Fifth Edition

Fundamentals of Structural Analysis

Kenneth M. Leet
Chia-Ming Uang
Joel T. Lanning
Anne M. Gilbert

McGraw Hill Education

Fundamentals of Structural Analysis

Fifth Edition

Kenneth M. Leet

Professor Emeritus, Northeastern University

Chia-Ming Uang

Professor, University of California, San Diego

Joel T. Lanning

Assistant Professor, California State University, Fullerton

Anne M. Gilbert, PE, SECB

Structural Engineer Consultant

McGraw Hill Education

FUNDAMENTALS OF STRUCTURAL ANALYSIS, FIFTH EDITION

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LCR 21 20 19 18 17

ISBN 978-0-07-339800-6
MHID 0-07-339800-4

Chief Product Officer, SVP Products & Markets: *G. Scott Virkler*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Design & Delivery: *Betsy Whalen*
Managing Director: *Thomas Timp*
Global Brand Manager: *Thomas M. Scaife, Ph.D.*
Director, Product Development: *Rose Koos*
Product Developer: *Jolynn Kilburg*
Marketing Manager: *Shannon O'Donnell*
Director, Content Design & Delivery: *Linda Avenarius*
Program Manager: *Lora Neyens*
Content Project Managers: *Jane Mohr, Rachael Hillebrand, and Sandra Schnee*
Buyer: *Laura M. Fuller*
Design: *Studio Montage, St. Louis, MO*
Content Licensing Specialist: *Melisa Seegmiller*
Cover Image: *Lou Lu, M.D., Ph.D. Self-anchored suspension main span of the eastern span replacement of the San Francisco-Oakland Bay Bridge in California.*
Compositor: *MPS Limited*
Printer: *LSC Communications*

Library of Congress Cataloging-in-Publication Data

Leet, Kenneth, author. | Uang, Chia-Ming, author. | Lanning, Joel author. | Gilbert, Anne M., author.
Fundamentals of structural analysis / Kenneth M. Leet, Professor Emeritus, Northeastern University, Chia-Ming Uang, Professor, University of California, San Diego, Joel T. Lanning, Assistant Professor, California State University, Fullerton, Anne M. Gilbert, Adjunct Assistant Professor, Yale University.
Fifth edition. | New York, NY : McGraw-Hill Education, [2018] |
Includes index.
LCCN 2016051733 | ISBN 9780073398006 (alk. paper)
LCSH: Structural analysis (Engineering)
LCC TA645 .L34 2018 | DDC 624.1/71—dc23 LC record available at https://lccn.loc.gov/2016051733

mheducation.com/highered

For Kenneth M. Leet

This page intentionally left blank

ABOUT THE AUTHORS

Kenneth Leet is a late Professor of structural engineering at Northeastern University. He received his Ph.D. in structural engineering from the Massachusetts Institute of Technology. As a professor of civil engineering at Northeastern University, he taught graduate and undergraduate courses in reinforced concrete design, structural analysis, foundations, plates and shells, and capstone courses on comprehensive engineering projects for over 30 years. Professor Leet was given an Excellence in Teaching award at Northeastern University in 1992. He was also a faculty member for ten years at Drexel University in Philadelphia.

In addition to being the author of the first edition of this book on structural analysis, originally published by Macmillan in 1988, he is the author of *Fundamentals of Reinforced Concrete,* published by McGraw-Hill.

Chia-Ming Uang is a Professor of structural engineering at the University of California, San Diego (UCSD). He received a B.S. degree in civil engineering from National Taiwan University and M.S. and Ph.D. degrees in civil engineering from the University of California, Berkeley.

Uang also coauthores the text *Ductile Design of Steel Structures* for McGraw-Hill. He received the UCSD Academic Senate Distinguished Teaching Award in 2004. He is also the recipient of the ASCE Raymond C. Reese Research Prize in 2001, the ASCE Moisseiff Award in 2004 and 2014, the AISC Special Achievement Award in 2007, and the T.R. Higgins Lectureship Award in 2015.

Joel T. Lanning is an Assistant Professor of structural engineering at California State University, Fullerton and is a registered Civil Engineer in California. He received a B.S. degree in civil engineering from the Ohio State University and M.S. and Ph.D. degrees in structural engineering from the University of California, San Diego. Professor Lanning is also involved with developing tools and content for McGraw-Hill SmartBook and Connect online products.

Anne M. Gilbert, PE, SECB, is a senior structural engineer at Rivermoor Engineering, LLC, Scituate, MA, and an architectural designer. She is a registered Structural Engineer in CT, ME and MA, and received a B.A. in architecture at the University of North Carolina, a B.S.C.E. from Northeastern University, and a M.S.C.E. from the University of Connecticut. Over the past 30 years, Gilbert specialized in structural design of institutional, commercial and residential buildings. Gilbert was an Assistant Professor (Adjunct) at Yale University, School of Architecture, and for over eight years taught structural engineering courses.

TABLE OF CONTENTS

PREFACE

This text introduces engineering and architectural students to the basic techniques required for analyzing the majority of structures and the elements of which most structures are composed, including beams, frames, trusses, arches, and cables. Although the authors assume that readers have completed basic courses in statics and strength of materials, we briefly review the basic techniques from these courses the first time we mention them. To clarify the discussion, we use many carefully chosen examples to illustrate the various analytic techniques introduced, and whenever possible, we select examples confronting engineers in real-life professional practice.

Features of This Text

1. **Major reorganization.** The number of chapters has been reduced from 18 in the previous editions to 16 for a more concise presentation of the materials. This is done by combining the cable and arch chapters into one as well as presenting the influence lines for both determinate and indeterminate structures in one chapter to avoid repeating information.
2. **Expanded treatment of design loads.** Chapter 2 is devoted to a discussion of loads based on the most recent ANSI/ASCE 7 Standard. This includes dead and live loads, snow, earthquake, and wind loads, and, new to this edition (and the ASCE Standard), tsunami loading. Further, a discussion on natural hazards and the ASCE Standard's probabalistic approach to natural hazard design loads is added. The presentation aims to provide students with a basic understanding of how design loads are determined for practical design of multistory buildings, bridges, and other structures.
3. **New homework problems.** A substantial number of the problems are new or revised for this edition (in both metric and U.S. Customary System units), and many are typical of analysis problems encountered in practice. The many choices enable the instructor to select problems suited for a particular class or for a particular emphasis.
4. **Computer problems and applications.** Computer problems, some new to this edition, provide readers with a deeper understanding of the structural behavior of trusses, frames, arches,

and other structural systems. These carefully tailored problems illustrate significant aspects of structural behavior that, in the past, experienced designers needed many years of practice to understand and to analyze correctly. The computer problems are identified with a computer screen icon and begin in Chapter 4 of the text. The computer problems can be solved using the Educational Version of the commercial software RISA-2D that is available to users at the textbook website. However, any software that produces shear, moment, and axial load diagrams, and deflected shapes can be used to solve the problems. An overview on the use of the RISA-2D software and an author-written tutorial are also available at the textbook website.

5. **Problem solutions have been carefully checked for accuracy.** The authors have carried out multiple checks on the problem solutions but would appreciate hearing from users about any ambiguities or errors. Corrections can be sent to Professor Chia-Ming Uang (cmu@ucsd.edu).
6. **Textbook web site.** A text-specific website is available to users. The site offers an array of tools, including lecture slides, an image bank of the text's art, helpful web links, and the RISA-2D educational software.

Contents and Sequence of Chapters

We present the topics in this book in a carefully planned sequence to facilitate the student's study of analysis. In addition, we tailor the explanations to the level of students at an early stage in their engineering education. These explanations are based on the authors' many years of experience teaching analysis. In this edition, we have streamlined the presentation by restructuring the book from 18 to 16 chapters while still keeping all the important materials.

Chapter 1 provides a historical overview of structural engineering (from earliest post and lintel structures to today's high-rises and cable-stayed bridges) and a brief explanation of the interrelationship between analysis and design. We also describe the essential characteristics of basic structures, detailing both their advantages and their disadvantages.

Chapter 2 on loads is described above in *Features of This Text*.

Chapters 3, 4, and 5 cover the basic techniques required to determine by statics bar forces in determinate trusses, and shear and moment in determinate beams and frames. Methods to identify if the structure is determinate are also presented.

Chapter 6 interrelates the behavior of arches and cables, and covers their special characteristics (of acting largely in direct stress and using materials efficiently).

Chapters 7 and 8 provide methods used to compute the deflections of structures. One direct application is to use it to analyze indeterminate structures by the method of consistent deformations in Chapter 9.

Chapters 9, 10, and 11 introduce three classical methods for analyzing indeterminate structures. The method of consistent deformations in Chapter 9 is classified as a flexibility method, while the slope-deflection and moment distribution methods in the other two chapters are classified as the stiffness method.

Chapter 12 introduces the concept of influence lines and covers methods for positioning live load that can vary in space on determinate and indeterminate structures to maximize the internal force at a specific section of a beam, frame, or bars of a truss. Engineers use this important concept to design bridges or other structures subject to moving loads or to live loads whose position on the structure can change.

Chapter 13 gives approximate methods of analysis, used to estimate the value of forces at selected points in highly indeterminate structures. With approximate methods, designers can perform preliminary member sizing, verify the accuracy of computer studies analysis results, or check the results of more traditional, lengthy hand analyses described in earlier chapters.

Chapters 14, 15, and 16 introduce matrix methods of analysis. Chapter 14 extends the general direct stiffness method to a variety of simple structures. The matrix formulation of the stiffness method, which is the basis of modern structural analysis software, is applied to the analysis of trusses (Chapter 15) and to the analysis of beams and frames (Chapter 16).

ACKNOWLEDGMENTS

This text was originally authored by Kenneth M. Leet and was published by Macmillan in 1988. Dionisio P. Bernal at Northeastern University contributed Chapters 15 and 16. Anne Gilbert served as a coauthor in the third and fourth editions.

For their assistance with the first McGraw-Hill edition, we thank Amy Hill, Gloria Schiesl, Eric Munson, and Patti Scott of McGraw-Hill and Jeff Lachina of Lachina Publishing Services.

For their assistance with the second and third editions, we thank Amanda Green, Suzanne Jeans, Jane Mohr, and Gloria Schiesl of McGraw-Hill; Rose Kernan of RPK Editorial Services Inc.; and Patti Scott, who edited the second edition.

For their assistance with the fourth edition, we thank Debra Hash, Peter Massar, Lorraine Buczek, Joyce Watters, and Robin Reed of McGraw-Hill, and Rose Kernan of RPK Editorial Services Inc.

For their assistance with this fifth edition, we thank Thomas Scaife, Jolynn Kilburg, Chelsea Haupt, and Jane Mohr of McGraw-Hill Education.

We also wish to thank Bruce R. Bates of RISA Technologies for providing an educational version of the RISA-2D computer program with its many options for presenting results. Mr. Nathanael Rea assisted in preparing the answers for the fifth edition.

We would like to thank the following reviewers for their much appreciated comments and advice:

Robert Hamilton, *Boise State University*
Blair McDonald. *Western Illinois University–Quad Cities*
Azadeh Parvin, *The University of Toledo*
Christopher Pastore, *Philadelphia University*
Jose Pena, *Perdue University Calumet*
Jey Shen, *Iowa State University*
Michael Symans, *Rensselaer Polytechnic Institute*
Steve Wojtkiewicz, *Clarkson University*

Kenneth M. Leet
Emeritus Professor
Northeastern University

Chia-Ming Uang
Professor
University of California,
San Diego

Joel T. Lanning
Assistant Professor,
California State University,
Fullerton

Anne M. Gilbert PE, SECB
Structural Engineer Consultant

This page intentionally left blank

McGraw Hill Education

connect®

Required=Results

©Getty Images/iStockphoto

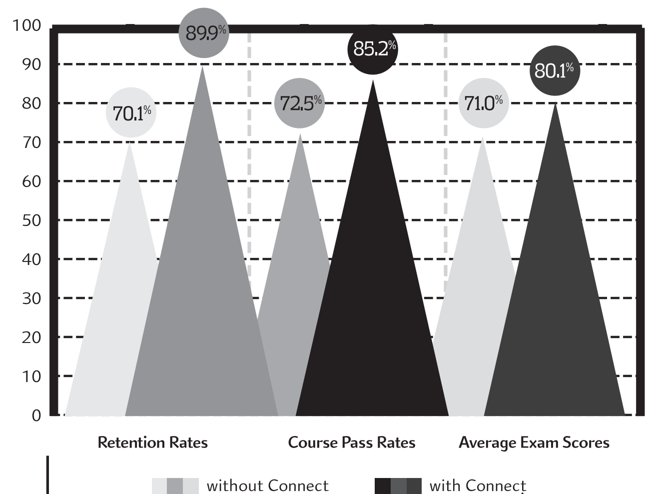
McGraw-Hill Connect®
Learn Without Limits

Connect is a teaching and learning platform that is proven to deliver better results for students and instructors.

Connect empowers students by continually adapting to deliver precisely what they need, when they need it, and how they need it, so your class time is more engaging and effective.

73% of instructors who use **Connect** require it; instructor satisfaction **increases** by 28% when **Connect** is required.

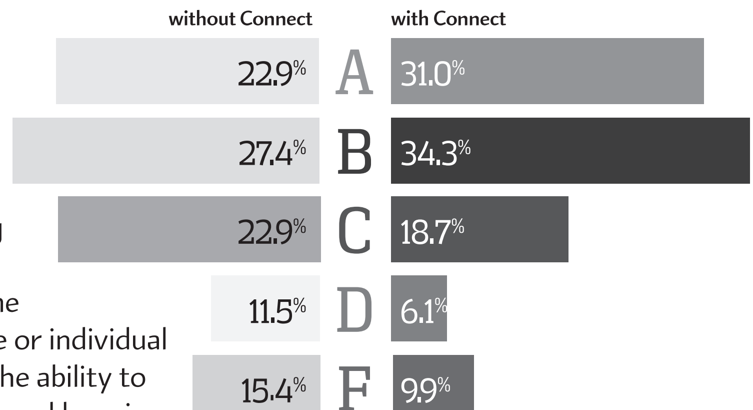
Connect's Impact on Retention Rates, Pass Rates, and Average Exam Scores



Using **Connect** improves retention rates by **19.8%**, passing rates by **12.7%**, and exam scores by **9.1%.**

Analytics

Impact on Final Course Grade Distribution



Connect Insight®

Connect Insight is Connect's new one-of-a-kind visual analytics dashboard that provides at-a-glance information regarding student performance, which is immediately actionable. By presenting assignment, assessment, and topical performance results together with a time metric that is easily visible for aggregate or individual results, Connect Insight gives the user the ability to take a just-in-time approach to teaching and learning, which was never before available. Connect Insight presents data that helps instructors improve class performance in a way that is efficient and effective.

Adaptive

THE **ADAPTIVE** **READING EXPERIENCE** DESIGNED TO TRANSFORM THE WAY STUDENTS READ

More students earn **A's** and **B's** when they use McGraw-Hill Education **Adaptive** products.

SmartBook®

Proven to help students improve grades and study more efficiently, SmartBook contains the same content within the print book, but actively tailors that content to the needs of the individual. SmartBook's adaptive technology provides precise, personalized instruction on what the student should do next, guiding the student to master and remember key concepts, targeting gaps in knowledge and offering customized feedback, and driving the student toward comprehension and retention of the subject matter. Available on tablets, SmartBook puts learning at the student's fingertips—anywhere, anytime.

Over **8 billion questions** have been answered, making McGraw-Hill Education products more intelligent, reliable, and precise.

www.mheducation.com

STUDENTS WANT

McGraw Hill Education SMARTBOOK®

95% of students reported **SmartBook** to be a more effective way of reading material.

100% of students want to use the Practice Quiz feature available within **SmartBook** to help them study.

100% of students reported having reliable access to off-campus wifi.

90% of students say they would purchase **SmartBook** over print alone.

95% of students reported that **SmartBook** would impact their study skills in a positive way.

Mc Graw Hill Education

*Findings based on 2015 focus group results administered by McGraw-Hill Education

This page intentionally left blank

Fundamentals of Structural Analysis

Skyway construction of the San Francisco-Oakland Bay Bridge

Segmental bridge construction was used for the mile-long viaduct, or Skyway, of the new San Francisco-Oakland Bay Bridge (see the book cover). The Skyway's decks comprise 452 precast concrete segments, which were transported by barge to the site and were lifted into place by winches. In balanced cantilever construction, as shown in this photo, the superstructure is erected by cantilevering out from opposite sides of the pier to maintain a relatively balanced system. As such, controlling deflection during the construction stage is very important for segmental bridge construction.

CHAPTER 1

Introduction

1.1 Overview of the Text

As an engineer or architect involved with the design of buildings, bridges, and other structures, you will be required to make many technical decisions about structural systems. These decisions include (1) selecting an efficient, economical, and attractive structural form; (2) evaluating its safety, that is, its strength and stiffness; and (3) planning its erection under temporary construction loads.

To design a structure, you will learn to carry out a *structural analysis* that establishes the internal forces and deflections at all points produced by the design loads. Designers determine the internal forces in key members in order to size both members and the connections between members. And designers evaluate deflections to ensure a serviceable structure—one that does not deflect or vibrate excessively under load so that its function is impaired.

Analyzing Basic Structural Elements

During previous courses in statics and strength of materials, you developed some background in structural analysis when you computed the bar forces in trusses and constructed shear and moment curves for beams. You will now broaden your background in structural analysis by applying, in a systematic way, a variety of techniques for determining the forces in and the deflections of a number of basic structural elements: beams, trusses, frames, arches, and cables. These elements represent the basic components used to form more complex structural systems.

Moreover, as you work analysis problems and examine the distribution of forces in various types of structures, you will understand more about how structures are stressed and deformed by load. And you will gradually develop a clear sense of which structural configuration is optimal for a particular design situation.

Further, as you develop an almost intuitive sense of how a structure behaves, you will learn to estimate with a few simple computations the approximate values of forces at the most critical sections of the structure. This ability will serve you well, enabling you (1) to verify the accuracy of the results of a computer analysis of large, complex structures and (2) to estimate the preliminary design forces needed to size individual components of multimember structures during the early design phase when the tentative configuration and proportions of the structure are being established.

Analyzing Two-Dimensional Structures

As you may have observed while watching the erection of a multistory building frame, when the structure is fully exposed to view, its structure is a complex three-dimensional system composed of beams, columns, slabs, walls, and diagonal bracing. Although load applied at a particular point in a three-dimensional structure will stress all adjacent members, most of the load is typically transmitted through certain key members directly to other supporting members or into the foundation.

Once the behavior and function of the various components of most three-dimensional structures are understood, the designer can typically simplify the analysis of the actual structure by subdividing it into smaller two-dimensional subsystems that act as beams, trusses, or frames. This procedure also significantly reduces the complexity of the analysis because two-dimensional structures are much easier and faster to analyze than three-dimensional structures. Since with few exceptions (e.g., geodesic domes constructed of light tubular bars) designers typically analyze a series of simple two-dimensional structures—even when they are designing the most complex three-dimensional structures—we will devote a large portion of this book to the analysis of two-dimensional or *planar* structures, those that carry forces lying in the plane of the structure.

Once you clearly understand the basic topics covered in this text, you will have acquired the fundamental techniques required to analyze most buildings, bridges, and structural systems typically encountered in professional practice. Of course, before you can design and analyze with confidence, you will require some months of actual design experience in an engineering office to gain further understanding of the total design process from a practitioner's perspective.

For those of you who plan to specialize in structures, mastery of the topics in this book will provide you with the basic structural principles required in more advanced analysis courses—those covering, for example, matrix methods or plates and shells. Further, because design and analysis are closely interrelated, you will use again many of the analytical procedures in this text for more specialized courses in steel, reinforced concrete, and bridge design.

1.2 The Design Process: Relationship of Analysis to Design

The design of any structure—whether it is the framework for a space vehicle, a high-rise building, a suspension bridge, an offshore oil drilling platform, a tunnel, or whatever—is typically carried out in alternating steps of *design* and *analysis*. Each step supplies new information that permits the designer to proceed to the next phase. The process continues until the analysis indicates that no changes in member sizes are required. The specific steps of the procedure are described below.

Conceptual Design

A project begins with a specific need of a client. For example, a developer may authorize an engineering or architectural firm to prepare plans for a sports complex to house a regulation football field, as well as seating 60,000 people, parking for 4000 cars, and space for essential facilities. In another case, a city may retain an engineer to design a bridge to span a 2000-ft-wide river and to carry a certain hourly volume of traffic.

The designer begins by considering all possible layouts and structural systems that might satisfy the requirements of the project. Often, architects and engineers consult as a team at this stage to establish layouts that lend themselves to efficient structural systems in addition to meeting the architectural (functional and aesthetic) requirements of the project. The designer next prepares sketches of an architectural nature showing the main structural elements of each design, although details of the structural system at this point are often sketchy.

Preliminary Design

In the preliminary design phase, the engineer selects from the conceptual design several of the structural systems that appear most promising, and sizes their main components. This preliminary proportioning of structural members requires an understanding of structural behavior and a knowledge of the loading conditions (dead, live, wind, and so forth) that will most likely affect the design. At this point, the experienced designer may make a few rough computations to estimate the proportions of each structure at its critical sections.

Analysis of Preliminary Designs

At this next stage, the precise loads the structure will carry are not known because the exact size of members and the architectural details of the design are not finalized. Using estimated values of load, the engineer carries out an analysis of the several structural systems under consideration to determine the forces at critical sections and the deflections at any point that influence the serviceability of the structure.

The true weight of the members cannot be calculated until the structure is sized exactly, and certain architectural details will be influenced, in turn, by the structure. For example, the size and weight of mechanical equipment cannot be determined until the volume of the building is established, which in turn depends on the structural system. The designer, however, knows from past experience with similar structures how to estimate values for load that are fairly close approximations of final values.

Redesign of the Structures

Using the results of the analysis of preliminary designs, the designer recomputes the proportions of the main elements of all structures. Although each analysis is based on estimated values of load, the forces established at this stage are probably indicative of what a particular structure must carry, so that proportions are unlikely to change significantly even after the details of the final design are established.

Evaluation of Preliminary Designs

The various preliminary designs are next compared with regard to cost, availability of materials, appearance, maintenance, time for construction, and other pertinent considerations. The structure best satisfying the client's established criteria is selected for further refinement in the final design phase.

Final Design and Analysis Phases

In the final phase, the engineer makes any minor adjustments to the selected structure that will improve its economy or appearance. Now the designer carefully estimates dead loads and considers specific positions of the live load that will maximize stresses at specific sections. As part of the final analysis, the strength and stiffness of the structure are evaluated for all significant loads and combinations of load, dead and live, including wind, snow, earthquake, temperature change, and settlements. If the results of the final design confirm that the proportions of the structure are adequate to carry the design forces, the design is complete. On the other hand, if the final design reveals certain deficiencies (e.g., certain members are overstressed, the structure is unable to resist lateral wind loads efficiently, members are excessively flexible, or costs are over budget), the designer will either have to modify the configuration of the structure or consider an alternate structural system.

Steel, reinforced concrete, wood, and metals, such as aluminum, are all analyzed in the same manner. The different properties of materials are taken into account during the design process. When members are sized, designers refer to design codes, which take into account each material's special properties.

This text is concerned primarily with the *analysis* of structures as detailed above. Design is covered in separate courses in most engineering programs; however, since the two topics are so closely interrelated, we will necessarily touch upon some design issues.

1.3 Strength and Serviceability

The designer must proportion structures so that they will neither fail nor deform excessively under any possible loading conditions. Members are always designed with a capacity for load significantly greater than that required to support anticipated *service loads* (the real loads or the loads specified by design code). This additional capacity also provides a factor of safety against accidental overload.

Although structures must be designed with an adequate factor of safety to reduce the probability of failure to an acceptable level, the engineer must also ensure that the structure has sufficient stiffness to function usefully under all loading conditions. For example, floor beams under service loads must not sag excessively or vibrate under live load. Excessively large deflections of beams may produce cracking of masonry walls and plaster ceilings, or may damage equipment that becomes misaligned. High-rise buildings must not sway excessively under wind loads (or the building may cause motion sickness in the inhabitants of upper floors). Excessive movements of a building not only are disturbing to the occupants, who become concerned about the safety of the structure, but also may lead to cracking of exterior curtain walls and windows. Photo 1.1 shows an office building whose facade was constructed of large floor-to-ceiling glass panels. Shortly after the high-rise building was completed, larger than anticipated wind loads caused many glass panels to crack and fall out. The falling glass constituted an obvious danger to pedestrians in the street below. After a thorough investigation and further testing, all the original glass panels were removed. To correct the design deficiencies, the structure of the building was stiffened, and the facade was reconstructed with thicker, tempered glass panels. The dark areas in Photo 1.1 show the temporary plywood panels used to enclose the building during the period in which the original glass panels were removed and replaced by the more durable, tempered glass. Similarly, for seismic design of multistory buildings the designer also needs to ensure that the relative lateral deflection between two adjacent floors is not excessive.

Photo 1.1: Wind damage. Shortly after thermopane windows were installed in this high-rise office building, they began failing and falling out, scattering broken glass on passers-by beneath.

Before the building could be occupied, the structural frame had to be stiffened and all the original glass panels had to be replaced by thicker, tempered glass—costly procedures that delayed the opening of the building for several years.

1.4 Historical Development of Structural Systems

To give you some historical perspective on structural engineering, we will briefly trace the evolution of structural systems from those trial-and-error designs used by the ancient Egyptians and Greeks to the highly sophisticated configurations used today. The evolution of structural forms is closely related to the materials available, the state of construction technology, the designer's knowledge of structural behavior (and much later, analysis), and the skill of the construction worker.

For their great engineering feats, the early Egyptian builders used stone quarried from sites along the Nile to construct temples and pyramids. Since the tensile strength of stone, a brittle material, is low and highly variable (because of a multitude of internal cracks and voids), beam spans in temples had to be short (Figure 1.1) to prevent bending failures. Since this *post-and-lintel* system—massive stone beams balanced on relatively thick stone columns—has only a limited capacity for horizontal or eccentric vertical loads, buildings had to be relatively low. For stability, columns had to be thick—a slender column will topple more easily than a stocky column.

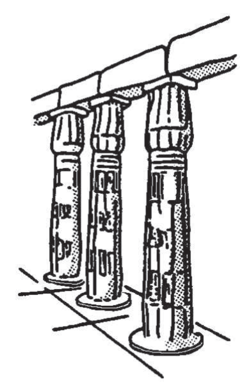


Figure 1.1: Early post-and-lintel construction as seen in an Egyptian temple.

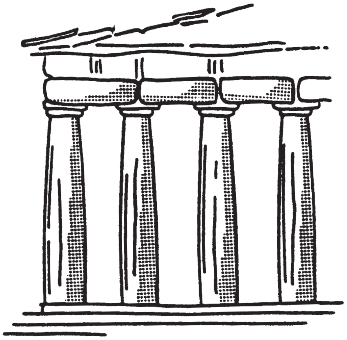


Figure 1.2: Front of Parthenon, where columns were tapered and fluted for decoration.

The Greeks, greatly interested in refining the aesthetic appearance of the stone column, used the same type of post-and-lintel construction in the Parthenon (about 400 B.C.), a temple considered one of the most elegant examples of stone construction of all time (Figure 1.2). Even up to the early twentieth century, long after post-and-lintel construction was superseded by steel and reinforced concrete frames, architects continued to impose the facade of the classic Greek temple on the entrance of public buildings. The classic tradition of the ancient Greeks was influential for centuries after their civilization declined.

Gifted as builders, Roman engineers made extensive use of the arch, often employing it in multiple tiers in coliseums, aqueducts, and bridges (Photo 1.2). The curved shape of the arch allows a departure from rectangular lines and permits much longer clear spans than are possible with masonry post-and-lintel construction. The stability of the masonry arch requires that (1) its entire cross section be stressed in compression under all loading conditions, and (2) abutments or end walls have sufficient strength to resist the large diagonal thrust at the base of the arch. The Romans, largely by trial and error, also developed a method of enclosing an interior space by a masonry dome, as seen in the Pantheon still standing in Rome.

During the Gothic period of great cathedral buildings (Chartres and Notre Dame in France, for example), the arch was refined by trimming away excess material, and its shape became far more elongated. The vaulted roof, a three-dimensional form of the arch, also appeared in the construction of cathedral roofs. Arch-like masonry elements, termed *flying buttresses*, were used together with piers (thick masonry columns) or walls to carry the thrust of vaulted roofs to the ground (Figure 1.3). Engineering in this period was

Photo 1.2: Romans pioneered in the use of arches for bridges, buildings, and aqueducts. Pont-du-Gard. Roman aqueduct built in 19 B.C. to carry water across the Gardon Valley to Nimes. Spans of the first- and second-level arches are 53 to 80 ft. (Near Remoulins, France.)

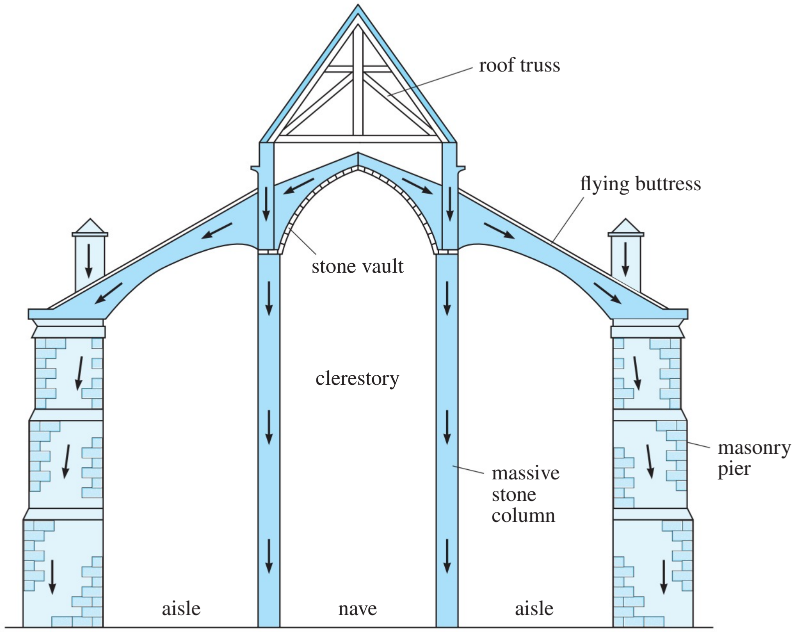


Figure 1.3: Simplified cross section showing the main structural elements of Gothic construction. Exterior masonry arches, called *flying buttresses*, were used to stabilize the arched stone vault over the nave. The outward thrust of the arched vault is transmitted through the flying buttresses to deep masonry piers on the exterior of the building. Typically the piers broaden toward the base of the building. For the structure to be stable, the masonry must be stressed in compression throughout. Arrows show the flow of forces.

highly empirical based on what master masons learned and passed on to their apprentices; these skills were passed down through the generations.

Although magnificent cathedrals and palaces were constructed for many centuries in Europe by master builders, no significant change occurred in construction technology until cast iron was produced in commercial quantities in the mid-eighteenth century. The introduction of cast iron made it possible for engineers to design buildings with shallow but strong beams, and columns with compact cross sections, permitting the design of lighter structures with longer open spans and larger window areas. The massive bearing walls required for masonry construction were no longer needed. Later, steels with high tensile and compressive strengths permitted the construction of taller structures and eventually led to the skyscraper of today.

In the late nineteenth century, the French engineer Eiffel constructed many long-span steel bridges in addition to his innovative Eiffel Tower, the internationally known landmark in Paris (Photo 1.3). With the development of high-strength steel cables, engineers were able to construct long-span suspension bridges. The Verrazano Bridge at the entrance of New York harbor—one of the longest bridges in the world—spans 4260 ft between towers.

The addition of steel reinforcement to concrete enabled engineers to convert unreinforced concrete (a brittle, stonelike material) into tough, ductile structural members. Reinforced concrete, which takes the shape of the temporary forms into which it is poured, allows a large variety of forms to be constructed. Since reinforced concrete structures are *monolithic*, meaning they act as one continuous unit, they are highly indeterminate.

Reinforced concrete is also used to *precast* individual structural components like beams, slabs, and wall panels. Both precast and monolithic

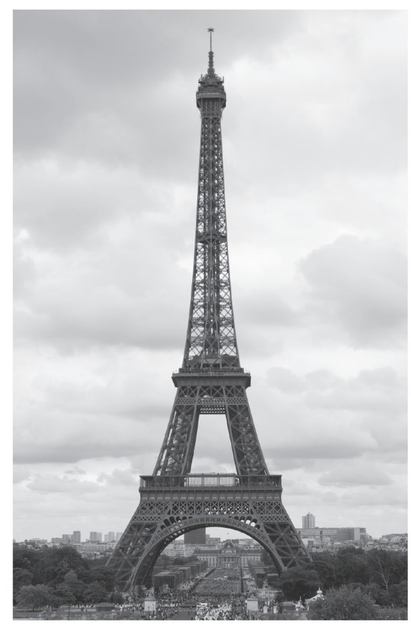


Photo 1.3: The Eiffel Tower, constructed of wrought iron in 1889, dominates the skyline of Paris in this early photograph. The tower, the forerunner of the modern steel frame building, rises to a height of 984 ft (300 m) from a 330-ft (100.6-m) square base. The broad base and the tapering shaft provide an efficient structural form to resist the large overturning forces of the wind. At the top of the tower where the wind forces are the greatest, the width of the building is smallest.