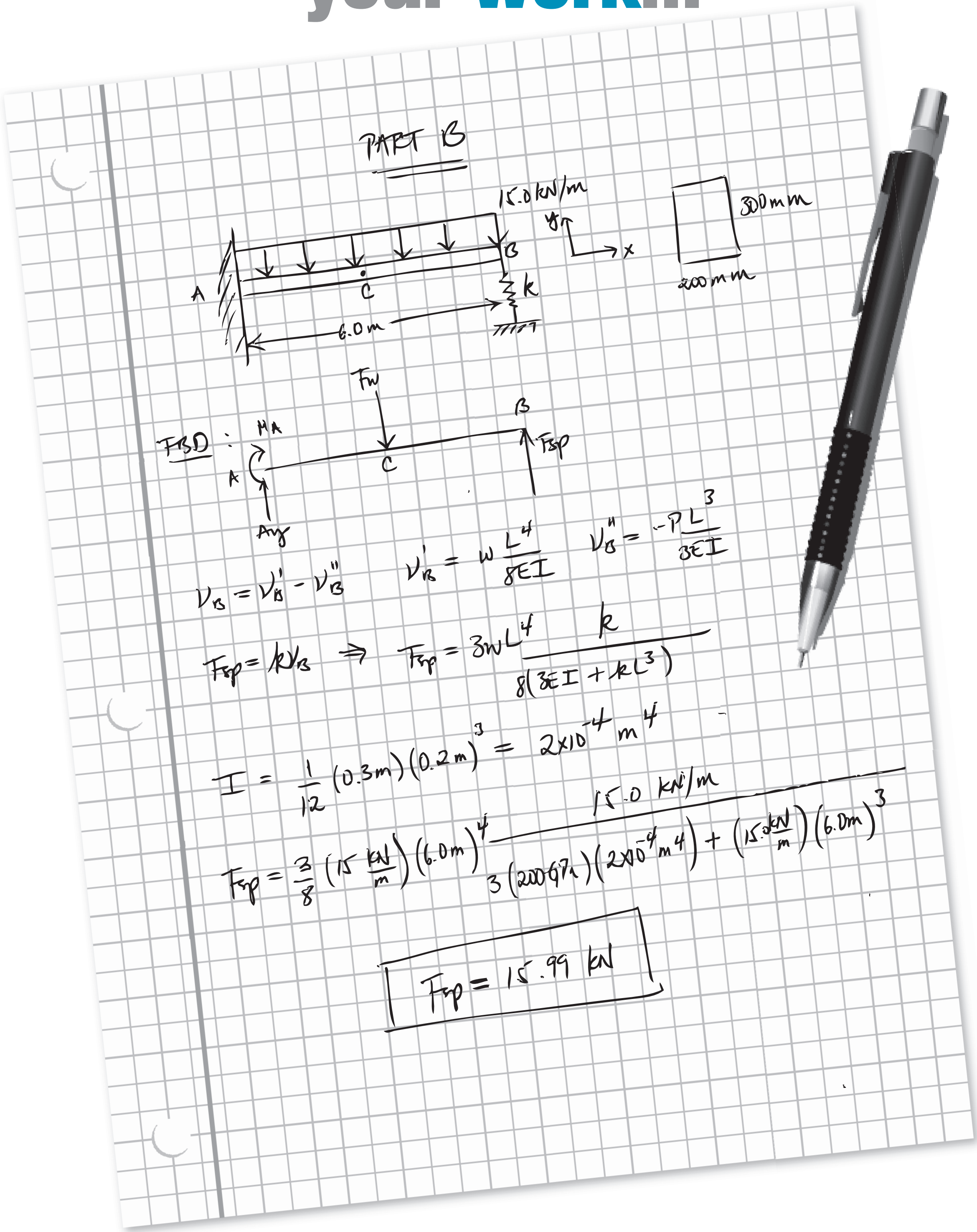
I would greatly appreciate hearing from you if at any time you have any comments or suggestions regarding the contents of this edition.

Russell Charles Hibbeler
hibbeler@bellsouth.net

your work...


PART B
15.0 kN/m
300 mm
200 mm
A
B
C
k
6.0 m
FBD:
Fw
MA
Fsp
Ay
νB = ν'B - ν''B
ν'B = w L^4 / 8EI
ν''B = -PL^3 / 3EI
Fsp = kνB ⇒ Fsp = 3wL^4 k / 8(3EI + kL^3)
I = 1/12 (0.3m)(0.2m)^3 = 2x10^-4 m^4
Fsp = 3/8 (15 kN/m)(6.0m)^4 15.0 kN/m / 3(200GPa)(2x10^-4 m^4) + (15.0 kN/m)(6.0m)^3
Fsp = 15.99 kN

your answer **specific feedback**

Part B - Spring force at *B*

Using the method of superposition, determine the force $\mathbf{F}_{sp}$ that the spring at *B* exerts on the bar. Assume that this force acts in the positive *y* direction.

Express your answer to three significant figures and include the appropriate units.

$\mathbf{F}_{sp}$ = 15.99 kN

reset shortcuts ? help

Submit Hints My Answers Give Up Review Part

Incorrect; Try Again

Review the equation used for the moment of inertia of the cross section.

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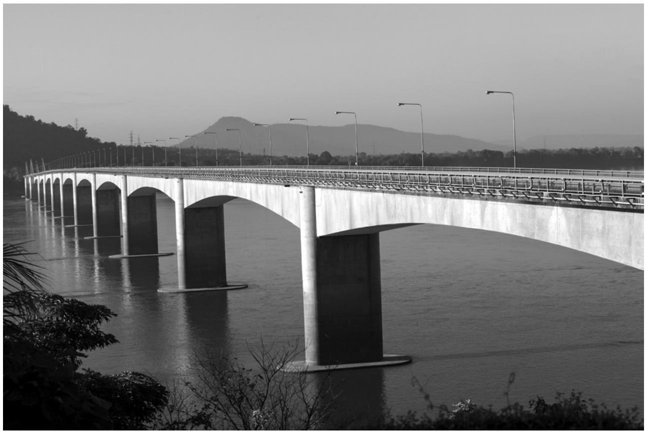

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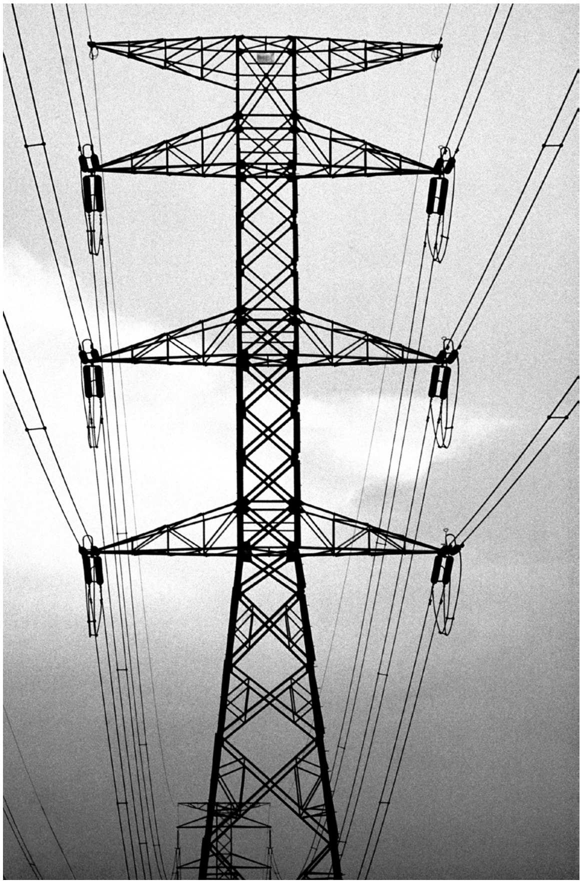

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STRUCTURAL ANALYSIS

Chapter 1

Severe wind loadings caused by a hurricane have caused noticeable damage to the windows of the high-rise building.

Types of Structures and Loads

This chapter provides a discussion of some of the preliminary aspects of structural analysis. The phases of activity necessary to produce a structure are presented first, followed by an introduction to the basic types of structures, their components, and supports. Finally, a brief explanation is given of the various types of loads that must be considered for an appropriate analysis and design.

1.1 Introduction

In this text we will present many of the different ways engineers model and then analyze the loadings and deflections of various types of structures. Important examples related to civil engineering include buildings, bridges, and towers; and in other branches of engineering, ship and aircraft frames, and mechanical, and electrical supporting structures are important.

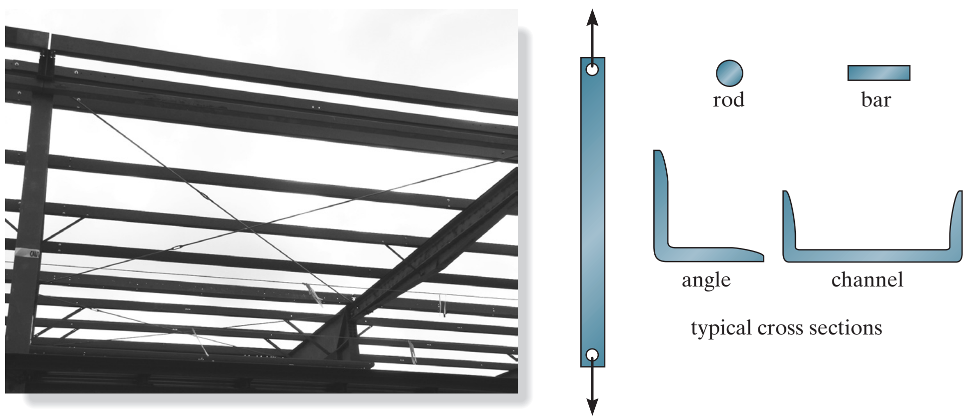
A ***structure*** refers to a system of connected parts used to support a load. When designing a structure to serve a specified function for public use, the engineer must account for its safety, esthetics, and serviceability, while taking into consideration economic and environmental constraints. Often this requires several independent studies of different solutions before final judgment can be made as to which structural form is most appropriate. This design process is both creative and technical and requires a fundamental knowledge of material properties and the laws of mechanics which govern material response. Once a preliminary design of a structure is proposed, the structure must then be *analyzed* to ensure that it has its required stiffness and strength. To analyze a structure properly, certain idealizations must be made as to how the members are supported and connected together. The loadings are determined from codes and local specifications, and the forces in the members and their displacements are found using the theory of structural analysis, which is the subject matter of this text. The results of this analysis then can be used to redesign the structure, accounting for a more accurate determination of the weight of the members and their size. Structural design, therefore, follows a series of successive approximations in which every cycle requires a structural analysis. In this book, the structural analysis is applied to civil engineering structures; however, the method of analysis described can also be used for structures related to other fields of engineering.

1.2 Classification of Structures

It is important for a structural engineer to recognize the various types of elements composing a structure and to be able to classify structures as to their form and function. We will introduce some of these aspects now and discuss others throughout the text.

Structural Elements. Some of the more common elements from which structures are composed are as follows.

Tie Rods. Structural members subjected to a *tensile force* are often referred to as ***tie rods*** or ***bracing struts.*** Due to the nature of this load, these members are rather slender, and are often chosen from rods, bars, angles, or channels, Fig. 1–1.



Tie rods used for wind bracing.

tie rod

Fig. 1–1

Beams. ***Beams*** are usually straight horizontal members used primarily to carry vertical loads. Quite often they are classified according to the way they are supported, as indicated in Fig. 1–2. In particular, when the cross section varies the beam is referred to as tapered or haunched. Beam cross sections may also be "built up" by adding plates to their top and bottom.

Beams are primarily designed to resist bending moment; however, if they are short and carry large loads, the internal shear force may become quite large and this force may govern their design. When the material used for a beam is a metal such as steel or aluminum, the cross section is most efficient when it is shaped as shown in Fig. 1–3. Here the forces developed in the top and bottom ***flanges*** of the beam form the necessary couple used to resist the applied moment **M**, whereas the ***web*** is effective in resisting the applied shear **V**. This cross section is commonly referred to as a "wide flange," and it is normally formed as a single unit in a rolling mill in lengths up to 75 ft (23 m). If shorter lengths are needed, a cross section having tapered flanges is sometimes selected. When the beam is required to have a very large span and the loads applied are rather large, the cross section may take the form of a ***plate girder***. This member is fabricated by using a large plate for the web and welding or bolting plates to its ends for flanges. The girder is often transported to the field in segments, and the segments are designed to be spliced or joined together at points where the girder carries a small internal moment.

Concrete beams generally have rectangular cross sections, since it is easy to construct this form directly in the field. Because concrete is rather weak in resisting tension, steel "reinforcing rods" are cast into the beam within regions of the cross section subjected to tension. Precast concrete beams or girders are fabricated at a shop or yard in the same manner and then transported to the job site.

Beams made from timber may be sawn from a solid piece of wood or laminated. ***Laminated beams*** are constructed from solid sections of wood, which are fastened together using high-strength glues.

Shown are typical splice plate joints used to connect the steel girders of a highway bridge.

The prestressed concrete girders are simply supported and are used for this highway bridge.

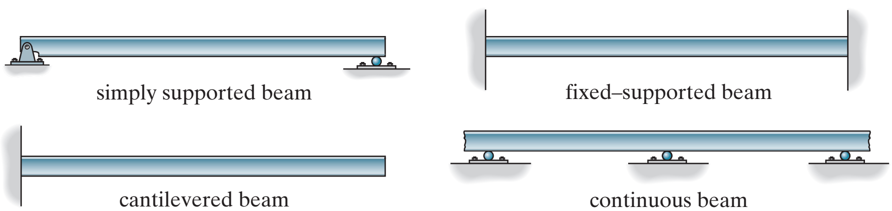


Fig. 1–2

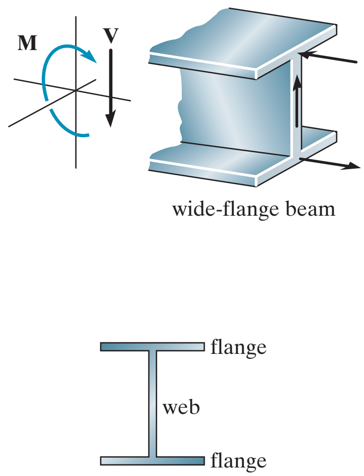
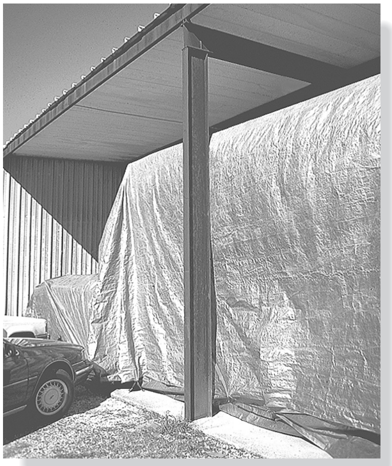


Fig. 1–3



Wide-flange members are often used for columns. Here is an example of a beam column.

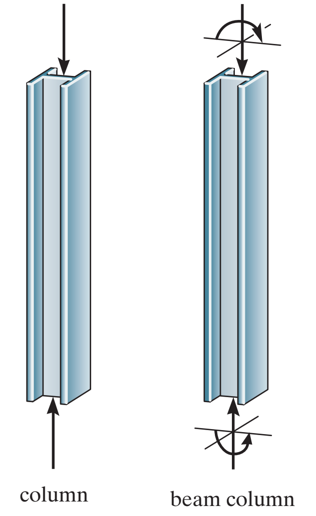


Fig. 1–4

Columns. Members that are generally vertical and resist axial compressive loads are referred to as ***columns,*** Fig. 1–4. Tubes and wide-flange cross sections are often used for metal columns, and circular and square cross sections with reinforcing rods are used for those made of concrete. Occasionally, columns are subjected to both an axial load and a bending moment as shown in the figure. These members are referred to as ***beam columns.***

Types of Structures.

The combination of structural elements and the materials from which they are composed is referred to as a ***structural system.*** Each system is constructed of one or more of four basic types of structures. Ranked in order of complexity of their force analysis, they are as follows.

Trusses. When the span of a structure is required to be large and its depth is not an important criterion for design, a truss may be selected. ***Trusses*** consist of slender elements, usually arranged in triangular fashion. ***Planar trusses*** are composed of members that lie in the same plane and are frequently used for bridge and roof support, whereas ***space trusses*** have members extending in three dimensions and are suitable for derricks and towers.

Due to the geometric arrangement of its members, loads that cause the entire truss to bend are converted into tensile or compressive forces in the members. Because of this, one of the primary advantages of a truss, compared to a beam, is that it uses less material to support a given load, Fig. 1–5. Also, a truss is constructed from *long and slender elements,* which can be arranged in various ways to support a load. Most often it is economically feasible to use a truss to cover spans ranging from 30 ft (9 m) to 400 ft (122 m), although trusses have been used on occasion for spans of greater lengths.

Loading causes bending of the truss, which develops compression in the top members, and tension in the bottom members.

Fig. 1–5

Cables and Arches. Two other forms of structures used to span long distances are the cable and the arch. ***Cables*** are usually flexible and carry their loads in tension. They are commonly used to support bridges, Fig. 1–6*a*, and building roofs. When used for these purposes, the cable has an advantage over the beam and the truss, especially for spans that are greater than 150 ft (46 m). Because they are always in tension, cables will not become unstable and suddenly collapse, as may happen with beams or trusses. Furthermore, the truss will require added costs for construction and increased depth as the span increases. Use of cables, on the other hand, is limited only by their sag, weight, and methods of anchorage.

The ***arch*** achieves its strength in compression, since it has a reverse curvature to that of the cable. The arch must be rigid, however, in order to maintain its shape, and this results in secondary loadings involving shear and moment, which must be considered in its design. Arches are frequently used in bridge structures, Fig. 1–6*b*, dome roofs, and for openings in masonry walls.

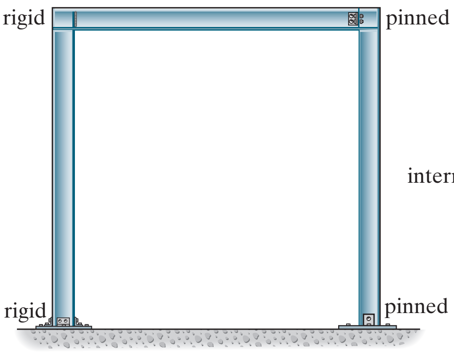
Cables support their loads in tension.

(a)

Arches support their loads in compression.

(b)

Fig. 1–6



Frame members are subjected to internal axial, shear, and moment loadings.

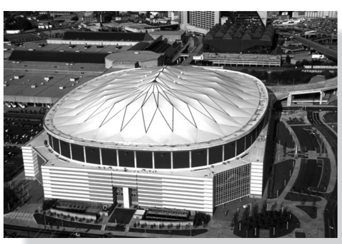
Fig. 1–7

Typical steel framework.

Frames. ***Frames*** are often used in buildings and are composed of beams and columns that are either pin or fixed connected, Fig. 1–7. Like trusses, frames extend in two or three dimensions. The loading on a frame causes bending of its members, and if it has rigid joint connections, this structure is generally "indeterminate" from a standpoint of analysis. The strength of such a frame is derived from the moment interactions between the beams and the columns at the rigid joints.

Surface Structures. A ***surface structure*** is made from a material having a very small thickness compared to its other dimensions. Sometimes this material is very flexible and can take the form of a tent or air-inflated structure. In both cases the material acts as a membrane that is subjected to pure tension.

Surface structures may also be made of rigid material such as reinforced concrete. As such they may be shaped as folded plates, cylinders, or hyperbolic paraboloids, and are referred to as ***thin plates*** or ***shells.*** These structures act like cables or arches since they support loads primarily in tension or compression, with very little bending. In spite of this, plate or shell structures are generally very difficult to analyze, due to the three-dimensional geometry of their surface. Such an analysis is beyond the scope of this text and is instead covered in texts devoted entirely to this subject.



The roof of the "Georgia Dome" in Atlanta, Georgia can be considered as a thin membrane.

1.3 Loads

Once the dimensional requirements for a structure have been defined, it becomes necessary to determine the loads the structure must support. Often, it is the anticipation of the various loads that will be imposed on the structure that provides the basic type of structure that will be chosen for design. For example, high-rise structures must endure large lateral loadings caused by wind, and so shear walls and tubular frame systems are selected, whereas buildings located in areas prone to earthquakes must be designed having ductile frames and connections.

Once the structural form has been determined, the actual design begins with those elements that are subjected to the primary loads the structure is intended to carry, and proceeds in sequence to the various supporting members until the foundation is reached. Thus, a building floor slab would be designed first, followed by the supporting beams, columns, and last, the foundation footings. In order to design a structure, it is therefore necessary to first specify the loads that act on it.

The design loading for a structure is often specified in codes. In general, the structural engineer works with two types of codes: general building codes and design codes. ***General building codes*** specify the requirements of governmental bodies for minimum design loads on structures and minimum standards for construction. ***Design codes*** provide detailed technical standards and are used to establish the requirements for the actual structural design. Table 1.1 lists some of the important codes used in practice. It should be realized, however, that codes provide only a general guide for design. *The ultimate responsibility for the design lies with the structural engineer.*

Since a structure is generally subjected to several types of loads, a brief discussion of these loadings will now be presented to illustrate how one must consider their effects in practice.

TABLE 1.1 Codes
General Building Codes
Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10, American Society of Civil Engineers
International Building Code
Design Codes
Building Code Requirements for Reinforced Concrete, Am. Conc. Inst. (ACI)
Manual of Steel Construction, American Institute of Steel Construction (AISC)
Standard Specifications for Highway Bridges, American Association of State Highway and Transportation Officials (AASHTO)
National Design Specification for Wood Construction, American Forest and Paper Association (AFPA)
Manual for Railway Engineering, American Railway Engineering Association (AREA)