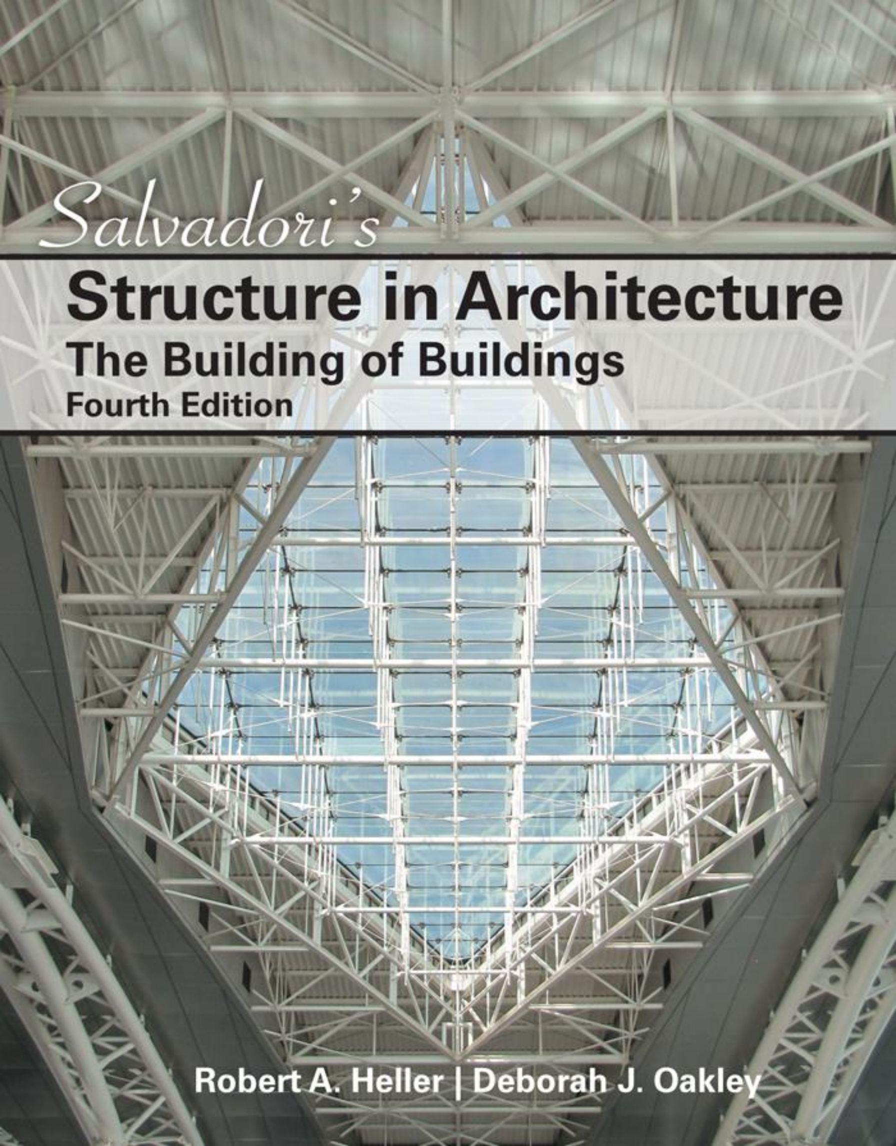

Salvadori's

Structure in Architecture

The Building of Buildings

Fourth Edition

Robert A. Heller | Deborah J. Oakley

Salvadori's STRUCTURE IN ARCHITECTURE

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FOREWORD

When *Structure in Architecture* first appeared in 1963, it awakened architects to a qualitative, conceptual understanding of structures that was lacking, as engineers had always described structures clouded with mathematics. Here was an important new path that showed how structures work rather than how they are computed. Not only architects but engineers themselves and the general public were able for the first time to learn from this innovative approach. A strength of this book is that it demonstrates that even the most complicated-looking structure can be deconstructed to reveal its elementary roots: beams, columns, frames, trusses, and shells, whose actions can be conceptually understood, clarifying the way in which the whole structure works.

In the 50 years since the first edition of this book was published, a vastly expanded catalog of available structural types has appeared; new materials have been developed, new shapes have been introduced, and, above all, advances in computing technology have allowed architects and engineers the freedom to conceive designs never before possible. A new edition was therefore inevitable.

Mario Salvadori was my teacher, my mentor, and then my partner in Weidlinger Associates. Together, we wrote four books on structural design, failures, and seismicity. All were descended from the approach Mario conceived in *Structure in Architecture* to explain technical concepts using simplified language, making them accessible to readers of any age. I am honored, and it gives me great pleasure to introduce both new readers and readers of previous editions of *Structure in Architecture* to this new edition. The classic work has now been greatly improved to bring the original into the twenty-first century with updated graphics and structural examples, as well as a revised text to reflect recent advances in structural typology. This new edition will undoubtedly stand for the next decades as the go-to reference to understanding how structures work.

Matthys Levy

PREFACE

It has been 30 years since Mario Salvadori updated the last edition of *Structure in Architecture*. On its initial publication in 1963, it was one of the first and only books of its kind to introduce the principles of structures to architectural students in a largely nonmathematical manner. The variety of textbooks of this genre has grown and changed dramatically since that time, and contemporary publishing practices have dramatically evolved as well. Now long out of print and superseded by many newer books presenting rich graphic content, *Structure in Architecture* has not only been surpassed in popularity by other texts, but the presentation may also seem dated or unappealing to contemporary students. Nevertheless, it remains an outstanding work of one of the most influential individuals in the area of architectural structures education. Rather than relegate it to the bin of history, a new edition to perpetuate its legacy was called for. This edition thus presents a substantial revision of the graphic presentation, while retaining the clarity of, and expanding on, the original text.

ON MARIO SALVADORI

To better understand the history, place, and authority of this text, it is helpful to understand briefly something about Mario Salvadori. Throughout his career, he wrote voluminously and taught extensively on the topic of architectural structures, as well as engaging in a number of conference discussions about the nature of the dialog between architects and engineers. Holding Italian doctorate degrees in mathematics *and* civil engineering, for nearly 50 years he taught in both schools of civil engineering and architecture at Columbia University in New York, rising to be one of the most distinguished faculty members of that era.

Fourteen years into his teaching career, while continuing his academic appointment, he joined the practice of the brilliant Hungarian engineer Paul Weidlinger. There, too, Dr. Salvadori distinguished himself by becoming a partner in 1963 and later chairman of Weidlinger Associates, thus impacting the design of many important structures, conducting numerous forensic structural investigations, as well as shaping the careers of generations of young engineering practitioners. For his lifetime of contributions, he was widely honored by engineering, architecture, and academic societies alike.

Of all the achievements of an illustrious career, however, Mario Salvadori was most proud of his work teaching science and math to inner-city children in the New York City region, using buildings and bridge structures as a springboard. The last three decades of his life were increasingly dedicated to this personal educational mission. The legacy of this work lives on today in the form of the Salvadori Center (salvadori.org), a nonprofit educational center that he established in 1987—an organization dedicated to the mission of educating children in what is now referred to as STEM, for Science, Technology, Engineering, and Math. Clearly decades ahead of his time, Mario was active with the Center until the very end of his life, passing away in 1997 at the age of 90.

ABOUT *STRUCTURE IN ARCHITECTURE*

Along with the works produced in his dual careers of academia and practice, Mario Salvadori wrote also for the lay audience. His most popular books such as *Why Buildings Stand Up* and *Why Buildings Fall Down* (coauthored with Matthys Levy) have been in print continuously since their first publication in 1980 and 1992, respectively. These can be seen as later-career books very much influenced by his work with children, written in a manner accessible to anyone with no formal training beyond basic schooling.

The first edition of *Structure in Architecture*, in contrast, came much earlier (1963), yet Dr. Salvadori had at this point been teaching at Columbia for nearly twenty-five years and this was already his fourth published book. Two subsequent editions in 1975 and 1986, plus ten foreign-language translations, attest to the interest and worldwide popularity of the book. Unlike the later popular texts, however, *Structure in Architecture* went deeply into principles that are important for architects to understand, though never with much mathematics.

The issue of just how technical an engineering education an architectural student requires has been a matter of debate for decades. A polarity exists even within the community of educators who teach and research in architectural structures: On the one hand, there are those who firmly believe that calculations are the basis for the study while, on the other hand, there are also those who feel quite the opposite. With his unique talents, Mario Salvadori was able to successfully bridge these two disparate worlds and recognize the commonality between the two. He was able to translate arcane principles of mathematics and science into simple language that—quite literally—even young children could understand. Dr. Salvadori believed that the conceptual approach was a vital starting point for (or at least concurrent study with) a more technical study. He was thus able to engage many architecture students who would otherwise have had no interest in the more technical aspects of architectural design.

THE INTENT OF THE FOURTH EDITION

Deborah Oakley was approached by Pearson Education to undertake the project as a new coauthor, joining with Robert Heller to revisit the manuscript for an update of this classic book. As noted previously, the objective was to appeal to a new audience, while retaining all of the strong points of the earlier editions. The organizational structure of the new edition has been largely retained from the previous. Rather than making any drastic changes to the text and examples of the third edition, we consider the book to be a mid-to-late career watermark of one of the most celebrated architectural technology educators, and thus important to conserve the spirit of the previous editions. Editing of the text was a shared effort between Deborah Oakley and Robert Heller, while the acquisition of photos and creation of the majority of illustrations and 3D models were by Deborah Oakley.

The approach was to strike a balance between what should be retained and/or expanded, and what should be updated or removed. With respect to the written text, it remains largely that of Mario Salvadori, with additions and alterations ranging from minimal to significant, depending on the chapter. Regarding example projects, where possible we retained those that are iconic and clearly illustrate fundamental principles, while replacing with contemporary projects some that had been superseded. Visually, the greatest difference will be seen in the graphics and computer renderings by the new author, and in the color photographs. Many illustrations have been provided with extensive supplemental captioning. Original 2D illustrations have been greatly expanded and are full color for best clarity. Some readers who know the earlier editions may miss the simple line drawings conceived by Robert Heller and executed by Felix Cooper. Unfortunately, the originals for these are lost to the sands of time. More than a few of them, however, live on in updated reproductions.

Among the more noticeable changes are that the text has been made gender neutral in language, following current practices and reality. Errors or omissions that we identified have been corrected, and contemporary topics have been added in various chapters. This edition therefore renews a classic volume with a new look and feel and more recent examples. In so doing, we intend for it to reclaim a place in the canon of modern architectural structures texts, and to reintroduce Mario Salvadori to a contemporary audience, a new generation of students, and even educators.

There are numerous books on architectural structures that feature extensive use of calculations, but far fewer that explain complex principles to new students using a largely nonmathematical, conceptual approach. With the updated graphic presentation, this book can be studied at the image and caption level first, and then more deeply in the text itself. This is a text that any intelligent individual with an understanding of elementary trigonometry and algebra should be able to pick up and learn from on his or her own. It remains an excellent preparatory or companion book for a numerically based study.

Looking to the future, we envision not only updates to examples but also branching into new media and learning resources of the digital age. But whatever may come to pass with future editions, one thing remains constant: The reason that a more than 50-year-old book such as this can still remain relevant in the twenty-first century is that the fundamental principles of structure have not changed. In fact (at the risk of oversimplification), it can be said that they have most elementally not changed since the time of Newton. Thus, Dr. Salvadori's voice remains vibrantly alive in this work, as it has in perpetuity with his several other works oriented toward the lay audience. We hope that the spirit of Mario Salvadori approves of the new edition, and that new generations are introduced to his work.

Deborah Oakley,
Las Vegas, Nevada

Robert Heller,
Burlington, North Carolina
June 2015

NEW FOURTH EDITION HIGHLIGHTS

- Entirely new graphics package:
  - Previous line illustrations updated with over 150 full color photographs, nearly 500 new full color rendered illustrations by Deborah Oakley, and extensive new image captioning
  - Many completely new illustrations added throughout the book to best demonstrate fundamental concepts
  - Designed to be accessible and attractive to the current generation of architectural students in a media-saturated world:
    - Big ideas can be grasped by studying the images and captions.
    - An in-depth understanding comes by studying the text with the images and experimenting with end-of-chapter exercises.
- Broken into three overall sections for better comprehension of organizational structure:
  - Part I: Fundamental Concepts (Chapters 1–5)
  - Part II: Structural Forms (Chapters 6–9)
  - Part III: Beyond the Basics (Chapters 10–15)
- New example structures illustrated throughout text
- Expanded content with enhanced text discussion and related graphics on critical topics such as beam behavior, moment of inertia, redundancy, and so on
- New at the end of each chapter:
  - Summary key ideas of chapter
  - Thought questions and simple exercises for further reflection
  - List of recommended key references of similar subject matter

FEATURES RETAINED FROM PREVIOUS EDITIONS

- Intuitive, nonmathematical approach
- Geared as an introductory text for beginning architectural students, students of technical schools, and interested laypeople
- Most of the historical examples, since they represent milestone accomplishments
- Most of the original text by Mario Salvadori

About metric units in the text It has been more than 40 years since the U.S. congress passed the Metric Conversion Act of 1975, and yet the country continues to use U.S. Customary (a version of British Imperial) units. When first written, this text was all in U.S. Customary units, and illustrations were created using whole numbers. This presents a quandary to the current edition. With an international audience, we cannot ignore the fact that as of 2015 all but two other countries (Liberia and Myanmar) have adopted SI units (*Système International d'Unités*, the international standard), and yet the text is directed primarily at a U.S. audience. SI units therefore accompany the U.S. units parenthetically and have been rounded to the nearest whole number equivalent (or no more than one decimal place). It is not an optimal solution, but it is also one that Mario Salvadori himself used in some of his other popular works. We continue to hope that a future edition may be wholly in SI units and thus dispense with this temporary workaround.

ACKNOWLEDGMENTS

Deborah Oakley would like to thank Pearson Education for the opportunity of undertaking this project and also the many individuals who have contributed photographs throughout the text (credit is provided with image captions). Thanks are extended to my colleague Vincent Hui at Ryerson University and his students for some of the initial 3D models in Chapter 6, as well as to my graduate assistants at the University of Nevada, Las Vegas School of Architecture; in particular Vincent del Greco, who also worked on some early Chapter 6 models, and Adam Bradshaw, for conducting photo research and assisting with the final image preparation. Special thanks are extended to Terri Meyer Boake of the University of Waterloo for the many photographs, as well as mentorship and friendship over the years. I would also like to thank my father, Donald Oakley—a writer by trade—for final proofreading. And the most important thanks of all go to the many students who have taught me how to teach structures to architecture students.

Robert Heller wishes to extend his appreciation to Deborah J. Oakley for her diligence, drive, and ingenuity in making this work, a tribute to the memory of his late friend Dr. Mario G. Salvadori, possible. Coauthoring the first edition of *Structure in Architecture* gave him the impetus to teach structural mechanics for 50 years.

AUTHOR BIOGRAPHIES

Deborah J. Oakley, AIA, PE

Deborah Oakley has been teaching structures to architecture students for nearly 20 years. She is an associate professor at the School of Architecture at the University of Nevada, Las Vegas, where she also teaches design studio classes. Uniquely qualified as both a Registered Architect and Professional Engineer, she came to academia with education and experience in fields of both civil (structural) engineering and architecture. She is a passionate crusader for the intergration of architecture and structure, including associated educational endeavors in the field. She is a founding member, past president, and board member of the Building Technology Educators' Society (BTESonline.org), the only North American academic organization of architectural educators focused on construction and structural technology education and research. Prior appointments have been as an assistant professor at the University of Maryland School of Architecture, Planning and Preservation and at Philadelphia University School of Architecture and Design. Her current work involves conducting Discipline-Based Education Research in the area of architectural structures pedagogy.

Robert A. Heller, PhD, PE

Robert Heller received his education at Columbia University. After earning a PhD in engineering mechanics, he joined the Faculty of Columbia's Department of Civil Engineering. There he was Mario Salvadori's colleague and eventually became his coauthor. After leaving Columbia, Heller was appointed Professor of Engineering Science and Mechanics at Virginia Tech. In that capacity, he developed new courses on probabilistic structural mechanics and reliability and service life of structures and courses for architects.

His series of educational videos entitled "Mechanics of Structures and Materials" has been widely used in Schools of Architecture and Engineering. Heller's research work on the Service Life of Solid Rocket Propellants and on Aircraft Fatigue for the Department of Defense has been published in numerous scientific journals.

FOREWORD TO PREVIOUS EDITIONS

In this thoughtfully written book, Professor Salvadori endeavors to eliminate one of the most serious gaps between theory and practice in the field of structures. His aim is to build a bridge between the more or less conscious intuition about structure, which is common to all mankind, and the scientific knowledge of structure, which gives a fair representation of physical reality on the basis of mathematical postulates.

No one doubts that the bridging of this gap is possible and that, if achieved, it would be extremely useful.

In order to invent a structure and to give it exact proportions, one must follow both the intuitive and the mathematical paths.

The great works of the distant past, built at a time when scientific theories were nonexistent, bear witness to the efficiency and power of intuition.

Modern theories are incessantly and progressively developed, and their refinement is illustrated by the construction of ever greater and more daring structures.

If structural invention is to allow the efficient solution of the new problems offered daily by the ever-growing activity in the field of construction, it must become a harmonious combination of our personal intuition and of an impersonal, objective, realistic and rigorous structural science.

In other words, theory must find in intuition a force capable of making formulas alive, more human and understanding, and of lessening their impersonal technical brittleness. On the other hand, formulas must give us the exact results necessary to obtain "the most with the least," since this is the ultimate goal of all human activities.

Through always clear and, at times, most elementary examples, Professor Salvadori's book tends to unify these two viewpoints (I was almost going to say, these two mentalities), which must be cast into a unique synthesis if they are to give birth to the essential unity of all great structures.

Future architects will find it particularly useful to study this book in depth and to meditate upon it, since even if they can entrust the final calculation of a structure to a specialist, they themselves must first be able to invent it and to give it correct proportions. Only then will a structure be born healthy, vital and, possibly, beautiful.

I feel that we must be particularly grateful to Professor Salvadori for undertaking this anything but easy task.

Pier Luigi Nervi

PREFACE TO THIRD EDITION

As stated in the preface to the first edition, this book has been written for those

- who love beautiful buildings and would like to know why they stand up;
- who dream of designing beautiful buildings and would like them to stand up;
- who have designed beautiful buildings and would like to better know why they stand up.

The principles of structure are eternal, but new developments in structural materials, methods of design, and construction techniques constantly change the application of such principles to the building of buildings, and require frequent reassessment of the field of construction.

As one starts revising a book such as this it becomes obvious that virtually every page requires clarifications, additions, and updating. Besides innumerable changes of this nature this edition contains:

- A new chapter on structural failures, a topic of increasing concern in our society.
- A new chapter on structural aesthetics, a subject of growing awareness to architects and engineers, that has interested me for many years.
- A new treatment of space-frames for large roofs that have become, because of their economy and beauty, the most popular structures of our time, the world over.
- The first presentation of new techniques for the erection of membrane roofs unsupported by air pressure.
- A new treatment of earthquakes and methods of earthquake attenuation.
- An updating of structural material properties and construction methods.
- A record of new limits reached in the field of architectural structures.
- Over eighty new or modified figures by the original illustrator, Felix Cooper.

The intuitive and descriptive presentation is unchanged from that used in previous editions: irrespective of background, the book can be understood by anyone interested in why buildings stand up.

The structural concepts presented here were formerly introduced mathematically to graduate students of the School of Architecture at Princeton University and, later, to students of the graduate School of Architecture at Columbia University. The same concepts have been presented without mathematics to freshmen in architecture at Columbia, with the help of the models and motion pictures of my friend Robert Heller. Professor Heller did not participate in the preparation of this edition, and the changes and new material are solely my responsibility.

I hope that my latest efforts will meet with the same favor accorded previous editions throughout the world.

My deep gratitude goes

- to my former collaborator, Dr. Robert Heller, for his help in conceiving the original illustrations and for his constructive suggestions;
- to my teachers at the Faculty of Pure Mathematics of the University of Rome, who made mathematics part of my mental makeup and allowed me to move beyond it;
- to Charles R. Colbert, the former dean of the School of Architecture at Columbia, for encouraging me to try this intuitive approach to structures;
- to Felix Cooper for drawing the illustrations;
- to Tim McEwen of Prentice-Hall for suggesting that I prepare this revised edition;
- to all my friends for their interest and support during the relatively brief but intense period when the thoughts accumulated in years of study became this book;
- to my wife, Carol, who stood by me from the time this book was first conceived to the day I corrected the proofs of this present edition.

New York — ***Mario Salvadori***

This book is joyfully dedicated
to my architectural students
who for thirty years taught me
how to teach structures.

PART I

FUNDAMENTAL CONCEPTS

Like many disciplines, the knowledge base of structures is rooted in fundamental concepts that apply at all levels of understanding. The first five chapters of this book introduce those essential principles upon which all the later chapters are developed. Chapter 1 discusses the basic idea of structures and the relationship between architects and engineers, while Chapter 2 describes the types of forces (loads) that structures must resist, and the relationship to building codes that prescribe them. Chapters 3 and 4 present the basic properties of materials used in construction and the basic conditions required for structures to exist, while Chapter 5 illustrates the essential types of behavior that structural elements are subjected to.

The Soccer Stadium in Braga Portugal (see Figure 2.1)

Photo courtesy of Deborah Oakley

CHAPTER
ONE

STRUCTURE IN ARCHITECTURE

1.1 WHAT IS STRUCTURE?

It can be argued that the essence of a building is structure, for no physical object, whether built or natural, can exist but for the structure that gives it form (Figure 1.1). Without the structural armature of our bones, we would be like jellyfish or octopi, slithering on the ground going about our daily business. It is the structure of its wood fibers that enables the tree to stand, just as it is the structure of the bridge that enables it to span a river. The difference between the two is merely that one developed from nature, the other by the will of a human creator. Over the centuries, humanity has come to understand many of the secrets of nature. We have learned how to employ that understanding to a desired end in the creation of structures that meet our specific needs for shelter, commerce, worship, recreation, and transportation.

FIGURE 1.1 The Burj Al Arab hotel in Dubai, UAE, is a stunning example of expressed structure in architecture. The steel exoskeleton provides for lateral stability in the region's high winds and perfectly compliments the sail-like shape of the design.

Photo courtesy of Joceclyn Hidalgo

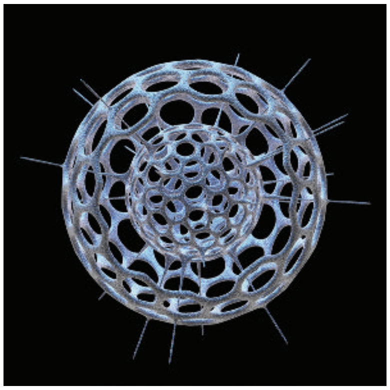
The purpose of this book is to take the reader on a journey into both becoming aware of the wide variety of built structures in the world and developing an understanding for the key principles that underlie them. The complete engineering design of a structure is normally a complex undertaking, especially for larger structures. It requires an ability to mathematically model forces that exist in response to the loads that the structure may experience during its useful life, and the proportioning of materials to resist those forces. Nevertheless, it is entirely possible to arrive at a very strong intuitive understanding of structural behavior and materials with little or no math. This text presumes no formal training in advanced mathematics, and so it is well suited for beginning students of architecture, as well as practitioners who need a refresher, or the serious lay student seeking to understand more about the subject. As such it can serve as a good preparation for the undertaking of more advanced study in the principles of engineering structures.

1.2 STRUCTURE IN NATURE

The place where we first and most directly encounter structure is not in architecture but within nature herself. Every living thing, from the smallest cell to the tallest tree, has a structural form that is shaped in direct response to the forces of its environment, such as gravity, water pressure, and wind. Other natural structures serve the needs of their builders. The spider's web is built of the arachnid's own secretion, The bee's geometrically precise honeycomb and the beaver's dam could not be better constructed by humans.

Each of us therefore has an innate understanding of structures at a very subliminal level because our very bodies *are* structure. We physically sense the pull of gravity and intuitively know to widen our stance and lean into a strong wind, for example. Capitalizing on this, we can use our own bodily sense and a growing awareness of structural forms in nature to help understand how built structures are designed and constructed.

The shape and proportions of a structural form are significantly a matter of scale (Figure 1.2a-c). We can observe that the branching pattern of a dandelion stalk is far more



(a)

(b)

(c)

FIGURE 1.2 Size matters: a microscopic radiolarian skeleton (a type of oceanic zooplankton), a dandelion, and a tree branch. A dandelion seed (b), light and made to catch in the wind, is a distinctly different pattern than that of a tree (c), and both far different than the radiolarian (a). In fact, scaled up to the size of a tree, the dandelion branches could not support their own weight. Every structure in nature has a unique shape that is largely determined by both its size and environmental influences.

(a) Photo: Alfred Pasieka/Stockbyte/Getty Images; (b) Photo: Achim Prill/123rf; (c) Photo: Potapov Alexander/Shutterstock

slender than if the plant were enlarged to the size of even a small bush, never mind a large tree. This is due to the fact that the amount of material increases by the cube of its size and yet the pull of gravity is essentially constant. This is to say that the doubling in size of an object or organism increases its volume by a factor of not two or four, but by *eight* times. An ant is known to be an organism that can carry a load many times its own body weight. Enlarge it to the size of an elephant, though, and the spindly legs of the ant, even if proportionally enlarged, would no longer be sturdy enough to even support itself despite how appropriate the form may be at its natural size (so much for 1950s science fiction films!).

We can therefore look to nature as an aid in our quest to understanding the behavior of human-created structures. Consider a tree branch (Figure 1.2c). It is essentially a cantilever, which is a beamlike element that is supported only at one end (see Chapter 7). Notice how the tree branch is thickest where it meets the tree trunk…this is also the place where the internal stresses that the wood fibers must resist are at their highest value for the branch. As a consequence, more material is needed here to resist these stresses. We can similarly look to the behavior of natural materials, many of which, such as wood and stone, we use in our constructed buildings. Hair is an example of a material that can have a high degree of ductility—it can be pulled and stretched somewhat before it breaks. A blade of grass, though exhibiting some ductility, will snap much more readily when pulled. These are but a few of the *engineering properties* of materials that will be discussed at length in Chapter 3, *Structural Materials.*

1.3 THE ARCHITECT AND THE ENGINEER

Architects interact with numerous specialists in the creation of a building, many of whom are engineers. It is helpful to gain a perspective of the variety of engineering disciplines and understand the roles that these professionals play in relation to architects. At its basis, engineering is the art of creation in the service of a desired end, by employing known principles of science and properties of materials. There are many branches of engineering that architects work with, and even within individual branches there are subspecialties.

Civil engineering is a very broad discipline, which encompasses a wide range of subspecialties. These include individuals responsible for site design (addressing land surveying, site grading, drainage, and parking), transportation engineers who design highways and other transit systems, environmental engineers who focus on the treatment processes to provide clean water and dispose of waste, fire protection engineers who focus on the safety of structures against fire hazard, and geotechnical engineers who specialize in the analysis of the soil and rock that buildings are built upon.

Electrical engineers are responsible for the design of systems to electrically power buildings, as well as the internal distribution of power to lighting, electrical outlets, and machinery. There are also electrical engineers with whom architects typically have little interaction, including those who are responsible for the large-scale production of power and distribution through the "power grid" on a regional scale, and electronics and computer engineers who design the "high-tech" systems of the modern world.

Mechanical engineering is another particularly broad discipline. Some mechanical engineers design automobiles (automotive engineers) or airplanes (aerospace engineers), while others create the many machines that we are all familiar with in our daily lives, such as kitchen appliances and household utilities. The types of mechanical engineers that architects most frequently interact with are those who design the heating, ventilation, and cooling systems in buildings, as well as elevators and escalators.

The most important branch of engineering in relationship to the subject of this book is yet another subspecialty of civil engineering, the structural engineer. Structural engineers, as the name implies, are responsible for the creation of safe structures. This includes those who design bridges and other highway structures, as well as those whose main focus is on the design of building structures. The subject of this book is fundamentally focused on the principles that underlie the profession of structural engineering.

What distinguishes engineers from architects? How do engineers think? The popular stereotypical image of an engineer is the introverted nerd lacking social skills with thick-rimmed glasses and a pocket protector. Although there may be some who fit that description, the truth is actually far from the reality. Engineering is, in fact, a very creative process and, fundamentally, engineers are problem solvers. It is actually rather difficult to lump engineers into one class, because there are so many branches of engineering. Many engineers are the types who enjoy logic puzzles or figuring out how to make something work and other intellectual challenges. A good percentage are tinkerers who like to work with their hands. If any generalization can be made, it is that all good engineers excel at rational problem solving.

So how do architects think in contrast to engineers? In many regards, architecture is among the last of the great humanist fields of study. Whereas engineers are most often specialists within their given field, architects are generalists who learn to see the big picture. A good architect must have a basic understanding of each of the many disciplines needed to construct a building. Architecture spans across many levels, from the most sublime sculpting of form and manipulation of such intangibles as light and shadow, to the social responsibility of the project at an urban scale, to the physical realization of building construction. With the increasing complexity of the world, and increasing recognition of the role that buildings play in our environment, a good architect is called on like never before to be conversant in the supporting roles of an ever-growing number of disciplines including, and going beyond, engineering and, of growing importance, environmental sustainability.

Fundamentally, architecture is a collaborative experience that requires the integration of all disciplines. In this regard, the architect can be compared with an orchestral conductor, the one individual who has an overview of the entire process. By integrating key decisions early on in the architectural design process—especially those that deal with the building structure—the best and most satisfying result is more likely to be achieved.

1.4 HISTORICAL DEVELOPMENT

As noted earlier, structure is an essential component of architecture, and has always been so. No matter whether man built a simple shelter for himself and his family or enclosed large spaces where hundreds could worship, trade, discuss politics, or be entertained, humans had to shape certain materials and use them in certain quantities to make their architectural creations stand up against the gravitational pull of the earth and other powerful forces of nature. Wind, snow, and rainstorms, earthquakes, and fires had to be resisted. If possible, this was accomplished with expenditures of labor and materials that were not unreasonable in relation to their availability and cost. And because from earliest times a sense of beauty has been innate in humans, all constructions by civilized peoples were also conceived according to certain aesthetic tenets. This would often impose on the structure far more stringent requirements than those of strength and economy.

It may be thought, therefore, that structure was always considered important, and, in a sense, dictated architecture. This is simply not so. Magnificent buildings have been created in the past, and are created even today, with a notable disregard for the "correctness of structure." The Parthenon (Figure 1.3), divinely beautiful as it is, translates

FIGURE 1.3 The Parthenon in Athens, Greece. This most majestic of all ancient buildings—an acknowledged architectural masterpiece—is nonetheless "incorrect" from a purely structural viewpoint. Stone as a building material is weak in tension and unsuited for spanning long distances; hence, the column spacing must be quite close to keep the stone spans very short.

Photo: Brent Wong/Shutterstock

structural forms typical of wood construction into marble and is, structurally speaking, "wrong." Since wood is a material capable of withstanding tension and compression, and long horizontal elements require both tensile and compressive resistance, they are well built out of wood but much less so of stone.

Stone withstands compression well, but has very little ability to carry tension. Thus, horizontal elements can be built in stone only by reducing their length and supporting them on heavy vertical elements, such as columns or pillars. Hence, horizontal elements of stone are "incorrect" from a structural point of view. On the other hand, Gothic cathedrals could span up to one hundred feet (30 meters) and cover hundreds of square yards (hundreds of square meters) crowded with worshippers by making use of the arch—a curved structural element in which tension is not developed. Thus, stone is the correct material for a vaulted type of structure, and the beauty of the Gothic cathedrals satisfies both our aesthetic sense and our feeling for structural strength (Figure 1.4). This precept is echoed in the famous statement by architect Louis I. Kahn when he "asked" a brick, "*What do you want to be?*" And, metaphorically, the brick replied, "*I like an arch,*" which is a pure compressive structure. Like stone, brick is a material weak in tension, and so structures in which it always remains in compression are the most appropriate form for such materials.

It has been argued by some architectural historians, as well as by some structural engineers, that a deep concern for structure will unavoidably lead to beauty. It is undeniable that a "correct" structure satisfies the eye of even the most unknowledgeable layman, and that a "wrong" structure is often offensively ugly. But it would be hard to prove that aesthetics is essentially dependent on structure. It is easy to show, instead, that some "incorrect" structures are lovely, while some "correct" ones are aesthetically unsatisfying. It may perhaps be wiser to say that correctness of structure is, most of the time, a necessary condition of beauty, but is not sufficient to guarantee beauty. Some contemporary architects and engineers, such as Santiago Calatrava and Christian Menn, or their equally famous predecessors, such as Felix Candela and Pier Luigi Nervi, are so imbued with artistic sense that their structures are beautiful (Figures 1.5a and 1.5b). But some grandiose buildings, recently erected by the use of daring engineering techniques, undeniably lack beauty.

We may thus conclude that knowledge of structures on the part of the architect is highly desirable, and that correctness of structure cannot but add to the beauty of architecture. But considerations of beauty aside, no architecture can be effectively constructed without consideration of structure, and so the better an architect understands the principles of structure, the more empowered will he or she be to make a positive impact on the design from the earliest stages. Final engineering will then be a confirmation of early design decisions, as opposed to a determination of conflicts that must be resolved in order to ensure structural strength and stability, potentially with negative consequences to the original design intent.

FIGURE 1.4 The groin vaults of the magnificent Rouen cathedral in northern France are an expression of a "correct" structure. Here, stone is used to its best ability in compression, with little or no tensile stresses being developed. The stone arches of the groin vault roof effectively channel the heavy load of the stone roof out and down to the exterior walls, where further structures on the exterior known as flying buttresses counteract the outward push.

Photo courtesy of Terri Meyer Boake

1.5 THE PRESENT INTEREST IN ARCHITECTURE

In the recent as well as the ancient past, the figure of the architect was unique: He or she was both an artist and a technologist, a designer, and a builder. Michelangelo could be a painter, a sculptor, an architect, and a master builder: The Vatican in Rome bears his imprint in all four fields. During the last century, however, specialization of knowledge has taken over the field of architecture, and the various functions—once entrusted to the same individual—are now frequently exercised by several different specialists. At least two key persons are essential in the construction team of any important building: the architect and the structural engineer. Today, no architect would dare design a building of even modest size without consulting a structural engineer. The roots of this dependence are to be found in the increasing importance of economic factors, in the technological direction of our culture, and, above all, in our mass civilization's need for an increasing number of all types of structures.

(a) (b)

FIGURE 1.5 The works of engineer-architects such as Felix Candela (a, Our Lady of the Miraculous Medal Church in Mexico City) and Santiago Calatrava (b, Planetarium at the Science Center, Valencia, Spain) exemplify the harmony possible between architecture and engineering. As with a Gothic cathedral, here structure *becomes* the architecture. In the case of Candela, structural efficiency shapes the structure in a series of tilted hyperbolic paraboloids (see Chapter 12), and in the case of Calatrava, high-tech kinetic architecture with operable components translates the abstract form of a human eye into a structure.

(a) Photo courtesy of Benjamin Ibarra-Sevilla; (b) Photo courtesy of Deborah Oakley

As the number of human beings multiplied at an increasing rate during the last few centuries so as to create a "population explosion," civilized societies have also given each human more services, sharply increasing the "psychological density" of the population. Each one of us requires and is given more schooling, more travel, more medical care, more entertainment. Large numbers of people gather under the same roof for all the gregarious activities so typical of our era. Large stations and airports, large stadia, large theaters, large churches, large arenas appear in increasing numbers. Urban agglomerations require the sprouting of taller buildings. The large structure has become a symbol of our culture and a monument to governments, churches, or corporations. In addition, housing the millions and supplying them with schools and hospitals are among the basic goals of civilized societies.

The architect is challenged by these tremendous tasks; the layman becomes aware of the importance of architecture in his own life. Thus, the specialists meet to solve new, difficult problems in a climate of public interest. The general public whose monies are often used for these large projects takes a personal interest in their construction. This interaction between the specialists and the public may lead to better, and more correct, architecture, provided the layman understands the basic problems of the specialist, and the specialists themselves have a common bond of mutual understanding. This is the central theme of contemporary architectural education, including both the education of the architect and the popularization of architecture.

1.6 STRUCTURES AND INTUITION

It is obvious that only the most serious training in mathematics and the physical sciences will allow a designer to analyze a complex structure to the degree of refinement required by modern technology. Today's structural engineer is a specialist among specialists, a subgroup among civil engineers. As new technologies develop, even structuralists specialize: At present some structural engineers specialize in reinforced concrete, others in reinforced concrete roofs only, and some in roofs of only one particular shape or even another material such as high strength fabric. One goes to these specialists for advice on a particular type of structure as one would go to a medical specialist for advice on a rare type of disease.

But it is just as obvious that, once the basic principles of structural analysis have been established, it does not take a specialist to understand them on a purely physical basis. As previously noted, we all have some familiarity with structures in our daily lives: we know at what angle to set a ladder so that it will carry our weight without sliding on the floor; we can have a good sense of how thick a board must be to function as a bookshelf between two supports. We instinctively lean into the wind and widen our stance on a gusty day. It is a fairly easy step to capitalize on these experiences, to systematize such knowledge, and to reach a basic understanding of how and why a modern structure works.

While the layman may find this inquiry fascinating, the architect should find it mandatory: Without it he or she will soon be out of the field of contemporary architecture. For the interested public, it may be one more hobby; for the architectural student and the practicing architect, it is one of the basic requirements of the profession.

Once he or she has grasped the fundamentals, the architect must become conversant with the more refined points of the theory of structures. This will allow the intelligent application of a wealth of new ideas and methods unavailable until a few years ago even to the greatest architects (Figure 1.6). Architecture at its finest incorporates an understanding of structure from the earliest planning stages rather than something that comes after the architectural design is complete. This is only truly accomplished in close collaboration with skilled engineers who understand and share a common vision with the architect.

There is an obvious danger in this new availability and freedom. Art is enhanced by limitations, and freedom may easily lead to anarchy. Since, today, almost any structure can be built, the important question is: "*Should* it be built?" instead of: "Can it be built'?" The architect is less hampered by technological difficulties and may be led astray into the world to the most unjustifiable structures. It is true that the average contemporary architect can aspire to greater achievements in the field of structures than even those of the exceptional practitioner of only a hundred years ago, but such achievements, the fruit of technology, are also obtained through blood, sweat, and tears. In the early decades of the twenty-first century, technological advances have enabled increasingly daring structures (Figure 1.7) that make even the tremendous technological leaps of a few decades ago seem pale (Figure 1.8).

What follows in the subsequent chapters of this book is an attempt to introduce the reader to the field of structures without appealing to a formal knowledge of mathematics or physics. This does not imply that structures will be treated in an elementary, incomplete, or simplified manner. On the contrary, some of the structural concepts presented in the last chapters of this book are refined and complex. Nevertheless, they can be grasped by the reader and recognized in general architectural constructions on a purely intuitive basis. It is hoped that this better knowledge of structural action may lead the interested student to a deeper understanding of the finer points of structural design, and architects to a better facility in embracing structure as a fundamental concept of architectural planning and aesthetic opportunity.

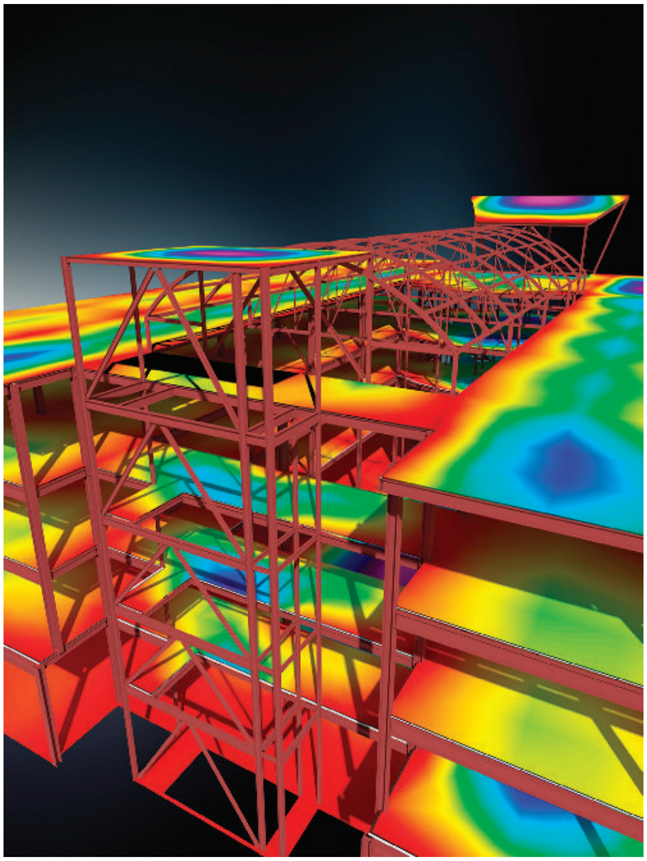


FIGURE 1.6 Contemporary structural analysis software enables visualization of forces in a structure in ways not previously possible. Such technologies enable both the practicing structural engineer and aspiring architect better understand the behavior of increasingly complex structures. The colors in the image are a visual depiction of deformations or stress levels in a structure under load.

Photo courtesy of Autodesk, Inc. © 2012

FIGURE 1.7 The Central China Television headquarters tower (CCTV) in Beijing. A stunning example of a gravity-defying structure impossible to construct even a few decades ago, but made possible through contemporary developments in computerized structural analysis and advancement in materials and fabrication capabilities. But is it an example of structure built simply because we can?

Photo: yxm2008/Shutterstock

FIGURE 1.8 The John Hancock Tower in Chicago, Illinois, regarded as an exemplary model of structural efficiency and simple elegance, was designed in an era before advanced computational methods were widely available.

Photo courtesy of Deborah Oakley

KEY IDEAS DEVELOPED IN THIS CHAPTER

- Structure is the external or internal armature that gives physical objects form and resistance to external forces.
- Structure may be human-made or natural.
- Built structures frequently imitate nature.
- Cooperation between architects and engineers is essential for successful structures; they complement each other. Multiple engineering disciplines are needed in a building project.
- Architecture evolved and changed with the development of building materials from stone and wood to steel, concrete, and composites.
- The advent of computers has simplified the design of complicated and daring forms.

QUESTIONS AND EXERCISES

1. Look around you at the world of your immediate experience. Everything you can see and touch is some form of structure: from the smallest mineral crystal to the largest high-rise building or the longest spanning bridge. Notice what types of materials they are made of, and the different patterns they take. Begin to develop a questioning mind of how and why a structure is made the way that it is. Take notes and draw sketches. Keep a record of these observations.
2. You've been living in and around built structures all your life, but have you ever stepped back to really look at the variety of systems comprising this built world? How many different systems and materials do you note in the buildings and structures you interact with every day? Do you see patterns in the types of systems? Are some of them more supportive of the architecture while others seem more utilitarian? The first step in learning structures is to begin to develop this type of awareness.

FURTHER READING

Rice, Peter. *An Engineer Imagines.* Ellipsis London Press Ltd. 1998.

Saint, Andrew. *Architect and Engineer: A Study in Sibling Rivalry.* Yale University Press. 2008.

Millais, Malcom. *Building Structures: From Concept to Design*, 2nd Edition. Spon Press. 2005.

Ching, Francis, D. K., Onouye, Barry S., and Douglas, Zuberbuhler. *Building Structures Illustrated: Patterns, Systems, and Design*, 2nd Edition. Wiley. 2013. (Chapter 1)

Wentworth, Thompson, D'Arcy. *On Growth and Form: The Complete Revised Edition.* Dover Publications. 1992.

Gordon, James. E. *Structures: Or Why Things Don't Fall Down*. Da Capo Press. 2003.

Moore, Fuller. *Understanding Structures*. McGraw-Hill. 1998.

CHAPTER

TWO

BUILDING LOADS AND CODES

2.1 THE PURPOSE OF STRUCTURE

Structures are always built for a definite purpose. This utilitarian element is one of the essential differences between structure and sculpture: There is no structure for structure's sake.

Structure's main purpose is to enclose and define a space, although, at times, a structure is only built to connect two points, as in the case of bridges and elevators, or to withstand the action of natural forces, as in the case of dams or retaining walls.

Architectural structures, in particular, enclose and define a space in order to make it useful for a particular function. Their usefulness stems, generally, from the total or partial separation of the defined space from the weather and may not require its complete enclosure: A suspended or cantilevered roof of a stadium stand protects the spectators from the weather without enclosing them in a space (Figure 2.1).

The enclosed space may serve many different purposes: the protection of the family, the manufacture of industrial products, the worship of deity, the entertainment of citizens, the gathering of lawmakers. Different purposes, served by different spaces, require different structures, but all structures, by the simple fact of their existence, are submitted to and must resist a variety of loads. Only in rare cases is resistance to loads the primary purpose of a structure: loads are, usually, an unavoidable design consideration in the creation of a structure.

2.2 BUILDING LOADS AND CODES

All structures, particularly buildings, must conform to a variety of regulations called building codes and zoning laws. Some of these are regulated by local authorities, such as minimum "setbacks" from roads and neighbors, maximum height and type of structure. On the other hand, safety-related concerns, load-carrying capacity, the strength of materials used, and fire resistance of materials are governed by the *International Building Code* (IBC), developed by the International Code Council (ICC). First published in 2000, the code is updated on a regular basis. Despite the title, it is predominantly a U.S. code, replacing the three previous codes used in different regions of the country.

The determination of the loads acting on a structure is a complex problem. The nature of loads varies with the design, the location of the structure, and the materials used. Loading conditions may vary with time, change of occupancy, and applied loads. The most important loads on an architectural structure change slowly with time: They are called static. These include the weight of the building, furniture, and so on, thermal expansion and contraction, snow, as well as

Figure 2.1 Partial protection from weather

The soccer stadium in Braga, Portugal, designed by the architect Eduardo Soto de Moura, utilizes suspended cables to support a roof that partially covers the seating areas. The cables supporting the roof are attached to a second seating area mirroring this one on the opposite side of the playing field.

Photo courtesy of Deborah Oakley

lateral earth and water pressures below grade. Rapidly applied loads such as violent winds, earthquakes, reciprocating machines, and explosions are considered to be dynamic loads. The IBC divides loads into various classifications, such as Dead, Live, Wind, Snow, Seismic loads, Soil and Water Pressures, and so on.

The load to be carried by the floor of a building varies so much, depending on the occupant of the floor, the distribution of furniture, the weight of machines, or the storage of goods, that codes substitute for it an equivalent load. This equivalent load is derived, on the basis of statistical evidence, for each type of building, and is modified from time to time as new conditions or knowledge arise (see Section 2.4).

Code loads are conventional loads: A floor load may be assumed to be a constant number of pounds on each square foot (PSF) of floor (or kiloNewtons per square meter (kN/m^2) in SI units), even though in practice no floor is ever loaded uniformly. Similarly, the pressure exerted on a building by the wind may be assumed to be constant in time and distributed uniformly over its surface. The wind, instead, blows in gusts, and wind pressure varies from point to point of a building. Here again, the code simplifies the design procedure by taking the wind variations into account statistically and suggesting "safe" conventional wind pressures.

Whenever the loads on a building are not considered by codes, and when they present characteristics that may endanger a structure's life, they must be accurately determined through experiments or by mathematical calculations. The effect of hurricane winds on a skyscraper may have to be found by means of aerodynamic tests on a model, conducted in a wind tunnel.

It is not always sufficient for the designer to consider only code loads, since the responsibility for the strength of the design rests with him and not with the code authorities; this is particularly true in circumstances where code regulations do not apply. It is therefore essential for the architect to acquire an awareness of loads.

2.3 DEAD LOADS

To determine the required structural strength, the loads to be applied to the components are dictated by the IBC. Because the loads carried by the floor of a building vary, depending on the occupants of the structure, location of furniture, the storage of goods, and so on, the code substitutes an "equivalent load" under which the floor will not fail or deflect so much as to become unusable. This code load must therefore be a multiple of the load that would produce failure or unacceptable deflection. This multiple is denoted as the "safety factor" (SF). The SF accounts for uncertainties in load estimation, as well as irregularities in materials and workmanship. It should be recognized that it is impossible to know these facts with 100 percent certainty.

The magnitude of the SF depends on the usage of the structure as well as on economics. A large SF may require larger components or stronger materials to make a structure much safer, but may make it more expensive or even dysfunctional. An airplane, for instance, may not be able to fly if it is too heavy when oversized parts are used.

New techniques based on probability methods have been developed that compare the statistical variations of loads and of the structural strength of the materials used in order to determine an optimal safety factor. A further discussion of these techniques follows the section on live loads. A more detailed analysis of "Load and Resistance Factor Design" (LRFD) is, however, beyond the scope of this book.

The unavoidable weight of the structure itself and the weight of all loads permanently on it constitute its dead load (Figure 2.2). It is one of the paradoxes of structural design that one must know the dead load beforehand in order to design the structure, while it simultaneously cannot be determined until the structure is designed. The dimensions of a structural element depend essentially on the loads acting on it, and one of these loads is the dead load, which in turn depends on the dimensions of the element. The designer is compelled to start the calculation of a structure by making an

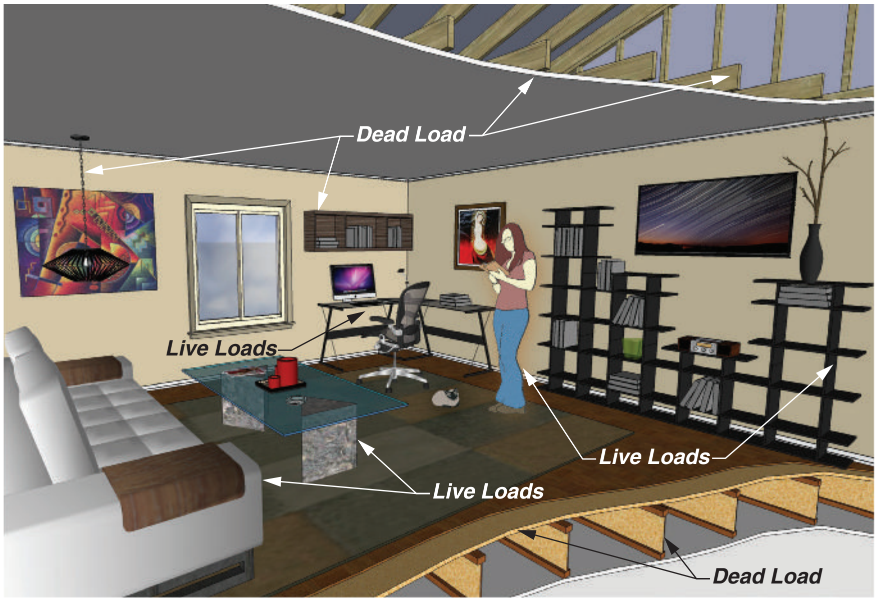


Figure 2.2 Live and dead loads

Live loads are characterized by their transient nature. It is likely obvious to the reader that people and easily movable furnishings like chairs are live loads. But so, too, are even more stationary furniture and shelving that is rearranged less frequently, but which is otherwise not permanently attached to or supported by a floor or wall.

Dead loads are those elements that are essentially permanent, such as the building structure, floor and wall surfaces and finishes, as well as mechanical and electrical equipment. The self-weights of typical building components determine these loads. Dead loads, however, also comprise built-in furnishings, such as shelving that is more or less permanently mounted to walls, as opposed to free-standing units that can easily be repositioned.

educated guess as to its dimensions and, hence, its dead load, which also depends on the construction material (e.g., concrete vs. steel). He or she then adds to it all the other loads, checks its strength, and finds out at the very end of the calculation whether the guess was correct. Long practice alone will prevent innumerable wrong guesses in structural design. The checking of the strength of a given structural element for given loads, called structural analysis, is a fairly routine operation. The initial educated guess, called structural design, must come from experience and is often the result of an almost artistic intuition rather than of scientific calculations.

The dead load is, in many cases, the most important load on a structure. It may greatly outweigh all other loads, particularly in large structures and those built of heavy materials. In bridges, in roofs over wide unencumbered areas (e.g., halls, churches, theaters), and in stone and masonry structures of a massive type (columns, buttresses, walls), the dead load often dictates the dimensions of the resisting elements. In certain cases, the dead load is not only important but also useful or even essential—as, for example, in a gravity dam (Figure 2.3), where it is used to resist the horizontal pressure of water.

Modern structural materials, such as high-strength steel, prestressed concrete, composites, or aluminum, in some cases reduce the importance of the dead load in relation to the other loads, but in no case can the dead load be ignored. Its main characteristic is its continuous presence: put it is a permanent load.

The dead load is easily computed. Once the dimensions of the structure have been determined on the basis of prior experience, its weight is evaluated by consulting tables of unit weights for structural materials (Table 2.1).

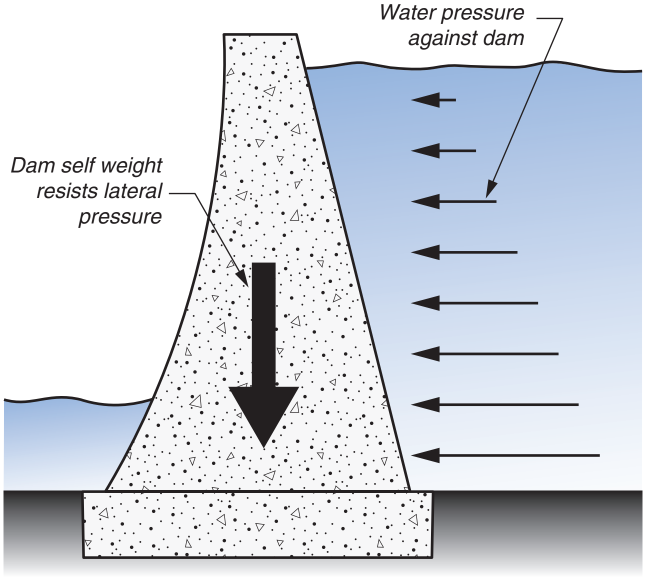


Figure 2.3 A gravity dam

The fluid pressure of water behind a gravity dam is balanced largely by the dead weight of the dam itself. The water pressure tends to slide the dam as well as topple it over, while the weight of the structure acts to stabilize it against these actions. The self-weight for such a structure is thus the most essential factor in its design.

TABLE 2.1 Weights of Some Building Materials

Material	Weight (lb/ft^3)	Weight (kN/m^3)
Aluminum	170	26.7
Wood (Dense)	40	6.3
Wood (Light)	28	4.4
Steel	490	77.0
Brick	120	18.9
Sand	95	15.0
Concrete	144	22.6
Glass	160	25.1

Though there are few uncertainties about the dead load, its calculation is a painstaking and tedious job. It is also a fundamental job, since the amount of material used in a structure is, together with labor, one of the major components of its cost.

2.4 LIVE, SNOW, AND WIND LOADS

Loads such as the weight of people, machines, movable furniture, partitions, nonstructural elements, and movable fixtures are of an uncertain nature and of uncertain location in a structure and hence require safe averages established by the codes. Some occupancy loads prescribed by the IBC are listed in Table 2.2.

The live loads suggested by the codes are usually so conservative that, in order to avoid unrealistically high live loads, the codes allow live load reductions depending on the number of floors of a building and the area supported by a single structural element, such as a column. Live load reductions take into account the negligible chance that every floor in a building, or the entire large area supported by a single structural element, will simultaneously carry the full live load.

The weight of snow depends on the climate and elevation of the region where the building is to be erected: For

TABLE 2.2 Occupancy Loads

Type of structure	Load (lb/ft^2)	Load (kN/m^2)
Balcony	80	4.8
Garage	50	2.5
Library	150	7.0
Office building	80	4.0
School room	40	2.0
Shop	100	5.0
Theater	60	3.0

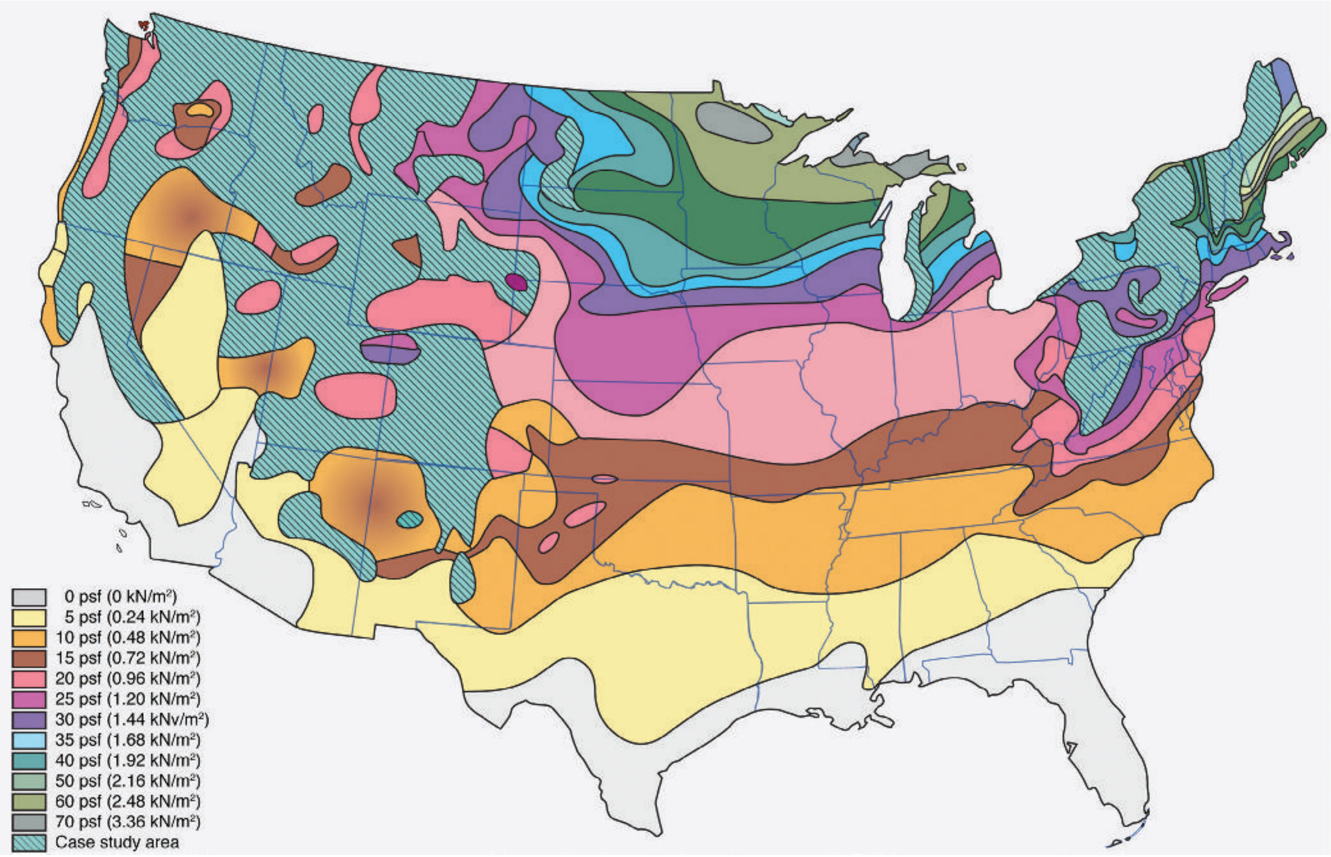


Figure 2.4 Snow loads on flat surfaces in the continental United States

The IBC maps out in detail the range of snow loads across the country. The magnitude varies greatly depending on latitude and elevation, with larger values farther north as well as higher in elevation. Many mountainous areas are extremely localized, and case study analysis of the exact location is required, whereas other regions can be generalized. Regions with graduated color are those where loads vary depending on elevation.

instance, according to the IBC, it is equivalent to 30 pounds per square foot (1.4 kN/m^2) in New York City, whereas it is 50 psf (2.4 kN/m^2) in Minneapolis, Minnesota. The map of Figure 2.4 presents the distribution of basic snow loads in the United States.

Snow load is usually measured on the horizontal projection of the roof. The slope of the roof affects the retention of snow; a steep roof has lesser retention than a flat one. The nearly flat roof of the Blacksburg, Virginia, High School auditorium collapsed under the weight of a 9 inch (23 cm) layer of snow (Figure 2.5). While not an extreme snow level, it contributed to the structure's demise because it coincided with some substandard welds connecting roof trusses to vertical columns. Subsequent examinations indicated that the foundation was also inadequate and uneven.

The wind load on a building is difficult to ascertain with any degree of accuracy, because it depends on the wind velocity and on the shape and surface of the building, as well as on the roughness of the surface terrain (Figure 2.6). Average wind velocities are known with some degree of certainty, but it is difficult to measure the highest instantaneous velocity of a hurricane wind, or to forecast the largest velocity the wind will have in a certain locality. Figure 2.7 illustrates the variation of design wind velocities in the United States.

The dead, live, and the other "gravity" loads due to the pull of the earth are resisted by suitable structural systems. Resistance to wind pressures and suctions and other horizontal loads often requires separate structural systems. Horizontal wind-bracing systems may be seen on the underside of bridges (Figure 2.8), while vertical wind-bracing systems are hidden within the inner walls of most buildings (Figure 2.9).

Framed buildings (see Chapter 8) may be wind braced by stiffening alternate bays at alternate floors with diagonals or panels (Figure 2.10). In the Areva (formerly Fiat) Tower in Paris, engineered by Weidlinger Associates, stiffening panels are set in the frames of the outer walls (Figure 2.11). In some buildings, the outer walls are wind braced by diagonals spanning a number of floors.

The influence of the building itself presents even greater uncertainties with regard to wind load: Its shape may produce pressures on the windward side and suction on the leeward side, and the roughness of its surface may change the value of the local pressures. In any case, codes approximate these fluctuating dynamic loads by prescribing safe, static pressures or suctions due to wind, which also vary with height. These code values are revised from time to time in order to take into account the knowledge continuously accumulated in the field of aerodynamics.

Figure 2.5 Blacksburg, Virginia, High School gymnasium roof after it collapsed under snow load

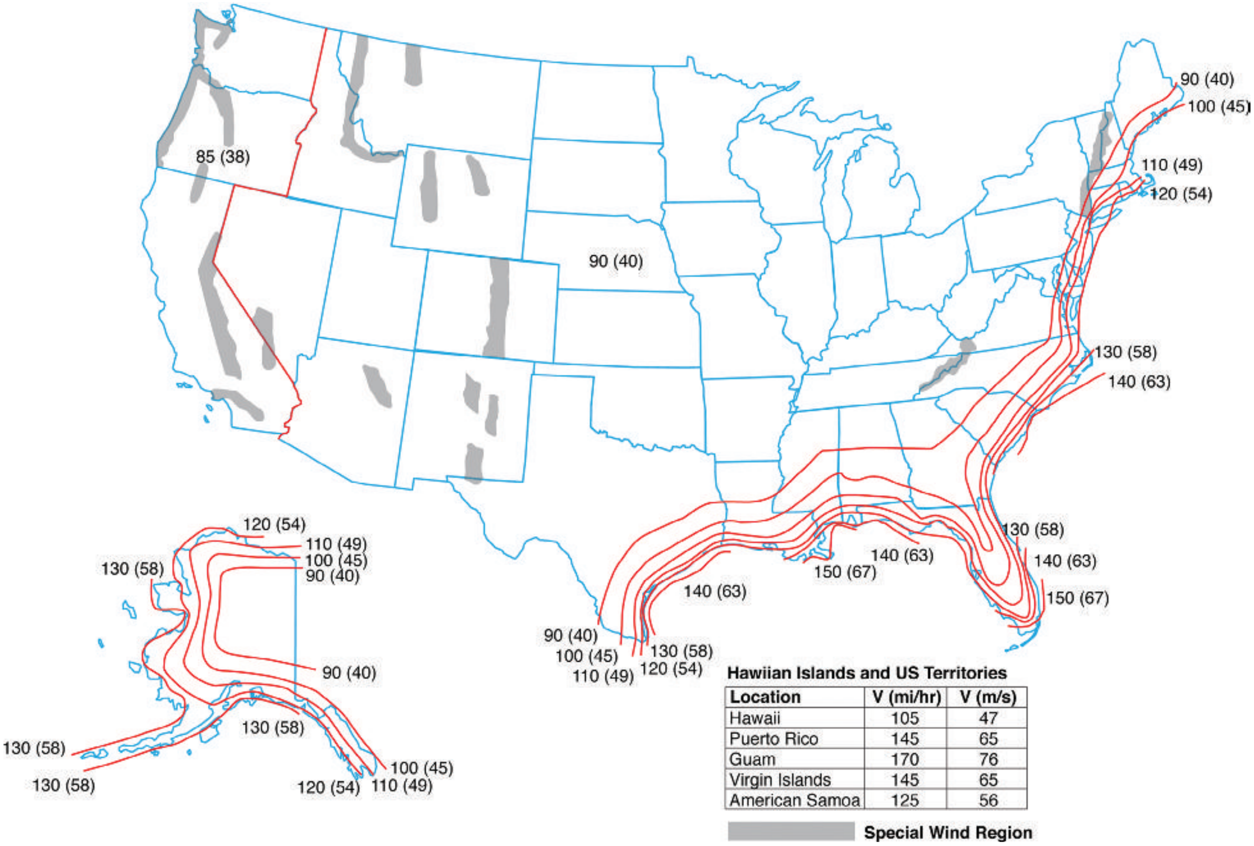
Under a relatively modest snow load, the flat roof structure collapsed through a combination of substandard construction, as well as inadequacies in the foundation.

Photo courtesy of Michael McDermott

Figure 2.6 Wind load

Wind loads can be quite substantial in coastal and island areas subjected to hurricane-speed winds. In recent years, the IBC has increased the maximum design wind velocities in these regions to better safeguard life and property from devastating storms.

Photo: Meghan Pusey Diaz/123RF



Hawiian Islands and US Territories

Location	V (mi/hr)	V (m/s)
Hawaii	105	47
Puerto Rico	145	65
Guam	170	76
Virgin Islands	145	65
American Samoa	125	56

Maximum Wind Velocity, mph (m/s)

Figure 2.7 Maximum wind velocities in the United States

As with ground snow load values, the IBC provides wind speed maps that specify design velocities. Also similar to snow loads, these values can have great variation in closely separated areas of coastal and mountain regions. The shaded areas represent mountainous regions where local conditions must be considered, and referred to as *"special wind regions"* in the IBC. The vast majority of the interior of the continental United States is designed for a wind speed of 90 mph (40 m/s). The highest wind speeds occur in costal or island areas subjected to hurricane-force winds.

Figure 2.8 Horizontal wind-bracing systems

All structures must transfer lateral forces through a horizontal plane. In bridge structures, the roadway must be stiff enough to perform this function. The underside of the road deck of the Akashi-Kaikyo bridge in Japan uses diagonal chevron bracing in the horizontal plane to stiffen the structure for transfer of the lateral wind forces to the supporting piers. The bracing creates a horizontal truss that functions as a very deep beam spanning horizontally between the supporting piers to resist wind forces.

Photo: Leung Cho Pan/123rf

Figure 2.9 Vertical wind-bracing systems

A variety of bracing schemes are used in building structures, such as chevron bracing (a), cross-bracing (b), and knee bracing (c). Each serves the function of preventing the structure from displacing laterally under the horizontal loads of wind or seismic forces. Members that serve to resist compression as well as tension forces must be noticeably heavier (a and c) than those that can be sized for tension only (b).

Bracing in only one plane is shown here for clarity, but in reality buildings must be constructed with bracing in multiple directions. Such bracing frames are often located in the core of buildings, as well as around their perimeters. Configurations will vary greatly depending on the size of the building, as well as the type and magnitude of the anticipated lateral forces. See Chapter 5 for a discussion of tension and compression and Chapter 8 for a complete discussion of building frames.

The wind velocities, V (in mph or Km/hr) may be converted into wind pressures, p, by means of code equations that take into consideration not only the speed of wind but also the effects of altitude, terrain roughness and ground obstructions, the shape of the building, as well as the surface on which the wind acts. These equations are derived from the basic physics equation stating that kinetic energy is equivalent to one half the mass of an object times the square of its velocity ($K = \frac{1}{2}MV^2$). The mass in this case is that of air at sea level.

It should be recognized that the depth of snow and wind velocity have statistical variations. Wind may be calm one day and become a gale or a tornado on the next. Similarly, there may be no snowfall today and a major blizzard tomorrow. Such extremes of weather are infrequent occurrences, and designing structures to withstand them with the same factors of safety as required for the more frequently occurring loads may be prohibitively expensive.

The strength of structures is also statistically variable. The strength of concrete, for instance, depends on the size

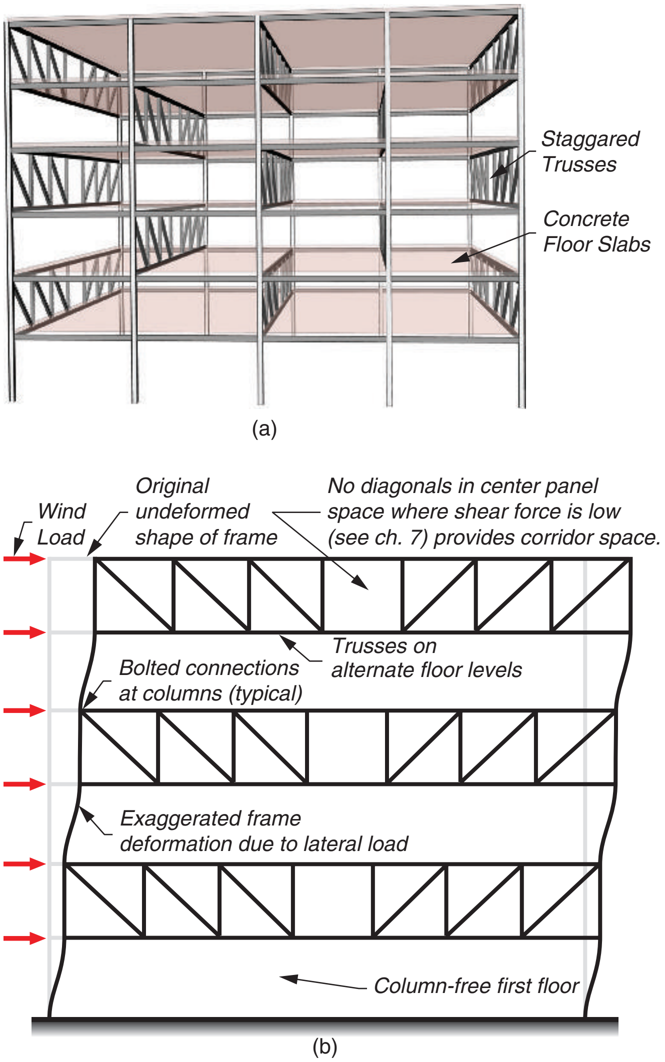


Figure 2.10 A staggered truss framing system

The staggered truss system is a unique approach to accommodate both gravity and lateral loads, while simultaneously increasing the usable uninterrupted floor space. It is particularly well suited for residential units. The floor structure is carried by the bottom chord of one truss and the top chord of another truss, thereby creating a two-bay column-free interior space. For lateral loads, the trusses connected to columns at their top and bottom chords, effectively creating rigid frames (see Chapter 8) that use simple and less expensive bolted connections compared to heavy welded moment connections. The entire ground floor is also completely free of interior columns.

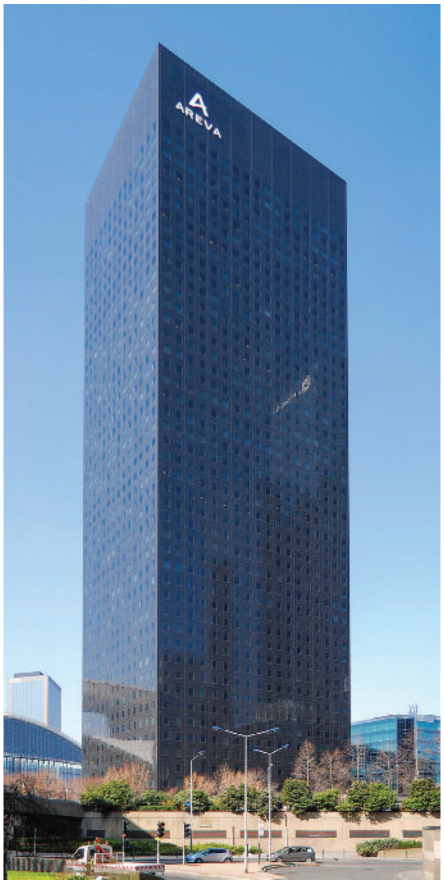


Figure 2.11 The Areva Tower in Paris

The wind bracing of the Areva (formerly Fiat) Tower, at the La Défense complex in Paris by Skidmore, Owings and Merrill and engineered by Weidlinger Associates, consists of stiffening panels set into the frames of the outer wall. These are pierced by window openings that decrease in area from the top to the bottom of the building. This increases the strength of the panels as the total wind force accumulates from the top to bottom of the tower.

Photo courtesy of Stéphane Renou

and strength of the stones in it, the amount of water used, and the length of cure time. To account for these variations of loads and strength, a “Stress-Strength Interference” method may be used. Loads are converted into stresses, and their frequencies of occurrence are plotted together with the frequencies of structural strength.

As seen in Figure 2.12, the two diagrams have an overlapping region. The size of this region indicates the chances that an infrequent extreme stress coincides with an equally

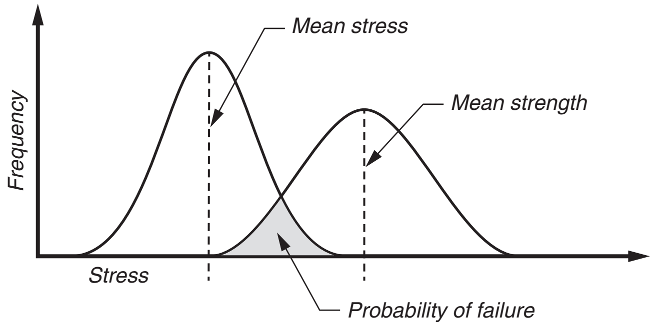


Figure 2.12 Stress (S)-Strength (R) Interference

Stress (S)-Strength (R) Interference diagram. The small shaded area represents the probability of failure of the structure.

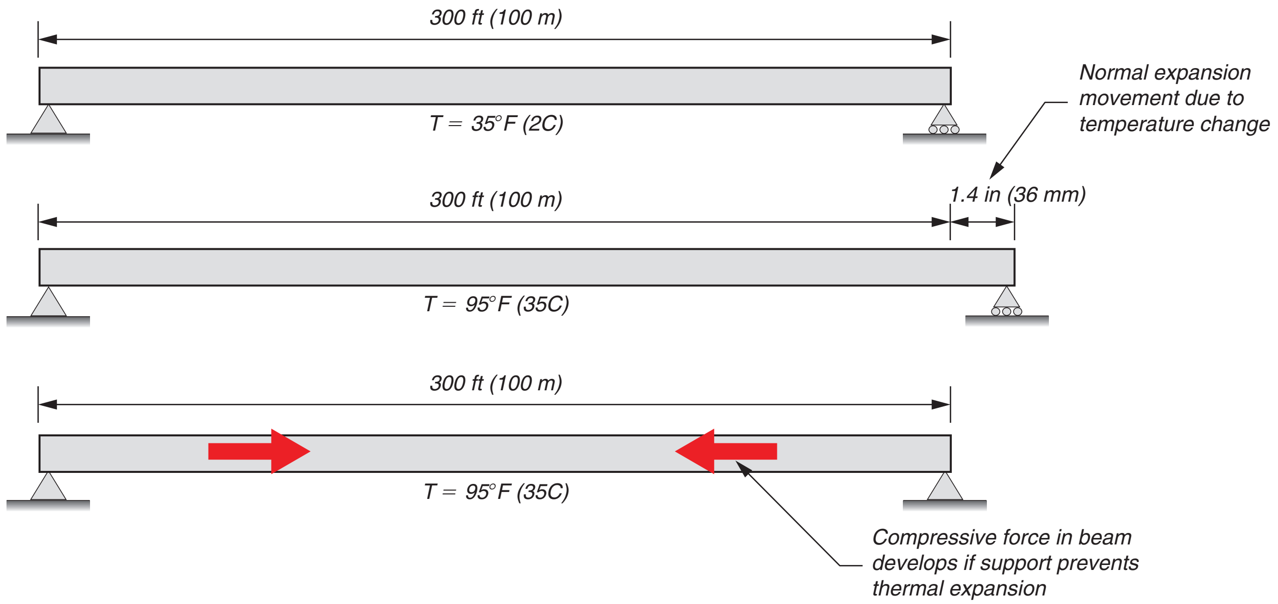


Figure 2.13 Thermal load

A bridge subjected to a temperature increase from when it was constructed will undergo an expansion in length. If this expansion is prevented, a compressive load will be developed in the member, which can be a sizable force.

infrequent understrength component and may destroy the structure. This had happened to the Blacksburg High School (Figure 2.5).

The designer can reduce this "Probability of Failure" by moving the two diagrams further apart. Either the size of the component may be increased, that is, by reducing stresses and thereby moving the stress diagram to the left, or by using stronger materials and moving the strength diagram to the right. Statistical variability will be further discussed in Chapter 13, "Structural Failures."

2.5 THERMAL AND SETTLEMENT LOADS

All structures are exposed to temperature changes, and change shape and dimensions during the cycle of day and night temperatures, and the longer summer and winter cycles. If restrained against movement, the effects of changes in dimensions due to thermal expansion and contraction are often equivalent to large loads, which may be particularly dangerous because they are invisible. A simple example of this type of loading condition will suffice to indicate its nature and importance.

A long steel bridge spanning 300 ft (~100 meters) over a river was built in winter, when the average temperature was 35°F (~2 degrees Celsius) (Figure 2.13). On a hot summer day, the air temperature may reach 95°F (35°C) and the bridge expands because it acquires the temperature of the surrounding air. The increase in length of the bridge may be calculated with the aid of the "thermal coefficient of expansion," which for steel is 6.5×10^{-6} in/in/degree Fahrenheit (1.17×10^{-5} mm/mm/degree Celsius). This is a physical property of the material itself that describes the amount of change in length it undergoes for a given change in temperature. Each material has its own characteristic coefficient of thermal expansion. Hence, the length change becomes the length multiplied by the temperature change and the thermal coefficient, or about 1.4 inches (36 mm). This change in length is small compared to its original length. But, if the bridge piers make it impossible for this expansion to take place, they develop in the bridge a horizontal compressive load capable of reducing the length to its winter value. Steel is very stiff in compression; it takes a large compressive load to reduce the length of the bridge by 1.4 inches (39 mm). This load is so high that it would use up half of the strength of the steel, leaving only 50 percent of its original strength to carry the loads for which the bridge was designed. The obvious way of eliminating such an overload is to allow the bridge to change its length with varying temperatures. This is usually done by supporting one of the bridge ends on a roller or "rocker" bearing (Figure 2.14).

The length change of the cables of suspension bridges due to temperature variations does not produce large stresses; it just raises or lowers the roadway. For example, the middle of the George Washington Bridge in New York changes its elevation by as much as 10 feet (3 meters) between winter and summer. Due to thermal conditions,

Figure 2.14 Rocker support of the New River Gorge Bridge in West Virginia

To permit free structural movement from thermal expansion and contraction, bearings are used to accommodate this displacement. The bearings either roll (as in the case of a roller bearing) or tilt (as in a rocker bearing, illustrated here). The gear teeth prevent slippage on this critical connection point. The bridge is the longest steel arch bridge in North America (Also see Figure 8.38 for an overall view of the bridge).

Photo courtesy of West Virginia Division of Culture and History

framed structures of high-rise, air-conditioned buildings may also develop stresses (see Section 7.4).

A similar condition of thermal movements, with different but equally dangerous consequences, is encountered in large domes. When the external temperature increases or decreases, the dome tends to expand or contract. Since it is usually prevented from so doing by its underground foundations, which remain at a constant temperature, it will move mostly up or down: The dome "breathes" (Figure 2.15). The top of a dome, covering a hall with glass walls and spanning 200 ft (~61 meters), may breathe up and down as much as 3 inches (~80 mm) due to air temperature changes, and if the

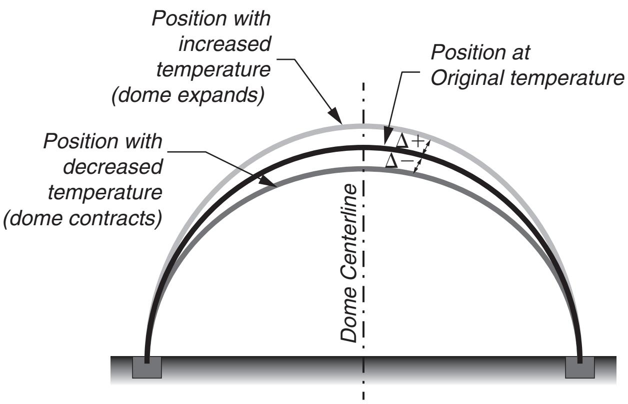


Figure 2.15 Thermal movements of a dome

As ambient air temperature rises and falls from the temperature at the time of original construction, a dome will expand and contract somewhat in response. The dome in effect "breathes" with the change in air temperature, although the actual amount of movement may be very small relative to the size of the dome.

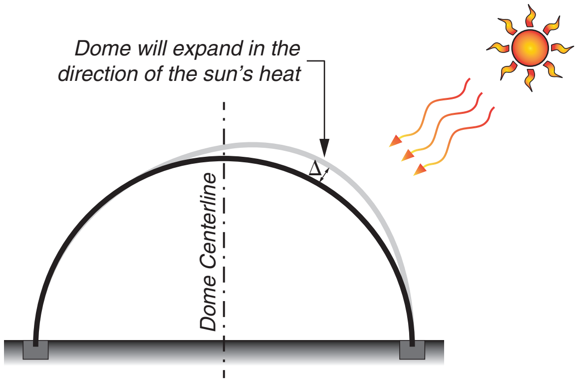


Figure 2.16 Asymmetric thermal distortion of a dome

As a dome is subjected to temperature change, it will expand upward or contract downward. When subjected to uneven heating, the expansion will be unequal, causing a distortion of the shape.

walls follow this movement, the glass panes break. A special type of sliding support eliminates this danger.

More complicated thermal loads are developed in a dome during the daily thermal cycle, when one of its sides is heated more than the other. The dome changes shape in an unsymmetrical fashion and becomes distorted (Figure 2.16). The stresses due to this distortion may be complex and high.

These simple examples show that a structure is particularly sensitive to thermal changes if by the nature of its shape, support conditions, and materials it tends to restrain the changes in dimensions due to temperature. On the other hand, acceptable deformations under loads require a structure to be stiff. Hence, the requirements for stiffness and for thermal deformations are opposite. Whenever a structure is to withstand heavy loads and small temperature changes, it may be made quite stiff; but if it must withstand large temperature changes and relatively small loads, it must be made flexible in order to accommodate such changes: The structure successfully resists this loading condition by giving in rather than by fighting it.

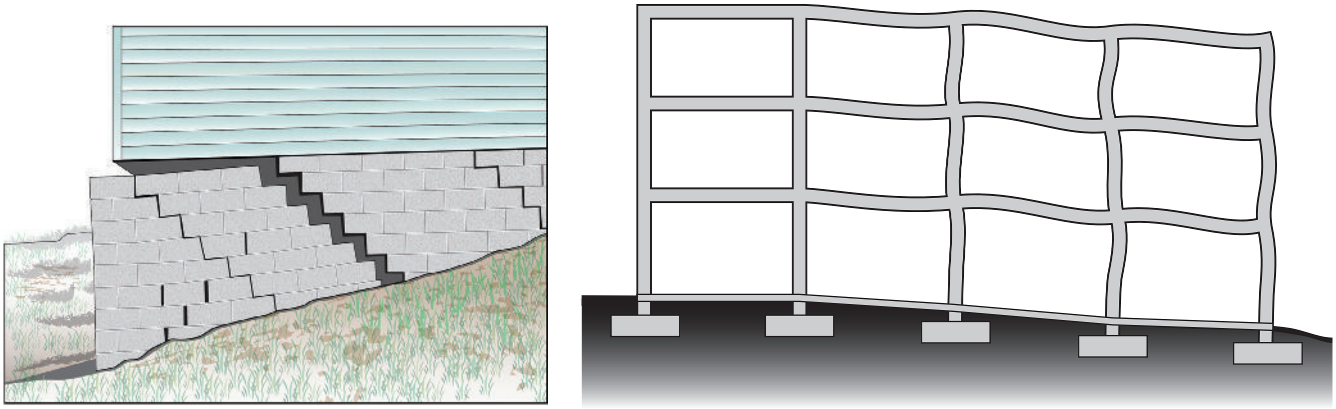
Another condition, producing effects equivalent to those of high loads, may stem from the uneven settlements of the building's foundations. A soil of uneven resistance, loaded by the weight of a building, may subside more in a specific portion of the foundation than in others. The soil deflections reduce the support of the foundation in certain areas and the structure may tilt. A prime example of such conditions is the Leaning Tower of Pisa (Figure 2.17).

The tower started leaning soon after construction started. The architects tried to straighten the upper floors but the structure continued to lean and was in danger of collapse. At the turn of the twenty-first century, the Italian government was finally able to stabilize the tower through a complicated process of soil extraction and heavy lead weights, which restored the tower's lean to the point at which it was in the early 1800s.

Figure 2.17 Foundation settlement

The famous Leaning Tower of Pisa, which began to experience uneven foundation settlement even before construction was completed in the twelfth century. Progressive uneven settlement threatened complete collapse of the tower until it was finally stabilized in 2001.

Photo: Lukiyanova Natalia/frenta/Shutterstock



(a) (b)

Figure 2.18 Uneven settlements of foundation

Uneven support settlements causing either a shearing off a portion of the building (a) or deformation of a frame (b).

A portion of a building above an inadequate foundation might either shear off from the rest of the building (Figure 2.18a) or hang partially from it (Figure 2.18b). No additional load has been applied to the building by the uneven settlement, but the supported portion of the building carries more load, and of a different type, than the load it was designed for. The unsupported section of the building is also under strain, as can be seen from the deflection of its beams (Figure 2.18b). Blacksburg High School's demise (Figure 2.5) is partially attributed to support settlement.

Thermal and settlement stresses are examples of stresses due to deformations rather than loads. An example of a stressed but unloaded structure may be built by cutting a piece out of a steel ring and welding the ring again so that it looks untampered with. If cut, this ring snaps open, demonstrating the stresses "locked" in it. A similar condition may be found in some rolled steel beams. If one of these beams is cut down the middle with a saw, its two halves open up and curve in opposite directions, indicating a certain amount of stress locked in by rolling process the (Figure 2.19). One of these beams might fail under load because the stresses produced by the loads are superimposed on the "locked-in" stresses and exceed safe values. Locked-in stresses are put to good use in

Figure 2.19 Locked-in stresses

Stresses locked into a steel beam due to the rolling manufacturing process may be released if the beam is cut down the center of its length, resulting in an outward curling of the sections.

prestressed and posttensioned reinforced-concrete structures (see Section 3.3) and other prestressed structures.

2.6 DYNAMIC LOADS

All the loads considered in the preceding sections were assumed to be stationary or vary slowly with time: They are considered to act statically. In codes, even the wind is assumed to act “statically” (for low and moderate height buildings), although it obviously does not.

Loads that change value or location rapidly, or are applied suddenly, are called dynamic loads. They can be exceptionally dangerous if their dynamic character is ignored.

The common experience of driving a nail with a hammer blow indicates that the sudden application of the moving hammer’s weight achieves results unobtainable by the slow application of the same weight.

In earlier times, in order to ring a heavy bell, a church sexton (keeper) would pull its rope rhythmically; the bell would then swing progressively further until eventually it rang. The sexton could not achieve this result by exerting a sudden hard pull on the rope: He must, instead, “yank in step” with the bell’s oscillations for a while until it rotated enough to ring. A similar but more common experience is that of being pushed on a swing (Figure 2.20). If one pushes with a sudden force, inertia is difficult to overcome and much force is needed to begin swinging. On the other hand, pushing gently and in rhythm with the swinging causes the person on the swing to go ever higher with each oscillation.

The force exerted by a hammer blow is called an impact load; the rhythmic push to someone on a swing is a particular case of a periodic force, referred to as a resonant load. In the first instance, the higher the velocity of the hammer or the shorter the time for the load to reach its peak value, the greater the effect: An instantaneous blow produces an extremely high force with possibly shattering results. In the second, a relatively small force applied “in step” for a long time produces increasing effects. In the case of the church bell, a small “in-step” force of a few pounds may eventually swing a bell weighing several tons into ringing.

Dynamic loads are exerted on structures in a variety of ways. A high-velocity wind gust may be similar to a hammer blow. A company of soldiers marching “in step” exerts a resonant load on a bridge when their step is in rhythm with the oscillations of the bridge. Workers on the Brooklyn Bridge in the late 1800s were admonished to “break step” to avoid such harmonic oscillations of the construction walkway (Figure 2.21). Although not in danger of overstress, the London Millennium footbridge took engineers by surprise with unexpected lateral motion created by pedestrian traffic. The amount of sway was severe enough to cause discomfort to some pedestrians. The bridge was closed shortly thereafter and renovated with viscous fluid dampers (similar to shock absorbers in cars) that eliminated the problem (Figure 2.22). Some small bridges are said to have collapsed under such resonant loads.

An impact load is characterized by a very short time of load increase and a resonant load by its rhythmic application. But when is an impact time “short?” And when is a varying load “in resonance” with a structure? All structures are, to a certain extent, elastic. They have the property of deflecting

Figure 2.20 Resonant load

Being pushed on a swing is a form of resonance. A person on a swing will sway with a natural period of vibration (the time it takes to swing from one position to the opposite side and back) that is related to the length of cable or rope on the swing. Physics dictates that weight does not affect the period of vibration; however, the greater a person’s weight, the more inertial resistance must be overcome. A single sharp push may require significant force to overcome inertia. By pushing in synchronization with the period of vibration, though, only a very small amount of effort can have a large effect, over time sending a person ever higher on the swing with each oscillation. Pushing out of sync, on the other hand, will tend to dampen or cancel the motion, requiring a much higher amount of force.

Photo: Shotsstudio/Fotolia

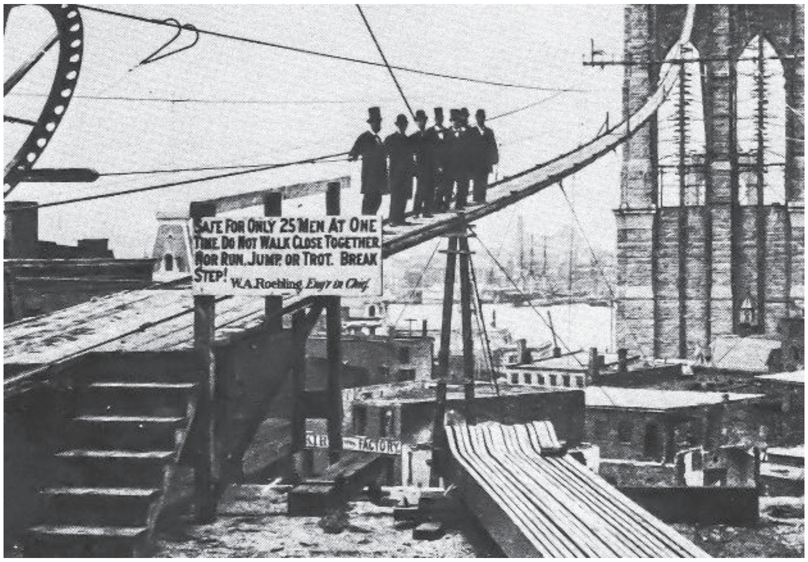


Figure 2.21 The Brooklyn Bridge under construction, circa 1883

Notice the warning sign about not only the maximum number of workers on the temporary construction bridge but also the admonishment to *break step*, lest the resonant frequency of the temporary bridge be reached, thereby possibly overloading it to failure.

Photo courtesy of New York Historical Society

Figure 2.22 London Millennium Footbridge

When inaugurated in the year 2000, the Millennium footbridge immediately suffered from severe harmonic oscillations simply by pedestrians crossing it. The lateral back and forth sway was controlled after the bridge was closed and fluid viscous damping mechanisms installed.

Photo courtesy of Alfredo Fernández-González

under loads, and of returning to their initial position once the loads are removed. As a consequence of their "elasticity," structures have a tendency to oscillate: a skyscraper swings after the passing of a wind gust, and a railroad bridge oscillates up and down after the passage of a train.

The time required for a structure to go freely through a complete swing, or up-and-down oscillation, depends on its stiffness and its weight, and is called its fundamental period (seconds per cycle), while the number of complete swings in a unit of time is referred to as the frequency of motion (cycles per second). When the frequency of load application coincides with the frequency of oscillation of the structure, the load is said to be in resonance with the structure. In order to go through a complete swing, a modern building will take anywhere from one-tenth of a second to 10 or more seconds. A stiff structure oscillates rapidly; a low, rigid building has a short period. A flexible structure oscillates slowly; a tall steel skyscraper may take over 10 seconds for a complete swing. It has a longer fundamental period. The fundamental period of a structure is, in fact, a good measure of its stiffness.

The time of application of a load is measured against the fundamental period of the structure: If the time is short in comparison with the fundamental period, the load has dynamic effects; if long, the load has only static effects. It is thus seen that the same varying load may be static for a given structure and dynamic for another. A low-velocity long wind gust on a stiff building of short period will have the same effect as a constant static pressure. A high-velocity short wind gust on a flexible building of long period may strain the structure to a much greater extent than its static pressure would lead one to predict.

In a variety of practical cases, the dynamic effects of a load are 100 percent larger than its static effects. If a two and one half-pound (11 Newton) brick is put slowly on the plate of a spring scale, the scale hand will stop at the two and one half-pound mark (22 N) on the dial. If the same brick is instead released on the plate suddenly, the hand will move to the five-pound mark (22 N) and then oscillate, stopping eventually at the two and one half-pound mark (Figure 2.23).

Most loads applied to architectural structures do not have impact characteristics, except those due to hurricanes,

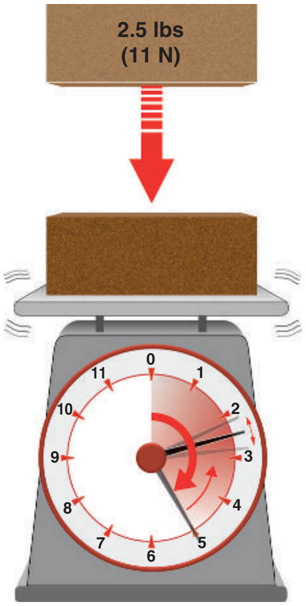


Figure 2.23 Dynamic loading

Effect of a weight dropping on a spring scale: The initial impact load may be as much as twice the weight of the object when applied in a static manner. The scale will bounce to the high point before settling down to the brick's actual weight of 2.5 lbs (11N).

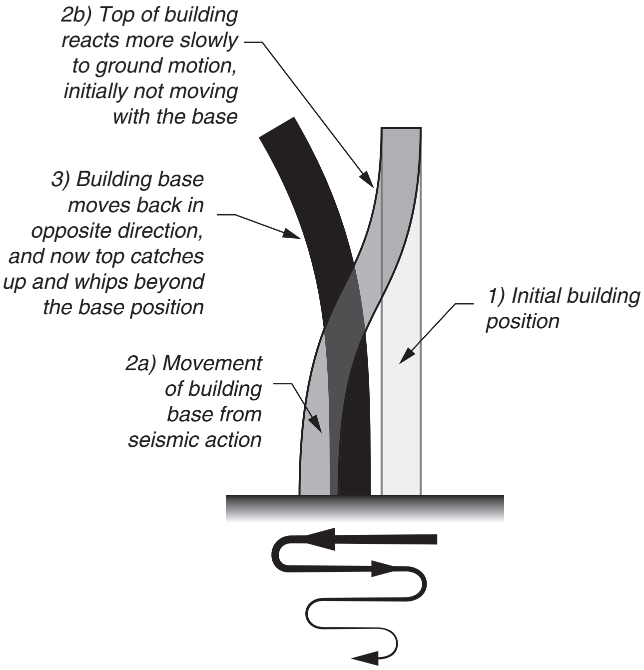


Figure 2.24 Earthquake motions

An earthquake creates complex movements of the ground, with back and forth, up and down, side-to-side, and compressing-extending movements. The greatest forces induced on a building or bridge are the side-to-side and back-and-forth types of movements. In these seismically induced oscillations of the ground, forces are generated in structures due to their own inertia resisting the acceleration of the ground. Structures essentially want to "stay put" while the ground moves below, thus generating shearing forces at the base. The top of taller structures then whip back and forth as the base moves below. The initial ground shaking can be quite intense and then die down over a period of several seconds or, in the case of large earthquakes, several minutes. This two-dimensional illustration is far simplified from the actual complex motions in all directions.

tornados, and earthquakes. Because such extreme winds have dynamic characteristics, the pressure predicted from the wind velocity formula may be doubled.

An earthquake is a sudden motion of the ground. This series of randomly variable jerks, transmitted to a building through its foundations, produces much larger oscillatory motions of the higher building floors (Figure 2.24). An earthquake occurs whenever the locked-in stresses in the earth crust, generated by movements in the molten mantle of the earth, become high enough to suddenly shift a portion of the crust with respect to an adjoining portion, opening up, at times, gaps several feet (meters) wide and hundreds of miles (kilometers) long, over underground fractures called faults. In the United States, faults exist all over the country but are particularly numerous and active in California, where strong earthquakes occur frequently. Figure 2.25 presents a Seismic Hazard Map of the United States, which highlights the most and least seismically-active regions of the country.

The study of earthquakes and the design of earthquake-resistant structures is still a relatively new science. Just as circularly expanding waves are generated by a stone dropped in a lake, the explosion of a small charge embedded in the earth crust generates outward-moving stress waves, whose speed depends on the value of the stresses locked in the crust. An increase in the speed of these waves indicates an increase in the value of the crust stresses and, hence, the danger of an impending earthquake.

Since the dynamic forces due to the jerky motion of the earth crust are mostly horizontal, they can be resisted by the same kinds of bracing systems used against wind. Various devices have also been invented to "isolate" buildings from earthquake vibrations: One of them consists of foundation piers, made out of alternate layers of elastic materials and steel, which act to effectively decouple the building movement from the ground and allow the soil to move under the building (Figure 2.26).

Inasmuch as the earthquake action on a building depends on the nature of the soil and the structural characteristics of the building itself, earthquake design is a complex chapter of structural theory. It is only in the last few years that enough information on earthquake motions and on dynamic building characteristics has been gathered to allow safe dynamic earthquake resistant design. Tall, more flexible, steel buildings thus correctly designed have survived earthquakes that destroyed smaller, more rigid, masonry buildings.

Wind force that act in resonance with tall buildings can also be the cause of discomfort for occupants, with reports similar to the effects of seasickness when the period of vibration closely matches that of the human digestive tract. Devices called tuned mass dampers function similar to the shock absorbers in automobiles but act horizontally. They reduce the building's motions by means of a large mass of concrete, steel, or lead. The mass tends to stay in place due

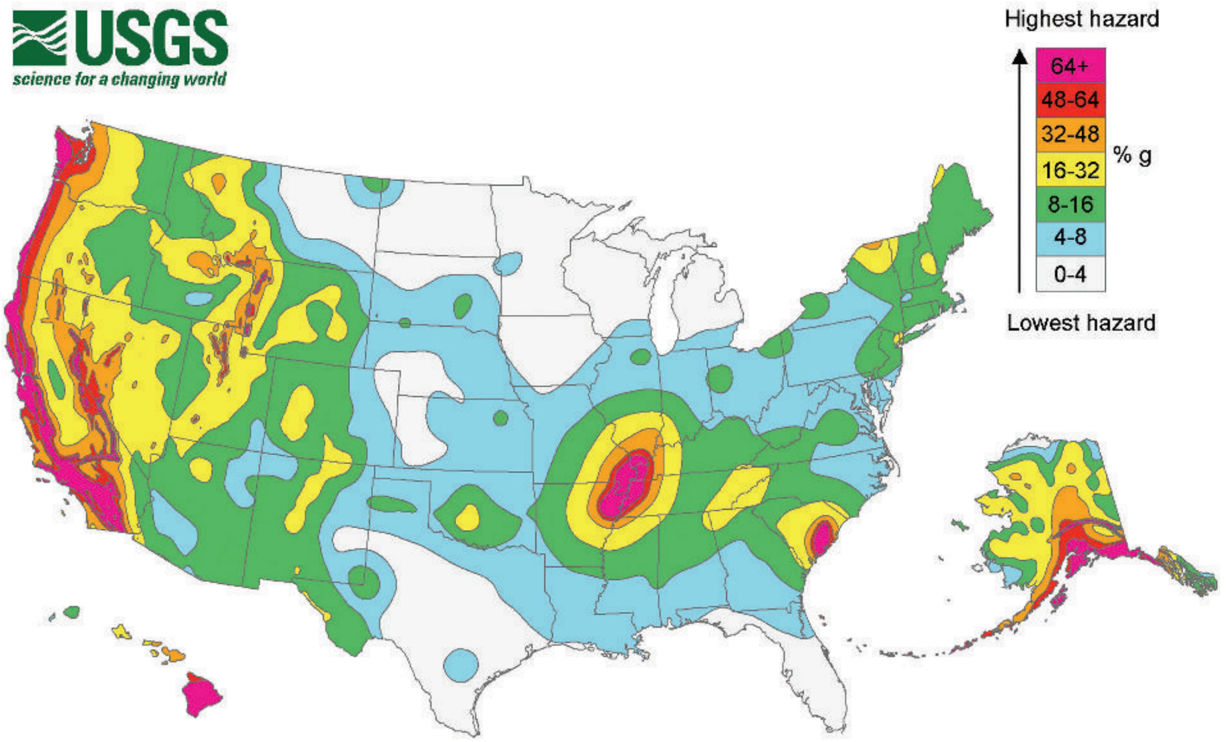
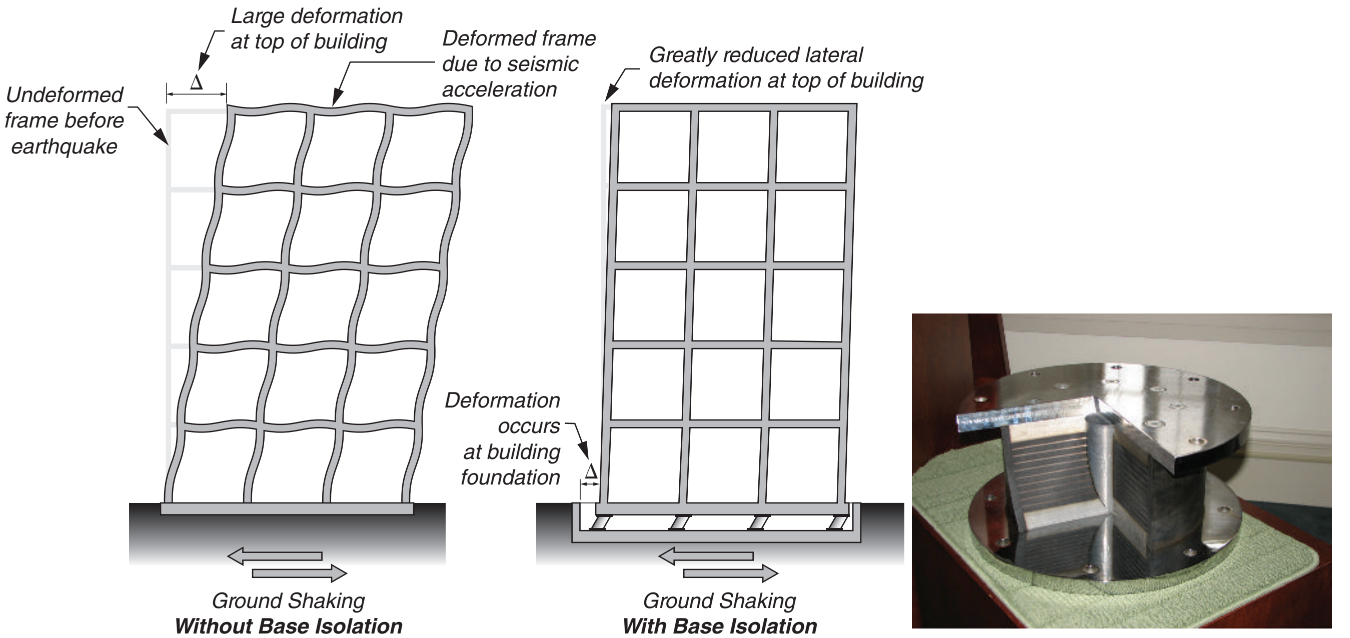


Figure 2.25 Seismic zone map of the United States

Seismic hazard map of the United States, produced by the U.S. Geological Survey. Similar to ground snow loads and wind velocity maps, the IBC has very detailed maps that indicate peak seismic accelerations throughout the country, which translates into a greater potential for structural damage. A complex interaction between the natural period of vibration of the building and the soil can greatly amplify these accelerations and consequent hazard.

Image: From Seismic Hazard Maps and Data - National Seismic Hazard Maps



(a) Effect of Base Isolation

(b) Seismic Base Isolator Model

Figure 2.26 Seismic base isolation

Base isolation is an effective and increasingly popular strategy to reduce the impact of seismic forces on structures. Base isolation separates the building or bridge structure from the ground motion with deformable foundation structures (a). There are a number of variations in the construction of these devices. The style illustrated in the 2/3 scale cutaway model (b), referred to as a *lead-rubber bearing*, is comprised of layers of steel plates and flexible elastic material, with a solid lead core to absorb energy. The isolator is capable of both carrying very high-gravity forces while allowing for lateral displacements of up to two feet (0.6m), owing to the layered plate structure. The effect is to reduce the fundamental vibrational period of the building such that it is not in phase with that of the soil on which it is founded.

(b) Photo courtesy of Deborah Oakley

to its inertia while the building moves, and the attachment to the buildings with fluid-filled dampers and springs absorbs the wind energy (Figure 2.27).

Such structures are frequently comprised of large blocks on near-frictionless bearings riding on a thin layer of oil (Figure 2.28). Some systems are actively computer controlled: Whenever the building moves under the impact of a wind gust, an electromechanical feedback system pushes the mass in the opposite direction, extending the springs on one side and compressing those on the other side, and these respectively pull and push back the building toward its original position.

Resonant vibrations may also be attenuated by *passive*-tuned dynamic dampers, in which the period of the mass-springs system is made equal to that of the building. The mass, whose motion relative to the building is damped by friction devices, passively (i.e., without an external control device) vibrates in resonance with the oscillations of the building but in opposite direction, thus keeping the building much closer to stationary through the action of the connecting dampers. A 730 ton (660 metric ton) sphere of steel hangs suspended near the top of the Taipei 101 tower in Taiwan to help dampen wind-induced oscillations (Figure 2.29). Unlike most dampers, the architects chose to make this a feature of the building viewable by patrons from several observation decks.

Resonant loads occur at times in architectural structures for other reasons as well. A piece of heavy machinery may vibrate because of the motion of its parts. If this vibration has a period equal to that of the supporting structure, the vibrations of the machine will be transmitted to the structure, which will swing with increasing oscillations. Floors,

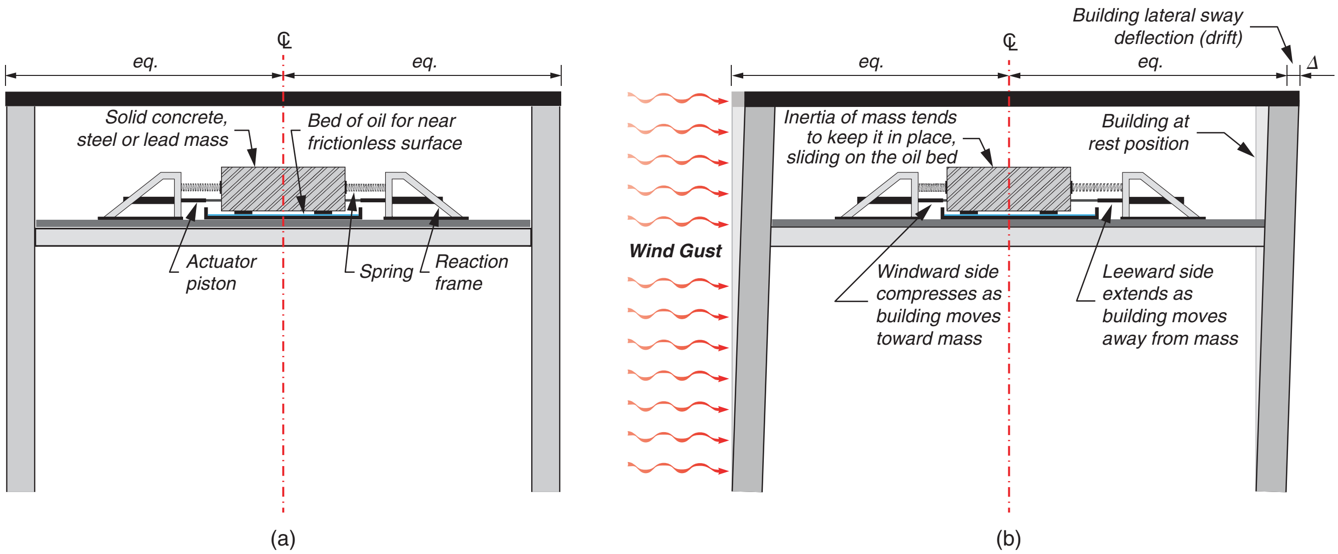


Figure 2.27 Feedback dynamic damper

Tuned mass dampers placed at the top of buildings are carefully calibrated to match the building's natural period of vibration. At rest, the damper remains centered (a). Under sway forces, the damper effectively shifts in the opposite direction due to its own inertia maintaining it in position while the building moves around it (b), thus canceling (dampening) much of the sway. Dampers may be actively controlled by a computer mechanism, or passively act by gravity, or a combination

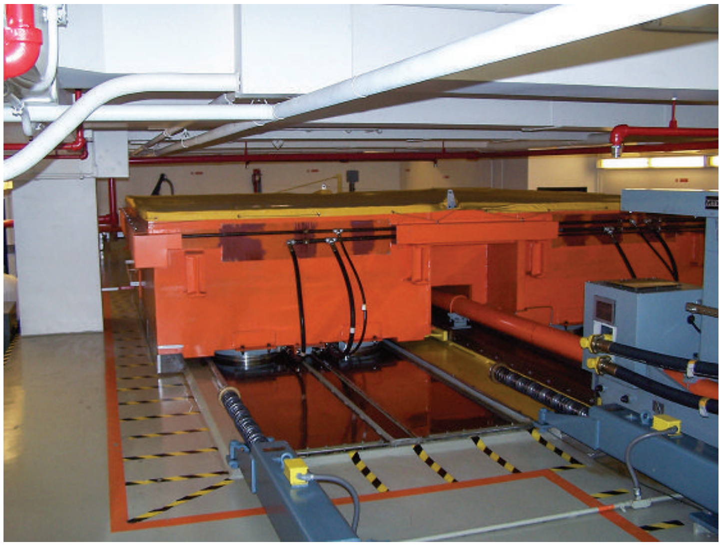


Figure 2.28 Semi-active tuned mass damper

Atop the John Hancock Tower in Boston, Massachusetts, two 300 ton (2.7 MN) semi-active dynamic dampers help to counter the sway due to wind load. Each of the masses (made of steel boxes filled with lead) sits on a near frictionless bed of oil and is attached to a series of hydraulic pistons, springs, and control mechanisms. When a large wind gust occurs, computer controls and actuators facilitate moving the large mass in the exact opposite direction of the building motion, thus canceling out the effects of the lateral load effects. In actuality, the mass is tending to stay in place while the building moves around it. Wind energy is thus dissipated as heat through the hydraulic pistons acting as giant shock absorbers for the mass.

Photo courtesy of LeMessurier Consultants

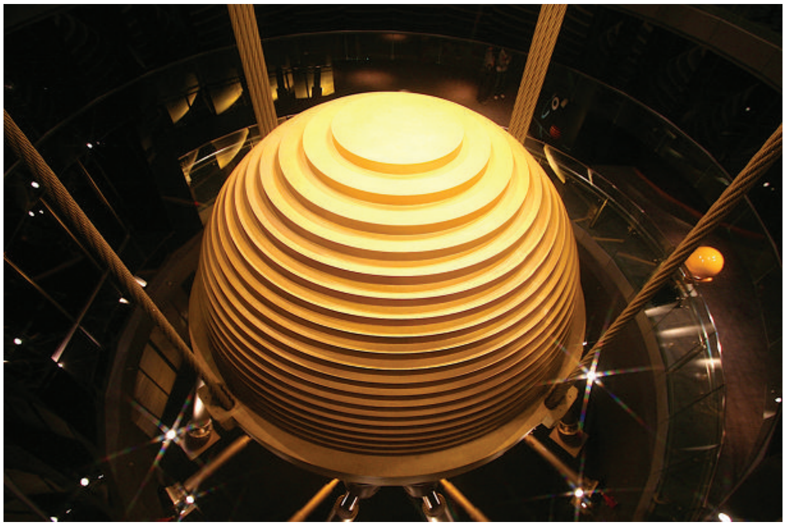


Figure 2.29 Passive tuned mass damper

Taipei 101 passive-tuned mass damper. The suspended sphere has the same fundamental period of the building itself, and so counters the sway by its own inertia. Hydraulic pistons attached to the sphere limit its travel as well as absorb energy and dissipate it as heat. Unlike most buildings where such structures are not visible to the public, the architects chose to make the sphere a prominent part of the architectural design. The damper is on public view at three levels on the restaurant and building observation decks.

Photo: Alvinku/Shutterstock

Figure 2.30 The Tacoma Narrows Bridge ("Galloping Gertie")

The original Tacoma Narrows bridge in Washington developed wild oscillations under light wind loadings. It was nicknamed "Galloping Gertie" by locals due to its tendency to sway in the wind. In 1940, after only four months in use, the bridge dramatically failed in a moderate wind of 42 mph. The bridge buckled up and down and twisted with increasingly more violent swings until it finally gave way and the center section collapsed to the river below.

Photo courtesy of Library of Congress Prints and Photographs Division [LC-USZ62-46682]

foundations, and entire buildings may thus be endangered by rather modest loads with a resonant period.

Whatever their origin, building vibrations can also be damped by friction devices applied at the intersection of any two members free to slide one with respect to the other. In steel frames, friction dampers are located at the intersection of diagonals that are not bolted or welded together.

Even more complicated dynamic phenomena are due to the wind. If a scarf is held out of the window of a moving car, it oscillates rapidly up and down. This "flutter," produced by the constant rush of wind on the scarf, is called an aerodynamic oscillation. The reader may produce such an oscillation by blowing against the edge of a thin piece of paper. Aerodynamic oscillations were produced by a wind of constant and fairly low velocity blowing for 45 minutes, against the Tacoma Narrows suspension bridge at Tacoma, Washington, in 1940; these increased steadily in magnitude, twisting and bending the bridge, until it collapsed (Figure 2.30).

Dynamic wind loads on a structure are also created by its deflection of the wind stream. This explains, for example, the dynamic overpressures measured on the windward side of a building, which may blow windowpanes in. Underpressures or suctions, on the leeward sides of buildings, may suck windowpanes out. All dynamic phenomena are complex. The designer must be aware of their action and utilize with circumspection even the "equivalent static loads" prescribed by codes.

A closer examination of the maps of snow loads, wind loads, and earthquakes (Figures 2.4, 2.7, and 2.30) indicates that all three dangerous conditions seldom occur simultaneously in the same localities and a structure does not need to be designed to withstand a combination of all three such loads.

KEY IDEAS DEVELOPED IN THIS CHAPTER

- Structure is the load-carrying part of physical objects.
- Loads are categorized as applied and hidden loads.
- Applied loads are the ones the structure must support. These are as follows: Dead loads (the weights of building materials and of all permanent fixtures); live loads (occupancy loads and movable fixtures); wind, snow, and earthquake loads; as well as others, such as dynamic loads produced by machinery.
- Hidden loads are produced by thermal environments and support settlements.
- Building codes dictate the design values for each load category depending on the purpose of the building. The codes may also prescribe heights, and type of construction depending on locality.

QUESTIONS AND EXERCISES

1. Look around the places where you live and work or go to school: What objects would be classified as dead loads and which ones as live loads? Are there any types of loads that possibly fall into either category? Why?
2. What types of structural elements can you observe in buildings you are familiar with that function to resist lateral forces? What makes them different from that part of the structure that resists gravity (i.e., primarily vertical) loads, and how can you tell the function?
3. A developer wishes to build a skyscraper hotel in Miami, Florida. What type of loading should be considered? If the same structure is to be built in Maine, should the loading be different? How about building it in San Francisco?
4. Why do houses located on the Palisades on the California Coast require special foundations? What type of foundations should be used?

FURTHER READING

Charleson, Andrew. *Seismic Design for Architects: Outwitting the Quake*. Oxford, England. Elsevier Press, 2008.

Millais, Malcom. *Building Structures: From Concept to Design*, 2nd Edition. Spon Press. 2005. (Chapter 1)

Sandaker, Bjorn N., Eggen, Arne P., and Cruvellier, Mark R. *The Structural Basis of Architecture*, 2nd Edition. Routledge. 2011. (Chapter 3)

CHAPTER THREE

STRUCTURAL MATERIALS

3.1 THE ESSENTIAL PROPERTIES OF STRUCTURAL MATERIALS

A wide variety of materials are used in architectural structures: stone and masonry, wood, steel, aluminum, reinforced and prestressed concrete, plastics, and newer "high-tech" materials such as carbon fiber. They all have in common certain essential properties that make them suitable to withstand loads.

Whether the loads act on a structure permanently, intermittently, or only briefly, the deformation of the structure (a) must not increase indefinitely, and (b) must disappear after the action of the loads ends. The distribution (average) of load (or *force*) over an area is referred to in engineering terms as *stress*, which is the same as the more conventional term *pressure,* measured as force per unit area. In U.S. customary units, this is expressed in pounds per square inch (lb/in^2, or psi). In S.I. (*Le Système International d'Unités*, the world's most widely adopted unit system), the units are Newtons per square meter (N/m^2), which is expressed as the *Pascal* (Pa)—that is, $1\ Pa = 1\ N/m^2$.

A material put into tension will experience tensile stress and stretch, and conversely a material placed into compression will experience compressive stress and contract. Stress is one of the most elemental and important concepts in structural mechanics. It will therefore frequently be referred to for the remainder of this book.

Understanding the concept of stress in one's daily life experience is intuitive. For example, the blow of a hammer on a nail will drive the nail into a piece of wood, but the blow of the same hammer *directly* on the wood will not similarly embed it into the wood; this is because the force of the hammerhead is distributed over a much larger area. In other words, even with the same force, the stress is much lower on the hammerhead itself than on the tip of a nail. The familiar "bed of nails" demonstration also illustrates this principle (Figure 3.1). Although the nail points are individually very sharp and can easily pierce skin, when the entire body weight of the performer is distributed over hundreds of nails, the force becomes so low on each individual nail that one can safely lie upon the bed without injury—no superhuman powers are required. Another example is the snowshoe, which enables one to walk on soft snow that would otherwise not be able to bear a hiker's weight (Figure 3.2).

A material whose deformation vanishes rapidly with the disappearance of the loads is said to behave *elastically* (Figure 3.3). All structural materials are elastic to a certain extent. If they were not, and a residual deformation were present in the structure after unloading, new loadings would

Figure 3.1 A bed of nails

The concept of stress illustrated by the "bed of nails" performance. Although a single nail pressed on by one's full body weight would easily pierce skin, when the same weight is distributed over many hundreds of nails the force becomes so low that one can safely rest on a bed of nails without injury. For example, if a man weighing 200 pounds (~890 N) has his weight distributed over 400 nails, the resulting force is only 200 pounds ÷ 400 nails, or one-half pound per nail . . . only eight ounces (~2.2 N)—about the weight of a small glass of water.

Photo courtesy of Chris Beckett

Figure 3.2 A snowshoe

As with the bed of nails, a snowshoe distributes force over a large area; the pressure is then reduced to the point that one may walk on soft snow without penetrating deeply through the surface.

Photo: Karolina Vyskocilova/123RF

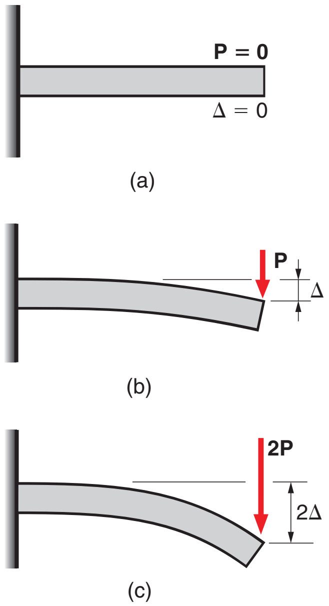


Figure 3.3 Linear elastic behavior

For a material that is linearly elastic, the deformation is directly proportional to the load. In a simple cantilever beam supporting a concentrated load "P" on its free end, the corresponding relative deflection is shown in 3.3b. A doubling of the load will lead to a doubling of the deformation (3.3c), and if the stress on the loaded member is kept within the elastic region, it will return again to its undeformed shape when the load is removed (3.3a).

gradually increase this residual deformation and the structure would eventually become useless. On the other hand, no structural material is perfectly elastic: depending on the type of structure and the magnitude of the loads, permanent deformations are unavoidable whenever the loads exceed certain values. Hence, the loads must be limited to values that will not produce appreciable permanent deformations: Structural materials are usually stressed within their so-called elastic range.

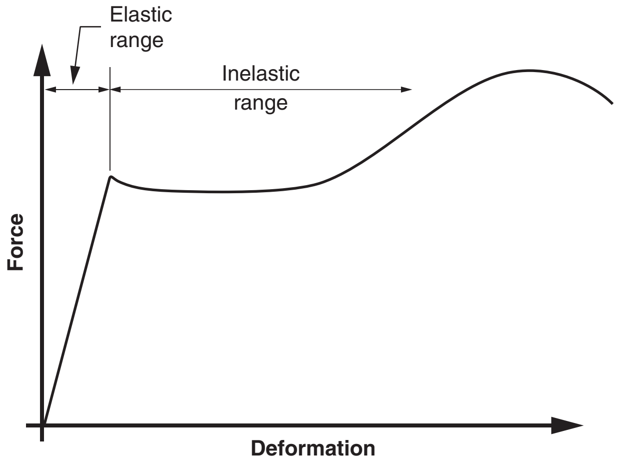


Figure 3.4 Force-deformation diagram

The graph illustrates the response of an elastic material to a force applied to it. The line plots the relative amount of deformation corresponding to the applied force. The sloping straight-line portion of the graph demonstrates that there is a direct proportionality between the amount of deformation (stretch) and the amount of force. For the type of material represented by this graph (such as steel and some plastics), this is true up to a limit, beyond which the proportionality breaks down and a large amount of inelastic deformation occurs with little increase in force.

Most structural materials are not only elastic but, within limits, are *linearly* elastic: This means that their deformation is directly proportional to the load. Thus, if a linearly elastic beam deflects one-tenth of an inch (2.5 mm) under a vertical load of 10 tons (88.9 KN), it will deflect two-tenths of an inch (5.1 mm) under a 20-ton (177.9 KN) load (Figure 3.3c). Most structural materials are used almost exclusively in their linearly elastic range.

These concepts may be visualized by examining a "Force-Deformation Diagram" (Figure 3.4), which illustrates the relative effects between load (plotted on the vertical axis) and deformation (plotted on the horizontal axis) for a structure in tension. When a force is applied to a structural component, it changes its shape: It stretches due to the internal material response of the external load. As the load is increased, the deformation (stretch) will similarly increase. In the elastic range, the initial straight-line portion of the diagram illustrates the direct proportionality of load and deformation.

While the force-deformation diagram provides an easy visualization for the structure in tension, the amount of deformation is dependent on the magnitude of the force and size of the member. In order to make the diagram independent of these values, they are normally plotted as a *stress-strain* diagram (Figure 3.5), which then illustrates a characteristic property for a given material. In terms of stress, if a steel rod with a 1 in^2 (645 mm^2) cross-section is pulled by a 1 pound (4.45 N) force (i.e., a 1 psi (6.9 KPa) stress), it stretches. The corresponding *percentage change* in its length is denoted by the term "strain." This is the change in length of the material relative to its original length, measured in units of inches per inch, millimeters per millimeter, and so on. The applied stress and the resulting strain are

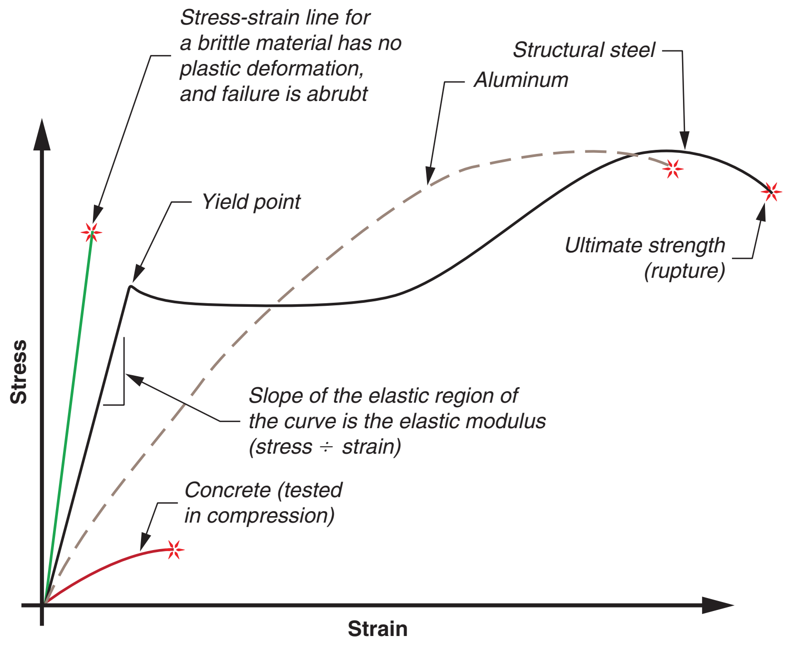


Figure 3.5 Stress-strain diagrams

By dividing the applied force by the cross-sectional area, the vertical axis becomes a plot of stress values, and by dividing the amount of deformation by the original length, the horizontal axis becomes a plot of strain. This diagram then represents a characteristic property for a given material, independent of the size and force magnitude, and provides important insight into the behavior of specific materials.

plotted, with stress on the vertical axis and strain on the horizontal axis, similar to the force-deformation diagram.

The stress-strain diagram for some typical structural materials is presented in Figure 3.5. Steel is an "ideal" material to explore in more depth because it has such a well-defined behavior over an extensive range. Because steel is a linearly elastic material up to a certain amount of strain, the initial portion is a straight line: For any increase in stress, there will be a direct increase in strain, such that doubling the stress will double the strain, and so on. Furthermore, elastic behavior means that removal of the force will return the material to both a zero-stress and zero strain condition.

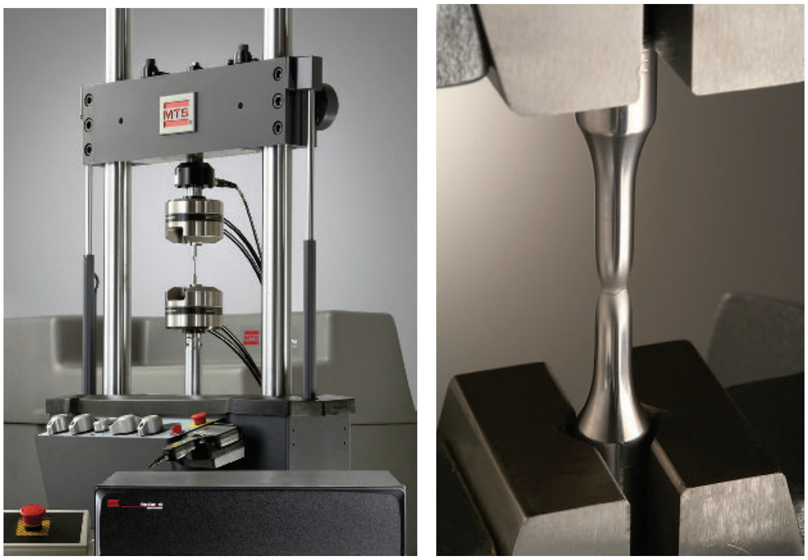
This behavior is true up to the "yield point" stress (F_y), at which point the steel undergoes a permanent deformation that will remain even after the load is removed. The load at which a material starts behaving in a clearly plastic fashion is called its yield stress or yield point. Further sustained loading beyond this point will cause strains to increase rapidly. This continued deformation with little change in load is referred to as *plastic* behavior (see Chapter 9 for a further discussion on plastic behavior).

Once the steel has completely yielded, which involves considerable deformation, it enters a new phase called *strain hardening*. The material exhibits very little change in strain while the stress level increases. The sample begins to exhibit a pronounced "necking down" in size, and an internal molecular transformation has caused it to become a very tough material. Finally, with continued tension the stress level exceeds the capacity of the steel's molecular bonds and it breaks at a stress called the *Ultimate Strength* (F_u) of the material. The photograph of Figure 3.6 shows a steel test sample after it has been loaded to failure.

Materials such as structural steel behave plastically above their elastic range, and have a clear and well-defined yield point. Other common building materials such as aluminum and concrete do not have such a well-defined behavior, or even a clear yield point. For such materials, a yield stress is empirically defined based on a specific strain amount (see Section 3.2).

Although large permanent deformations are to be avoided, plastic behavior above the elastic range does not actually make a material unsuitable for structural purposes: in fact, the opposite is true. For example, while the material is in the linearly elastic range, its deformations increase at the same rate as the loads. Above the yield point, deformations increase more rapidly than the loads (Figure 3.7), and eventually keep increasing even if the loads are not increased. This "flow" or yield under constant loads is thus the clearest sign, and a good warning, that failure is imminent. There are other structural advantages of plastic behavior as well, which are discussed in Section 9.3.

Materials to be used for structural purposes are chosen so as to behave elastically in the environmental conditions and under the type of loads to be expected during the life of the structure. The importance of this requirement can be illustrated by a simple example. If a wax candle is improperly inserted in a candlestick, the seemingly stiff candle will slowly bend out of shape at a warm temperature, and after a few weeks or months (depending on the temperature and type of wax) may be completely bent over (Figure 3.8). This deformation would occur much more rapidly in an oven, while in a refrigerator it



(a) (b)

Figure 3.6 Failure of steel test sample

Figure 3.6a illustrates a machine performing a tensile test on a material sample. The device is capable of generating substantial forces, great enough to break samples while simultaneously carefully recording the magnitude of force and deformation. The test sample enlarged in 3.6b is a steel rod loaded to failure, as evidenced by the thin crack at its center. Notice the pronounced "necking-down" of the specimen near the center. When such necking occurs, the steel has gone well beyond its yield point, the location on the graph of figure 3.5 where diagram sharply changes direction.

Photo courtesy of MTS Systems Corporation

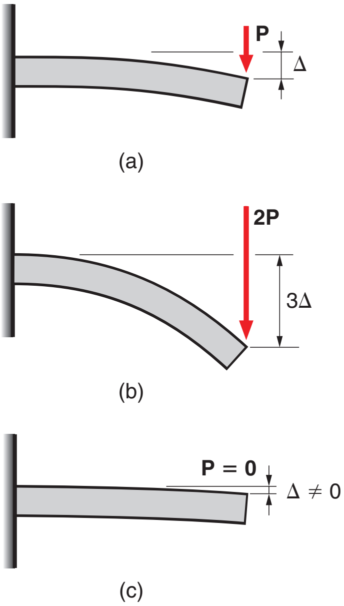


Figure 3.7 Plastic behavior

Unlike elastic behavior, the response of the cantilever beam is not proportional to the applied load (i.e., a doubling of the load can lead to *greater* than doubling of the deflection (Figure 3.7b)). Furthermore, when the load is removed, there remains a permanent deformation (or *set*) in the beam and it does not return to its original position. The beam has deformed plastically (Figure 3.7c).

Figure 3.8 Candle deformed

An ordinary wax candle will plastically deform under its own weight, given sufficient time in a warm environment. With an increase in temperature, the plastic flow will become more pronounced, whereas with a decrease in temperature, the candle becomes a brittle material.

Photo: Laurie Fish/123rf

might be indefinitely limited. Under arctic conditions, therefore, wax is "more structural" than in the tropics.

While given a sufficiently long time, a candle will deform under its own weight alone, if one tries to bend it quickly, it breaks; it becomes brittle. All structural materials exhibit a similar behavior: at low temperatures and under fast load applications they are elastic and brittle; at high temperatures and under long-time loads they "flow." The temperature and time required for flow differ for different materials.

Materials that are linearly elastic up to failure, such as ordinary annealed glass (the type used in a picture frame, for example) and some plastics (note the misnomer), are highly unsuitable for structural purposes. They cannot give warning of approaching failure and often shatter under impact (Figure 3.9). Recent developments, however, that combine the flexibility of plastics and the strength of glass have lead to exciting architectural developments. *Laminated structural glass* is comprised of sheets of high strength tempered glass combined with resilient plastic film fused into

Figure 3.9 Brittle failure

Some materials, such as glass, are brittle by nature. They have little elastic behavior; instead of deforming gradually, internal stresses are released suddenly and powerfully, rupturing the material itself.

Photo: Cosma/Fotolia

Figure 3.10 Laminated structural glass

Widely popularized in Apple computer stores, laminated structural glass has made it possible to design architectural elements such as this circular stairway in Boston, Massachusetts. The inherent brittleness of glass is overcome by laminating multiple layers of glass with plastic material. All primary load-bearing elements are comprised of glass with stainless steel connectors, where the highest stresses need to be transferred between individual glass elements.

Photo courtesy of Deborah Oakley

multiple layers. Its strength and flexibility is such that it can be used in applications such as beams and floor slabs that have previously been impossible. Dramatic multistory facades, stairways, and floors made of structural glass combined with steel tensile elements have now become commonplace (Figure 3.10). Structural glass and other materials such as reinforced concrete (which combines plain concrete

Figure 3.11 Brittle fracture of a steel beam

On an unusually cold winter night in 1985, a roof girder for the open-air theater at Wolf Trap Center for the Performing Arts in Vienna, Virginia, suffered a brittle fracture. A complex combination of brittle steel and minute fabrication flaws combined with the bitter cold was determined as the cause. Fortunately, enough redundancy was present that the roof did not collapse and the building was subsequently strengthened and has been successfully functioning ever since.

Photo courtesy of Deborah Oakley

with structural steel; see section 3.3) are referred to as *composite* materials. They combine the best properties of two or more materials into one new material that has unique properties all its own.

Steel at normal temperatures has a useful linearly elastic range up to the yield point, followed by a long plastic range. It will, however, become suddenly brittle at a temperature of −30° Fahrenheit (−34°C). Some unexpected failures of steel bridges in Canada in the 1950s were traced to this sudden transition from elastic-plastic to brittle behavior at low temperature. A similar brittle fracture failure occurred on an unusually cold winter night in 1985 to one of the main roof girders of the open-air roof pavilion of the Filene Center Theater at the Wolf Trap Performing Arts Center in Vienna, Virginia (Figure 3.11).

At high temperature, even steel—one of the strongest structural materials—loses most of its strength: It keeps deforming more and more, even under constant loads. At not much above 1000° Fahrenheit (538°C) it loses almost all bending resistance and becomes limp like cooked spaghetti (though it does not melt until much more than twice that temperature) (Figure 3.12). Hence, if steel is to be used safely in a building, it must be protected, or *fire-retarded*, so that it will not reach high temperatures at least for a few hours, during which time the building can be safely evacuated. When a material is fire retarded for an indefinite time, it is said to be fireproof: Reinforced concrete is practically fireproof, provided the reinforcing steel is sufficiently protected by a cover of concrete. Building codes have specific requirements for fire retardation.

Some materials have a relatively limited elastic range and behave plastically under low loads. Certain plastics (thus correctly named in this case) flow under almost any load. The yielding behavior of these plastics, and the brittle

Figure 3.12 Warping of steel due to fire

While unprotected steel will not burn in a fire, at around 1100°F (538C) it substantially loses stiffness and will warp like plastic under its own self weight. It is notable that this loss of stiffness occurs more than 1500°F (816C) below its melting point.

behavior of others, makes them unsuitable for structural purposes. But reinforced plastics, such as fiberglass, present acceptable structural characteristics, and their increased use is easily foreseeable. Materials such as these are specifically useful in certain applications such as the corrosive environments of chemical manufacturing plants and wastewater treatment facilities where unprotected steel would be quickly damaged.

Modern structural materials, such as steel, are what are known as *isotropic* (from the Greek *isos*, meaning "equal," and *tropos*, meaning "direction") and homogeneous, that is, their properties and behavior under load are the same throughout the structural component. Because of this, their resistance does not depend on the direction in which they are stressed. Wood, on the other hand, is *anisotropic* (from the Greek *an*, meaning "not"), since it has different strengths in the direction of the grain and at right angles to it. This drawback is remedied by joining, with plastic glues, sheets or pieces of wood with grain in different directions. The *engineered wood* thus obtained presents more homogeneous strength characteristics and moreover can be made weather resistant. Many varieties of engineered lumber are now widely available such as plywood, oriented-strand board (OSB), particle board, medium-density fiberboard (MDF), glued-laminated timber (GluLam), parallel-strand lumber (PSL), and others. Each of these not only improves upon the properties of natural wood (which is subject to the variations that accompany any organic material), but of increasing importance allows the use of small pieces of "leftover" materials that would formerly have been waste, thus making better use of resources.

Structural materials can also be classified according to the kind of basic stresses they can withstand: tension, compression, and shear. These basic forces are discussed in depth in Chapter 5. In brief, tension is the kind of stress that pulls apart the particles of the material and lengthens elements (Figure 3.13a); compression pushes the particles one against the other and shortens elements (Figure 3.13b); shear, however, tends to make the particles slide, as they do

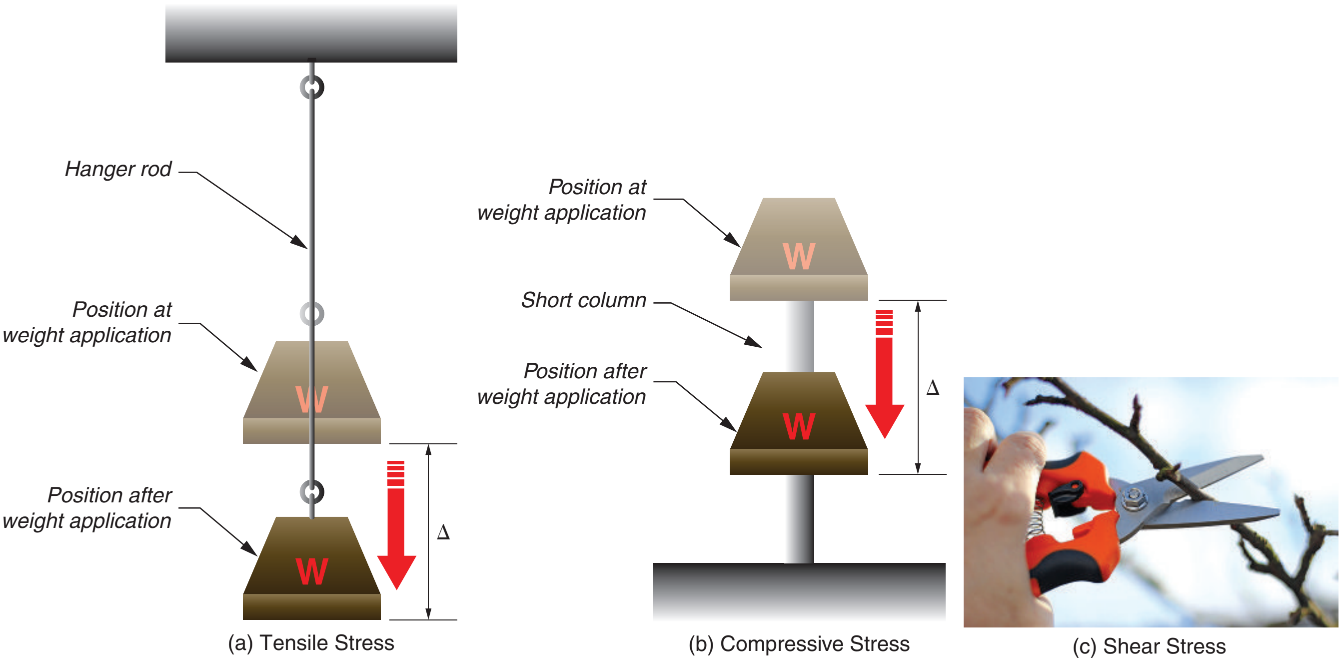


Figure 3.13 Basic types of stress

An element that is pulled is in tension (a), one that is pushed or squeezed is in compression (b), and one that experiences a slicing or transverse force (such as a pair of scissors or a branch pruner) experiences shear (c). It should be noted, that longer members in compression are subject to buckling behavior (see Chapter Five). All deformations in these diagrams are exaggerated for clarity.

(c) Photo: Zbigniew Guzowski/123rf

in in a pair of wood pieces glued together under either tension or compression, or as they do in a wire or branches sheared by a pair of cutting pliers (Figure 3.13c).

All structural materials can withstand compressive stresses. Some, such as steel, resist compressive and tensile stresses equally well. Others, such as stone, brick, unreinforced concrete, or wood loaded perpendicular to its grain, do not: Their tensile strength is about one-tenth of their compressive strength. Their use is necessarily limited to loads and shapes that will not develop significant tensile stresses. Materials capable of resisting tensile stresses usually resist shearing stresses also; materials that are essentially useful in only compressive loads, on the other hand, do not have high shear strength either (see Section 5.3).

3.2 MATERIAL CONSTANTS AND SAFETY FACTORS

For structural purposes, materials are mostly used within their linearly elastic range, and this implies that their deformations are proportional to the loads upon them. But different materials deform differently under the same loads. If a steel wire 5 feet long (1.5 m), 1/16 of an inch (1.6 mm) in diameter, is loaded by a weight of 1000 pounds (4.45 kN), it lengthens by 2/3 of an inch (17 mm); the same wire made of aluminum stretches three times as much, that is, 2 inches (51 mm) (Figure 3.14).

Steel is stiffer in tension than aluminum. The measure of this stiffness is a property of each structural material, called its tensile *elastic modulus*. The higher a material's elastic modulus, the stiffer it is—meaning that it will stretch or deform less than a material having a lower elastic modulus. The elastic modulus is the force theoretically capable of stretching elastically a wire, 1 square inch (645 mm^2) in area, to twice its original length (theoretically, because in actuality the wire will break before stretching that much). Another concept, toughness, is the energy required to tear a piece of material apart. Materials with a long plastic range are tougher then brittle materials.

The elastic modulus (E) of a material may be determined from the stress-strain diagram. For highly elastic materials; it is the slope of the initial, straight-line portion of the diagram, that is, the ratio of a stress level and the corresponding strain. For the structural steel of Figure 3.5 at a stress of 30,000 psi (207 MPa), the strain is 0.001 in/in (0.025 mm/mm). Consequently, E = 30,000,000 psi (207 GPa). The slope of the stress-strain curve for aluminum is flatter. The strain at 30,000 psi (207 MPa) is 0.003 in/in (0.076 mm/mm) and E = 10,000,000 psi (69 GPa).

It is seen on the diagram that aluminum does not have a well-defined yield point. A yield stress is defined for such materials by drawing a line parallel to the initial straight portion of the diagram at a strain of 0.2 percent. The stress level where the line intersects the curve is the yield stress. For the aluminum of Figure 3.5, F_y = 36,000 psi (248 MPa).

The modulus in compression differs, in general, from the modulus in tension. The compressive modulus of concrete varies with its composition and has an average value of 4 million pounds per square inch (27.6 GPa); its tensile modulus has little significance, since its tensile strength is negligible. The compressive modulus of wood varies between 1 and 2 million pounds per square inch (6.9 GPa and 13.8 GPa) in the direction of the fibers, and is approximately 3/4 million pounds per square inch (5.2 GPa) at right angles to them. Since they are isotropic and homogeneous, steel and aluminum have the same moduli in tension and compression.

For purposes of safety, knowledge of the stress at which a material will start yielding is of the utmost importance. The yield stress or yield strength in tension or compression for common structural steel (and for aluminum) varies

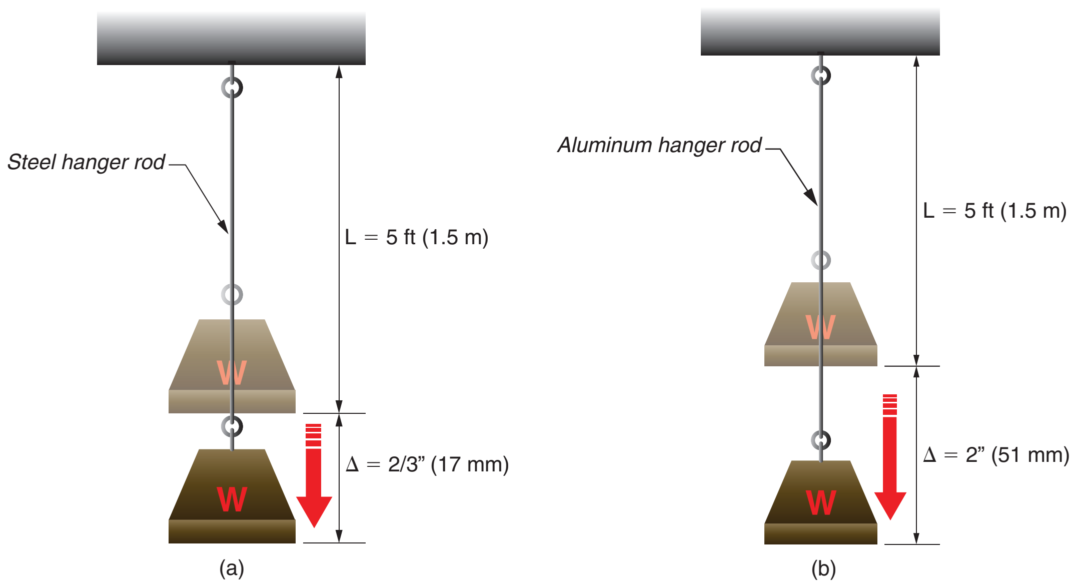


Figure 3.14 Tensile deformations

A rod of aluminum will stretch three times as much as a steel rod supporting the same load, because the elastic modulus of aluminum is 1/3 that of steel.

between 36 thousand and 50 thousand pounds per square inch (248 to 345 MPa). Since structures cannot be allowed to yield under loads lest their permanent deformations accumulate in time, safe stresses are usually assumed as a fraction of the yield point of their material (usually 60 percent, or a safety factor of about 1.7). Thus, steel and aluminum may be safely stressed in tension or compression to about 20 to 30 thousand pounds per square inch (138 to 207 MPa), and concrete in compression to approximately 1 to 5 thousand pounds per square inch (7 to 34 MPa).

The safety factors thus introduced depend on a variety of conditions: the uniformity of the material, its yield and strength properties, the type of stress developed, the permanency and certainty of the loads, and the purpose of the building. This last factor is of great importance from a social viewpoint: The safety of a large hall is more critical than the safety of a one-family house—and most certainly more critical than a storage shed—and so must be evaluated more conservatively. Building codes (Chapter 2) define appropriate safety factors for most commonly used structures. Factors of safety for buildings of exceptional dimensions, to be occupied simultaneously by large numbers of people, are established today so as to make it highly improbable that even a predetermined, small number of persons would be killed by a structural failure during the life of the structure. The calculation of such safety factors involves the use of probability theory and leads to results gauged in terms of human lives. (See Sections 2.3 and 13.5.)

Safety factors cannot be established on the basis of the yield point whenever the material does not present a well-defined yield point, or does not exhibit a distinct yielding behavior. The first case occurs with concrete, which does not have a clear transition from elastic to plastic behavior; the second with brittle materials, which behave linearly up to failure. In these cases, safety must be measured directly against failure, as far as the material is concerned. It is thus important to realize that steel will break in tension at a stress of 50 to 300 thousand pounds per square inch (345 MPa to 2.1 GPa), and concrete in compression at a stress of 3 to 12 thousand pounds per square inch (21 MPa to 83 MPa). These stresses are called the *ultimate strength, F_u,* of the material.

The load, or combination of loads, inducing stresses equal to the ultimate strength of an element, is called the *ultimate load* for that element. When the design of a reinforced concrete structure is based on ultimate strength (an approach called *strength design*), codes specify that certain load combinations should not reach values higher than the ultimate load, U. For example, indicating by "D" the dead load, by "L" the code live load, and by "W" the code wind load (up until recently when the factors have become more complex), the American Concrete Institute (ACI) code required that U be less than $0.75 \times (1.2D + 1.6L + 1.6W)$, or less than $1.2D + 1.6L$ in the absence of wind. Similar ultimate design formulas are also becoming the preferred approach in steel and wood design as well.

Some advantage may be realized in establishing safety factors on the basis of failure, even when the yield point is clearly defined. These safety factors give direct information on the overload the structure can support before it collapses, rather than on the overload that will make the structure unusable because of excessive deformations. Knowledge of both overloads may be useful in establishing higher safety factors for permanent and semi-permanent loads on the basis of yield, and lower safety factors for exceptional loads (hurricane winds, earthquakes) on the basis of failure. This criterion is accepted by most codes: A combination of normal gravity loads and of exceptional lateral loads (such as full wind or earthquake forces that have a minimal chance of occurring simultaneously) is often allowed to stress the structure 33 per cent above the stresses due to gravity loads acting alone.

3.3 MODERN STRUCTURAL MATERIALS

Iron has been used as a structural material for thousands of years, mainly in combination with other materials. Since the tensile properties of iron and the compressive properties of wood were well known, a combination of wood struts in compression and iron tie-rods in tension was often used in trusses spanning the naves of medieval churches, for example (Figure 3.15). It should be noted, however, that iron has

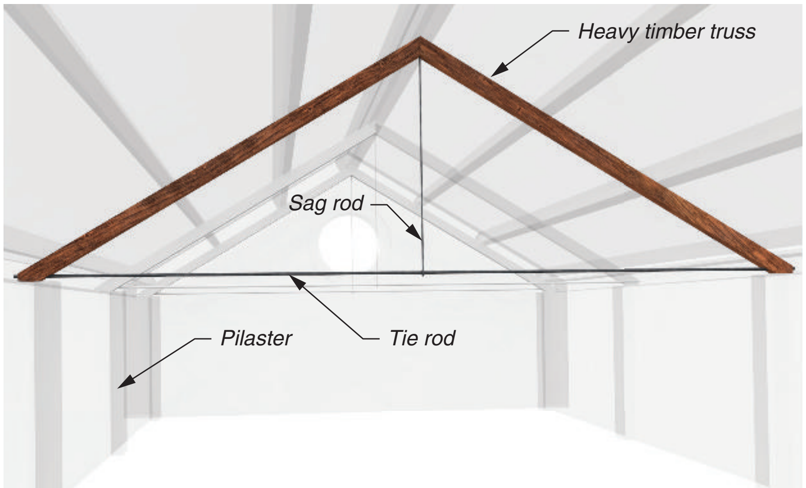


Figure 3.15 Wood and iron truss

Heavy timber structures often employ iron (and today, steel) tie rods and sag rods. The function of the sag rod is simply to prevent the tie rod from deflecting under its own weight. The sag rod serves no other structural function, unless a large object such as a chandelier is suspended below it, in which case it transfers that weight up to the top timber members. The purpose of the pilasters is to provide a good bearing surface for the truss and to strengthen the walls.

a much smaller elastic range than structural steel. Cast iron is actually brittle—it does not exhibit any plastic behavior, thereby limiting its use. Steel, with its greatly improved properties, could only be produced in small quantities until the Industrial Revolution. Steel was thus limited to small objects and weaponry like swords until the middle of the nineteenth century, when large quantities of steel suitable for construction projects could be produced.

Increased knowledge in metallurgy, chemistry, and physics has substantially improved the properties of structural materials during the last 150 years. Stainless steel has all but eliminated the danger of rust in most applications, while rust-resistant steel, such as U.S. Steel's "Corten" (also known as "weathering steel"), stops rusting after two or three years and does not require painting. This tough rust coating acts similarly to the oxide coating that aluminum develops, both of which form a protective layer that inhibits continued corrosion under ordinary usage. Ultimate tensile stresses of steel alloys have reached values as high as 300 thousand pounds per square inch (2.1 GPa), and those of minute steel "whiskers," millions of pounds per square inch (7 GPa and higher), forecasting revolutionary developments in steel design. Similarly, some new aluminum alloys have the strength of structural steel and are only one-third as heavy. Plastic glues have transformed wood into a more permanent, practically isotropic material. Glass reinforced plastics combine the strength of glass with the nonbrittle behavior of plastics.

Possibly the most interesting (and one of the most important) modern structural materials is reinforced concrete, which combines the compressive strength of concrete with the tensile strength of steel. The use of reinforced concrete in contemporary construction is so pervasive that it may surprise the reader to learn it was only developed in the mid-1850s, and did not achieve wide usage until the early part of the twentieth century. Although the Romans used a form of concrete made with volcanic ash (known as *pozollana*) for many centuries, it was never combined with steel to create reinforced concrete. The art of creating the pozollana disappeared with the fall of the Empire. Its modern incarnation, *Portland cement*, was developed in 1824 by the Englishman Joseph Aspdin.

Concrete is actually a mixture of Portland cement, stone aggregates, and water. When activated by water, a chemical reaction is initiated in the cement causing it to set and harden to make the structure a single, monolithic entity. Concrete has been likened to "liquid stone" and can be poured in a variety of shapes with a wide range of textures, so as to adapt itself to the architecture of the building and the loads on it. A new freedom in the design of structures has thus been realized, far greater than that inherent in assembling beams and columns of standard shapes like those of rolled steel sections or sawn lumber.

Concrete is very strong under compressive stresses. The continued use of ancient Roman structures such as the Pantheon (to this day the largest unreinforced concrete dome in the world) give testament to its durability when used in a compressive manner. Under tensile stresses, however, concrete is very weak and breaks easily. The reinforcing steel therefore acts like a web of tensile elements, which pervades and holds together the mass of concrete.

The properties of steel depend on the careful proportions of ore mixtures, furnace and quenching temperatures, and minute amounts of alloyed chemicals. The properties of concrete depend on the quality and amounts of components in the mixture. Concrete is so sensitive to variations in mixture that it must be carefully and scientifically "designed" in specialized laboratories when used in large construction projects. The grain size and distribution of the sand and gravel aggregates, the quality of the cement, and the quantity of water used, all substantially affect the concrete strength and its hardening time.

It should be noted that concrete does not become hard by "drying out." In fact, moisture is a critical component of the hardening process, which is actually a chemical reaction known as *hydration*. During hydration (or as more commonly referred to, the curing process), heat is produced, and unless the concrete is properly protected from both low and high temperatures, it may set improperly and crack, or have an ultimate strength lower than its design strength. Cracks due to drying shrinkage may permit humidity and water to reach the reinforcing steel, which then rusts and eventually disintegrates the entire reinforced concrete mass. It is therefore a critical part of the process that each batch of concrete placed in a building, bridge or other construction project be tested to guarantee that its strength is in agreement with the laboratory design, and be properly cured in a moist and temperature-controlled environment, lest it need to be ripped out and replaced—a time-consuming and expensive process which has resulted in numerous lawsuits over the decades.

The manufacture of concrete is thus seen to be a delicate process, requiring as much care as that of any chemical. The concrete for important construction jobs is seldom mixed at the site; it is manufactured off site in concrete plants and transported to the site. On the other hand, because concrete properties vary so much with composition and methods of mixture, many different types of concrete can be obtained, each suited for a specific purpose. Concrete with a compressive strength as high as 12,000 pounds per square inch (6.9 MPa), rapidly hardening concrete, and concrete with lightweight aggregates, are constantly being introduced. In addition, *chemical admixtures* of many types (such as those improving weather resistance in freeze-thaw cycles, those yielding a speeding up or retarding of curing time, and those making the mixture more flowable and easily pumped up many stories) are also under continual development. The reader will appreciate the potentialities of this new material after becoming acquainted with some of its applications to structural systems.

As previously noted, the function of the reinforcement in concrete is to carry tensile stresses in a member, and there are several methods of employing the tensile reinforcement: one that is "passive" and two that are "active." Fundamentally (as will be further discussed in Chapters 5 and 7), a concrete beam on two supports that is loaded by downward forces has its upper surface in compression while the lower portion is in tension and would crack if not reinforced by steel (Figure 3.16a). The oldest and still most common method of reinforcing a beam (referred to as *conventionally reinforced)* provides steel that acts in a passive manner. When a steel rod is inserted in the lower portion of a beam, it is in the region of tensile force on the beam and tightly bonded to the concrete. The reinforcing steel (colloquially referred to as "rebar") is stamped with ribbed patterns to ensure a good bond between the concrete and steel—an essential transfer of force if the steel is to carry loads from the concrete. In bending under load, the concrete engages this tensile steel and prevents cracking as illustrated in Figure 3.16a.

Introduced in the mid-twentieth century, prestressed concrete further advanced the basic concept of a passive tensile reinforcement for a nontensile material by actively precompressing the concrete member. There are two methods of creating prestressed concrete. The difference between the two techniques has to do with *when* the pretensioning occurs: One type is referred to as *precast prestressed* (or more commonly just *prestressed*), and the other as *post-tensioned*. Prestressed concrete is created in factories for the prefabrication of structural elements. Here, *tendons* of exceptionally strong wire are pulled against the ends of steel forms in which the concrete is poured. Once the hardened concrete grips the tendons, these are cut from the formwork ends and their tension puts the concrete in compression as the tendons naturally attempt to return to their initial unstressed state. In post-tensioned concrete, slack tendons are threaded through hollow sleeves (known as *ducts*) set in the concrete forms and, once the concrete reaches a sufficient strength, are pulled against the hardened concrete by outside jacks thereby compressing it (Figure 3.16b). Post-tensioning is used mostly on site and, in large structures, may proceed in stages as required by the stresses in an element, which increase under the increasing dead load.

An unloaded beam of prestressed concrete may appear from the outside to be unstressed, but "locked-in" stresses compress the concrete and tense the steel. The tensile stresses developed in a beam by the loads reduce, or at most wipe out, the initial compressive stresses due to prestressing, so that the concrete is never in tension. With no appreciable tension, it has less of a tendency to crack (see also see Chapter 7 for a more thorough presentation of beams). Early investigators of reinforced concrete first proposed the prestressing of concrete members in the mid-nineteenth century. Unfortunately, the steel available at the time had a low yield point and could not be stressed high enough to allow the tendons to remain substantially tensed following the plastic flow of the concrete under the prestressing compressive stresses. Only after high-strength steel suitable for this

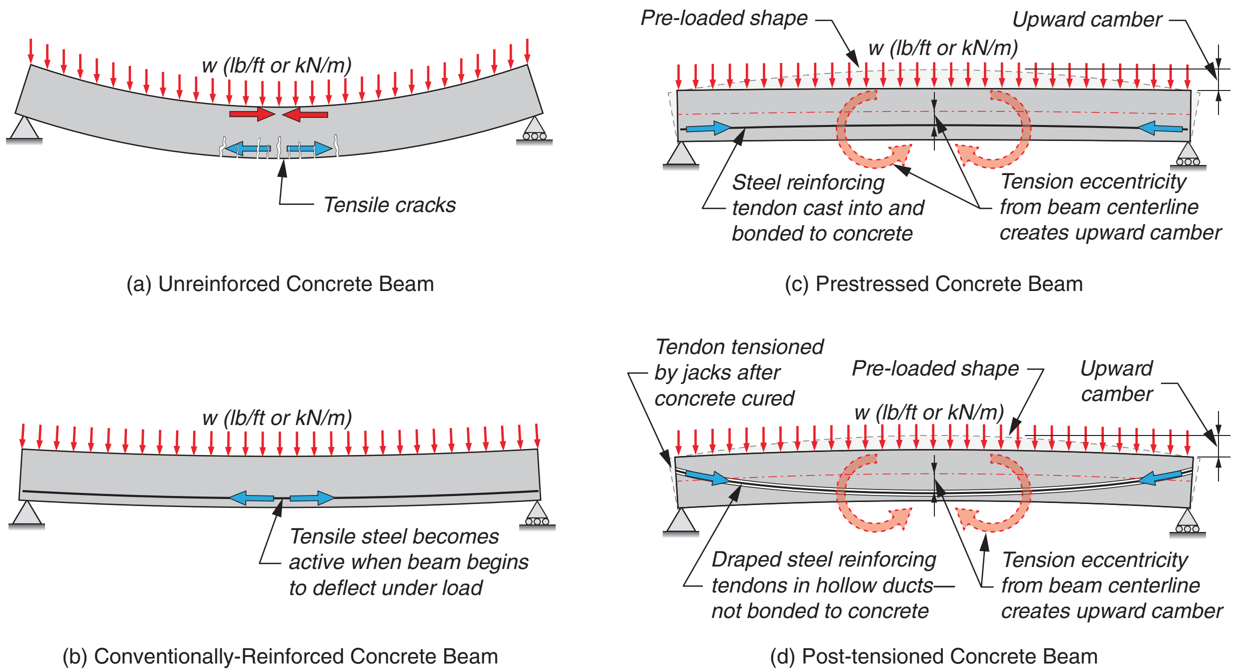


Figure 3.16 Concrete beams: Unreinforced and reinforced

A concrete beam with no reinforcement has little tensile capacity. With downward loads, the bottom surface will be put into tension, while the upper surface is in compression (see Chapter 5) and thus crack and fail at a modest level of load (a). Conventional reinforcement bonds to the concrete to form a composite element where concrete carries compressive stresses (which it is well suited for) and steel carries tensile stresses (b). Conventional reinforcement is *passive*: no stress is placed on the steel until the beam is placed under load. An *active* form of reinforcing is to either pre- or posttension the steel with powerful hydraulic jacks (c and d). When the tension is released, it places the bottom surface of the concrete into compression, thus counterbalancing loads that would put it into compression. A pre- or posttensioned beam requires less reinforcement than a conventionally reinforced beam, although in complete buildings both pre- and posttensioned reinforcement is still augmented with conventional reinforcement.

Figure 3.17 Ferrocement

Rather than using heavy reinforcing bars or high-strength strands, Ferrocement uses multiple layers of fine mesh placed in random layers to distribute reinforcement throughout a thin structural member. Ferrocement has been used for boat hulls and larger projects, and is a technique favored in regions where labor is plentiful but materials are expensive. It can be molded into virtually any shape.

Photo courtesy of Milinkovic Company

purpose was manufactured at reasonable prices did prestressed concrete become an economic reality in the mid-twentieth century.

"Ferrocement" (iron-concrete), a structural material first successfully used by Italian engineer Pier Luigi Nervi, is a combination of dense steel mesh and cement mortar. In Ferrocement, a number of layers of wire mesh, with square holes less than half an inch on a side, are packed randomly one on top of the other across the thickness of thin elements and embedded in a mortar of cement, water and sand with no coarse aggregate (Figure 3.17). The resulting material has the compressive capacity of an excellent concrete and the tensile strength of steel, since the steel is so thoroughly distributed through the mortar as to hold its particles together even when tension is applied to it. One of the most successful applications of Ferrocement is to the construction of small-boat hulls, which Nervi started in the 1920s. Nervi went on to create a number of spectacular architectural projects using this material (Figure 3.18).

In a more recent development, steel reinforcing bars or mesh have been replaced by short glass or metal fibers mixed with the concrete, thus allowing the creation of structural elements capable of resisting tension homogeneously in all three dimensions. Furthermore, new *Ultra-High Performance Fiber Reinforced Concrete* mixtures (such as the proprietary mixture known as *Ductal® Concrete* by the French company, Lafarge) produce concrete with previously unobtainable tensile strength. Delicate tracery and shapes formerly possible only with cast steel can now be formed with this high-tech wonder concrete (Figure. 3.19).

The high compressive strength of ceramic tile may similarly be combined with the tensile strength of steel and the cohesive properties of concrete to create a material similar

Figure 3.18 Cathedral of St. Mary of the Assumption in San Francisco, California

One of the last projects in his life by famed Italian engineer Pier Luigi Nervi, the roof of the cathedral is comprised of triangular "pans" of Ferrocement tiles following the profile of the hyperbolic paraboloid roof (see Chapter Twelve). The tiles are both formwork for the concrete cast on the outer roof surface, as well as creating the final exposed interior surface, thereby eliminating additional formwork. The edges of the pans link together to form thin skewed beams (see Chapter 10) on the interior surface. Nervi is renowned for his modern reinvention of this material first explored in the mid-1800s. He completed a number of prominent projects with this technique, most located in his native Italy. See also figure 14.16b for an exterior photograph.

Photo courtesy of Deborah Oakley

in behavior to reinforced concrete. Italian engineering pioneer of reinforced concrete, Eduardo Torroja, among others, showed how imaginatively one could use such material in countries where steel is prohibitively expensive and labor costs are low (see Section 10.6).

Plastics, synthetic materials using organic substances as binders, are finding widening applications in the field of structures because of their varied properties, but, generally, are not yet widely used as structural materials because of their relatively high costs.

Most structural plastics are glass reinforced. Glass fibers with a tensile strength of up to 600 thousand pounds per square inch (4.1 GPa) are commonly used to reinforce epoxy resins molded into airplane parts and other structural elements. Glass fabrics give tensile strength to epoxy and polyester resins used to manufacture structural panels, and to polyvinyl and other plastic materials constituting

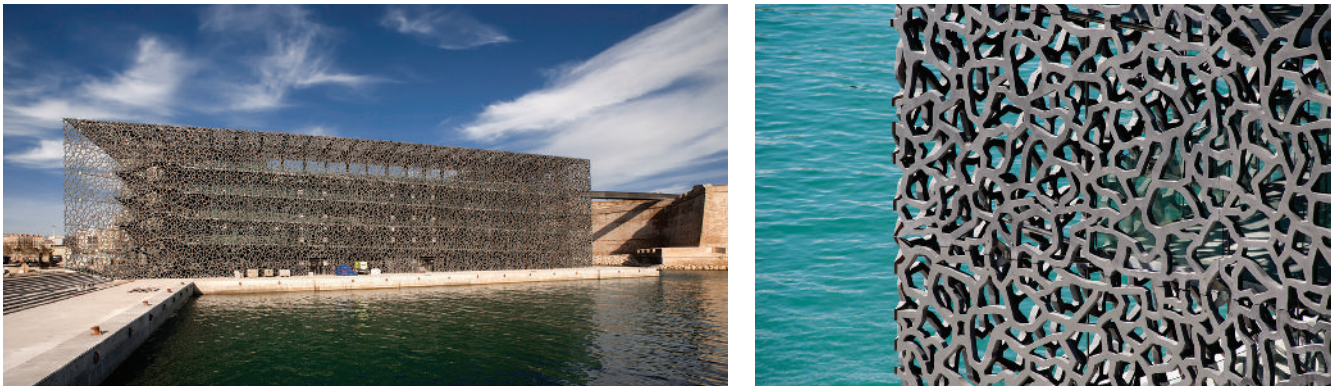


Figure 3.19 Ultra High-Performance Fiber-Reinforced Concrete

Ductal® is a proprietary fiber-concrete mixture developed by the French company Lafarge. Elements created using this material can be far thinner than conventionally-reinforced concrete, and the high tensile capacity enables it to be used in applications such as thin tracery where previously only cast steel could have been employed. The entire southeast and soutwest-facing facade (as well as much of the roof) of the Museum of European and Mediterranean Civilizations (MuCEM) in Marseille, France, by architect Rudy Ricciottti, is wrapped in a bris soleil web of Ductal® concrete.

Photo courtesy of Rudy Ricciotti

the membranes of large air-supported roofs (see Section 11.3). Urethane and polystyrene foams, with low compressive and tensile strength but sufficient shear strength, are used as cores of sandwich panels of plywood, gypsum, aluminum, steel, or plastics, with excellent weight-to-strength ratios and thermal-insulating properties (see Section 10.6).

Perhaps one of the most exciting new materials is graphite carbon fiber reinforced plastic. Carbon fiber combines an extremely high tensile strength with very low weight. Filaments of carbon fiber can be woven into textile sheets like any conventional fabric. When combined with epoxy or other resins, they can be formed into virtually any shape imaginable to form an extremely tough yet flexible and strong but lightweight structural element. Presently used extensively in the manufacture of sporting goods as well as in the aerospace industry (in the famous *Stealth* fighter plane and the Boeing "Dreamliner," for example), its use in construction projects is still limited to specialized applications where its superior "strength to weight ratio" is important. Because their manufacture is a highly laborious process, carbon epoxy structures are expensive. New research in this area, however, portends the day when large-scale application in buildings and bridges will be commonplace. It is easy to forecast that the ever-growing developments in the field of plastics will make these materials more and more competitive with classical structural materials.

This chapter has briefly introduced some of the most important characteristics of the various materials used in structures; it is really the tip of the iceberg of an entire field known as *materials science*. Nevertheless, this basic understanding can create a framework of understanding to carry the reader through an appreciation of much of the field of structures. It should also be seen that the proper use of structural materials is essential to correct design, since the availability of materials limits the choice of structural systems in any important structure.

KEY IDEAS DEVELOPED IN THIS CHAPTER

- Materials of construction must carry loads without permanent deformation. They may be (1) elastic, within a certain range; (2) elastic-plastic; and (3) brittle.
- Some materials are able to carry tensile and compressive loads equally well, while others can only be used with compressive loads.
- Stress is defined as the force per unit area and strain as elongation per unit length. There are specific characteristic properties of yield point, yield stress, and ultimate strength for any given material.
- Rigidity/flexibility of a material is quantified by the modulus of elasticity, defined as the ratio of stress to strain.

QUESTIONS AND EXERCISES

1. Many common plastics used in household products possess a remarkably similar behavior to structural steel, including heavy-duty trash bags. You can experiment with this by taking a cutting from a trash bag, approximately 1/2 inches (13 mm) wide by 6 inches (152 mm) long, and pulling on it. Depending on the plastic, there will be some stretch initially, but it will return to the initial state after the pulling force is removed. Pull hard enough (but not so hard as to break it) and a permanent set will be made in the plastic. It has thus reached its yield point. Some plastics are highly anisotropic due to their manufacturing process. This means that strips cut 'across the grain' (so to speak) will exhibit a pronounced necking down, whereas strips cut 'parallel to the grain' will not. Try both ways to see the difference!

   If the cuts are clean (no notches or defects on the sides), continued pulling will result in a surprising amount of stretch of this material. This is the plastic range of the material. Finally, it will become very "tough" and resistant to further stretching. Continued pulling will not stretch it further, but one can notice the increase in force that the material will sustain. This is the point of strain hardening for this material. Ultimately, when the force is high enough, it will suddenly break. It has reached its ultimate stress level. This characteristic behavior is, in miniature, exactly the way structural steel behaves.

2. Make a beam out of foam rubber, about 1 in square cross-section and a foot long (25 mm wide and 300 mm long). Hold one end in your hand and put a small weight on, or simply press on, the free end. Observe the deflection. Now cover the top side with transparent tape and repeat the loading. Observe the reduced deflection: You have created a reinforced beam!
3. Turn over the reinforced beam and apply the load again. Notice the wrinkling of the tape. Why is it wrinkled?

FURTHER READING

Millais, Malcom. *Building Structures: From Concept to Design*, 2nd Edition. Spon Press. 2005. (Chapter 5)

Sandaker, Bjorn N., Eggen, Arne P., and Cruvellier, Mark R. *The Structural Basis of Architecture*, 2nd Edition. Routledge. 2011. (Chapter 4)

Allen, Edward and Zalewski, Waclaw. *Form and Forces: Designing Efficient Form and Forces: Designing Efficient, Expressive Structures*. John Wiley & Sons, Inc. 2009. (Chapter 13)

CHAPTER
FOUR

STRUCTURAL REQUIREMENTS

4.1 BASIC REQUIREMENTS

All structures must conform to certain physical and human constraints. Modern developments in materials production, construction techniques, and methods of structural analysis have introduced new freedoms in architectural design that were inconceivable even in the recent past, considerably widening its scope.

These new freedoms, however, do not exempt modern structures from satisfying certain basic requirements that have always been the foundations of good architecture. We may list them under the following headings: *equilibrium, stability, strength, functionality, economy*, and *aesthetics*. The sections of this chapter will address each of those conditions in turn.

4.2 EQUILIBRIUM

The fundamental requirement of equilibrium is concerned with the guarantee that a building, or any of its parts, will not move. More technically this is *static* equilibrium versus *dynamic* equilibrium, which deals with objects in motion. For simplicity in this text it will be simply referred to as equilibrium. Obviously, this requirement cannot be interpreted strictly since some motion is both unavoidable and necessary (*thermal expansion, etc.*). The displacements allowable in a building, though, are usually so small compared to its dimensions that the building appears immovable and undeformed to the naked eye.

The principles governing the motion of bodies, published by Sir Isaac Newton in 1687, are called Newton's laws. The particular cases of these laws governing equilibrium (i.e., the lack of motion) are of basic importance in structural theory because they apply to all structures and are sufficient for the design of many of them. Such structures, called statically determinate, support loads by developing reaction forces whose values do not depend on the material used. These reaction forces can be determined by the two simple equations of linear and rotational equilibrium, stating that the numerical sum of all forces and of all rotational actions must equal zero for static equilibrium to exist.

Structures that cannot be designed on the basis of Newton's laws alone and which require a knowledge of material properties are called *statically indeterminate*, meaning that the external forces supporting them cannot be determined solely by the basic equations of statics. Many modern structures are statically indeterminate, and possess certain advantages such as using less material, as well as the ability to redistribute loads, making them more resilient. Modern computing methods have made the design of statically indeterminate structures far easier than in in the past when calculations were performed with manual techniques.

Newton's three Laws of Motion can be concisely stated as follows: (1) Inertia: An object at rest will remain at rest, or an object in motion will remain in motion, unless acted on by an external force; (2) Force is directly proportional to the mass of a body multiplied by its acceleration; and (3) Equilibrium: Every force action has an equal and opposite reaction.

The first and third laws together form the engineering field of study referred to as "statics," and adding the second refers to the engineering field of "dynamics." Dynamics is all about our modern world, from the cars and airplanes we travel in to the machinery in factories that make the "stuff" of our daily lives. Strikingly, a basic understanding of statics, coupled with knowledge of material properties and their internal response to forces, is sufficient for the design of the vast majority of all building structures. Very tall buildings, long span bridges, or structures located in regions of high seismic activity are notable exceptions, however.

As noted above, there are essentially only two basic conditions of equilibrium: linear and rotational. Linear equilibrium states that for an object to stay at rest, a straight push or a pull on the object in any direction in space must be balanced by a net equal force in exactly the opposite direction (this opposite force is referred to as an *equilibrant*). Rotational equilibrium refers to a similar balance of forces. In this case, however, a force that causes an object to *rotate* about a point must be balanced by an equal and opposite rotational tendency. To look at these conditions more closely, it is easiest to first visualize linear equilibrium.

4.2.1 Linear Equilibrium

Certain elementary conditions of linear equilibrium in simple structures can be easily visualized. An elevator hanging from a cable (Figure 4.1a) is supported by the pull of the cables; the cables, in turn, hang from the pulley at the top of the building.

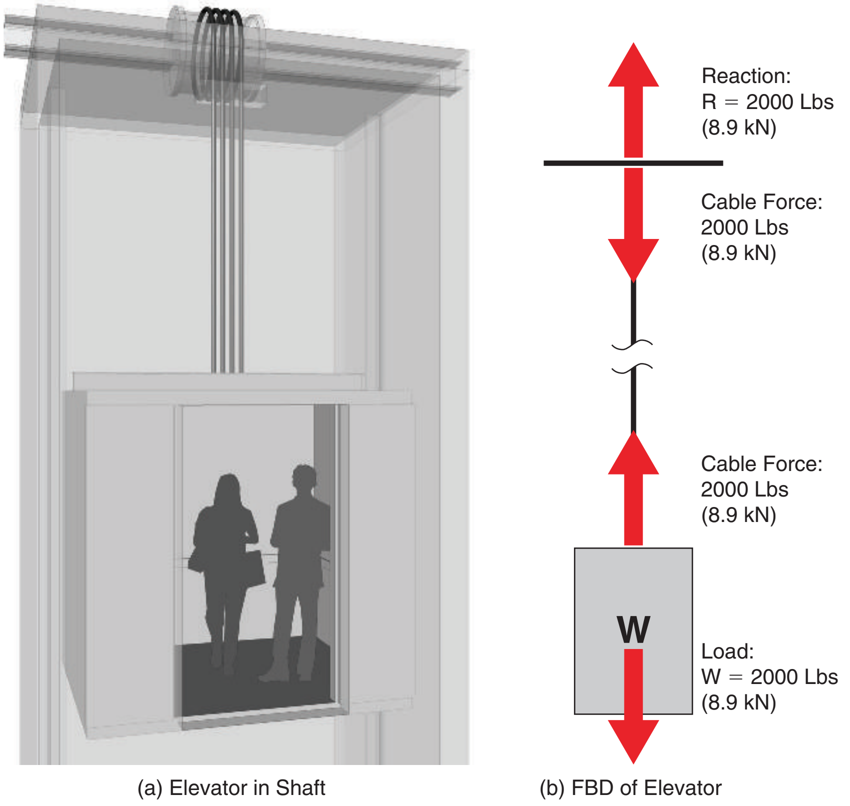


Figure 4.1 Free body diagram of elevator

A schematic representation of equilibrium called a *Free Body Diagram* (FBD) illustrates forces as vector arrows, typically with lengths proportional to the force magnitude. The FBD (4.1b) illustrates the equilibrium between acting and reacting forces on an object. In this illustration, the acting forces include the weight of the elevator itself as well as the live load of the occupants (*W*). The reacting force on the cables (*R*) must be equal and opposite for static equilibrium to exist.

Multiple cables support a traction elevator to both reduce the cable diameter and provide for greater safety. The four cables in this example would each carry ¼ of the total weight, or 500 pounds (2.2 kN) each. Notice that the cable forces appear to be *pushing* toward the center, which may at first appear to be compression. With respect to the load however, they point in the opposite direction *pulling away* from the elevator cab, and thus in tension. In a static condition, force actions and reactions always balance linearly.

If the elevator and its occupants weigh two thousand pounds (8.9 kN) and is at rest, the cable exerts on the elevator a pull of two thousand pounds (8.9 kN). The weight (i.e., *the downward force of gravity acting on an object*) of the elevator and the upward pull of the cable are equal and "balance out": the elevator is "in linear equilibrium" (Figure 4.1b). The simplified abstraction of this balance of forces, which uses vector arrows to represent the forces, is referred to as a *free body diagram*, (FBD), and is one of the most essential conceptual tools in engineering mechanics.

In another example, children pulling on a rope with total equal and opposite forces do not move: The rope is in horizontal linear equilibrium (Figure 4.2). But if one or more individual exerts a greater pull than the others, this will yank the opponents off their stands, and all individuals and the rope will move: Equilibrium is lost. Similarly, if a sculpture weighing 1000 pounds (4.5 kN) is set on a pedestal (Figure 4.3), the pedestal exerts an upward push of 1000 pounds (4.5 kN) on the sculpture. The pedestal weight of 2500 pounds (11.2 kN) *plus* the sculpture weight then apply a combined total load of 3500 pounds (15.7 kN) to the ground, distributed across the entire surface of the pedestal base. If the soil is soft and exerts a smaller upward push, the sculpture would move down, and there would be lack of linear equilibrium, and the principles of dynamic structures would come into play.

These elementary examples show that a body does not move in a certain direction if the forces applied to it in that direction balance out: A force exerted in a given direction must be opposed by an equal force exerted in the opposite direction. Whenever this happens, there is linear (or *translational*) equilibrium in that direction.

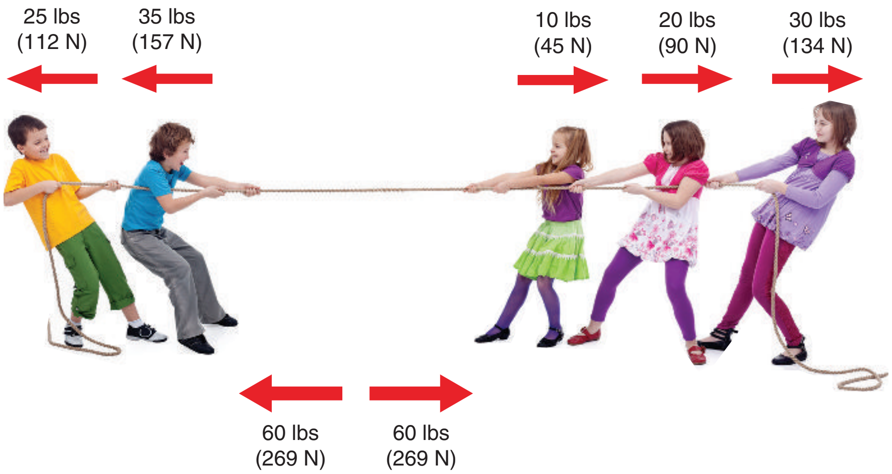
4.2.2 Rotational Equilibrium

Rotational equilibrium is an everyday experience. It is readily visualized by the familiar experience of a seesaw, which the reader may have personally had as a child. Two children of identical weight sitting at the end of a seesaw *at equal distances from the fulcrum* (i.e., pivot point) will place the seesaw into rotational equilibrium. The upward force at the pivot of the seesaw is in linear equilibrium with the combined weights of the two children and the board of the seesaw (though the forces are not along the same line, they are all vertical). We thus say that it "equilibrates vertically" the weights of the two children and "reacts" with an

Figure 4.2 A Tug-of-war

The rope being pulled on by the children is in linear equilibrium. So long as the *total force* exerted is the same magnitude but in opposite directions on each side, there will be linear equilibrium even when the children individually pull with different force magnitudes.

Photo: Ilike/Shutterstock



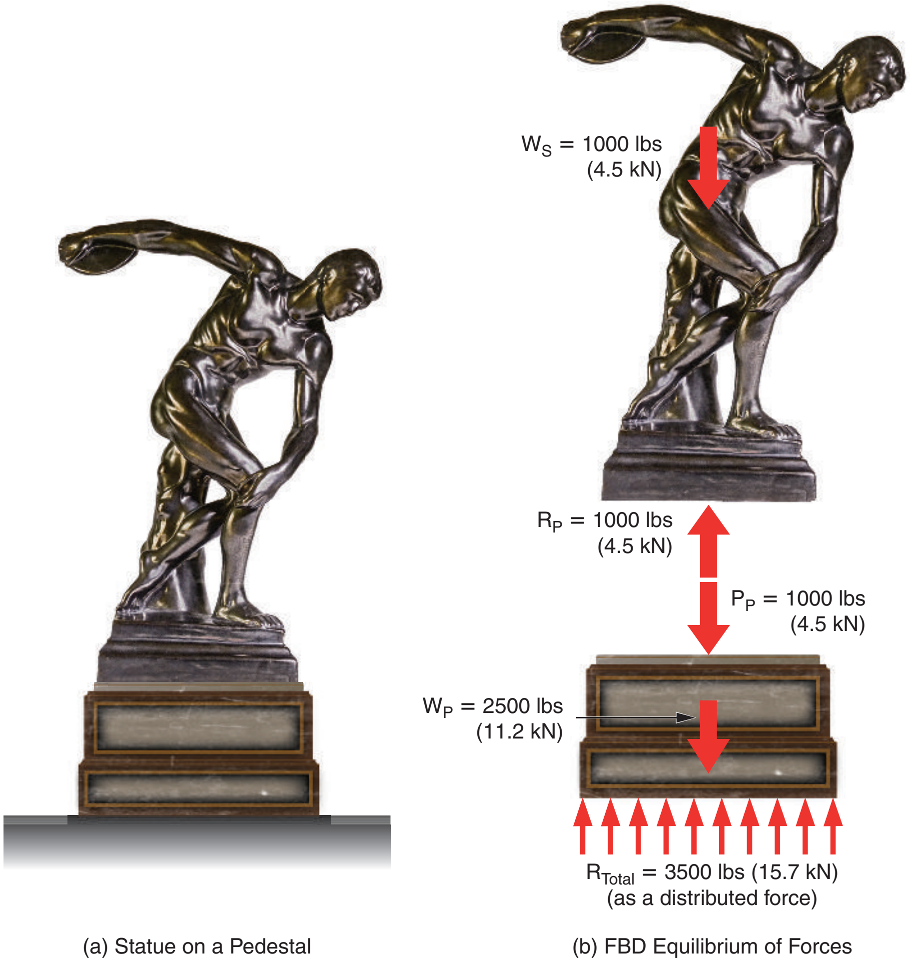


Figure 4.3 Equilibrium of vertical forces

Figure 4.3a shows a statue as it appears before us. Unseen are the forces at play internally. In the FBD of 4.3b, we see that the total weight of the statue (W_S) is supported by a reaction force at the statue pedestal (R_P) that is equal and opposite to that of the statue weight. This reaction force can then be considered as a load (P_P) of the same magnitude acting in the opposite direction on the pedestal itself. The weight of the pedestal (W_P) is then added to the load on the pedestal, the total reaction on the ground then being the sum of all components. This reaction at the bottom of the pedestal (R_{Total}) is distributed across the entire surface of the pedestal base. In reality, the weight of the sculpture on the top of the pedestal is also a distributed force, but shown here as a concentrated force for clarity.

upward push equal to their combined weight and that of the board. The supporting force is therefore known as a *reaction* (Figure 4.4 a).

The two children will also be balanced rotationally about the pivot point, and thus the board stays level. Rotational equilibrium breaks down, however, when the children sit at different distances from the point of support: The see-saw rotates in the direction of the child sitting farther away from the pivot (Figure 4.4 b). Such distances from points of support are called "lever arms." In order to guarantee "equilibrium in rotation" when the two children have equal weights, their lever arms must be equal. If the two children have different weights, equilibrium in rotation can still be obtained by giving the lighter child a larger lever arm and the heavier child a smaller lever arm.

Equilibrium in rotation requires that the weight times the length of the lever arm of each child have the same value (Figure 4.4 c) and tend to rotate the board in opposite directions. The product of a force multiplied by its lever arm is referred to as the ***moment of the force*** (Figure 4.5).

Such simple equilibrium principles apply to all structures. Equal and opposite forces guarantee linear equilibrium in a given direction, and equal and opposite moments (i.e., the products of forces times lever arms) guarantee equilibrium in

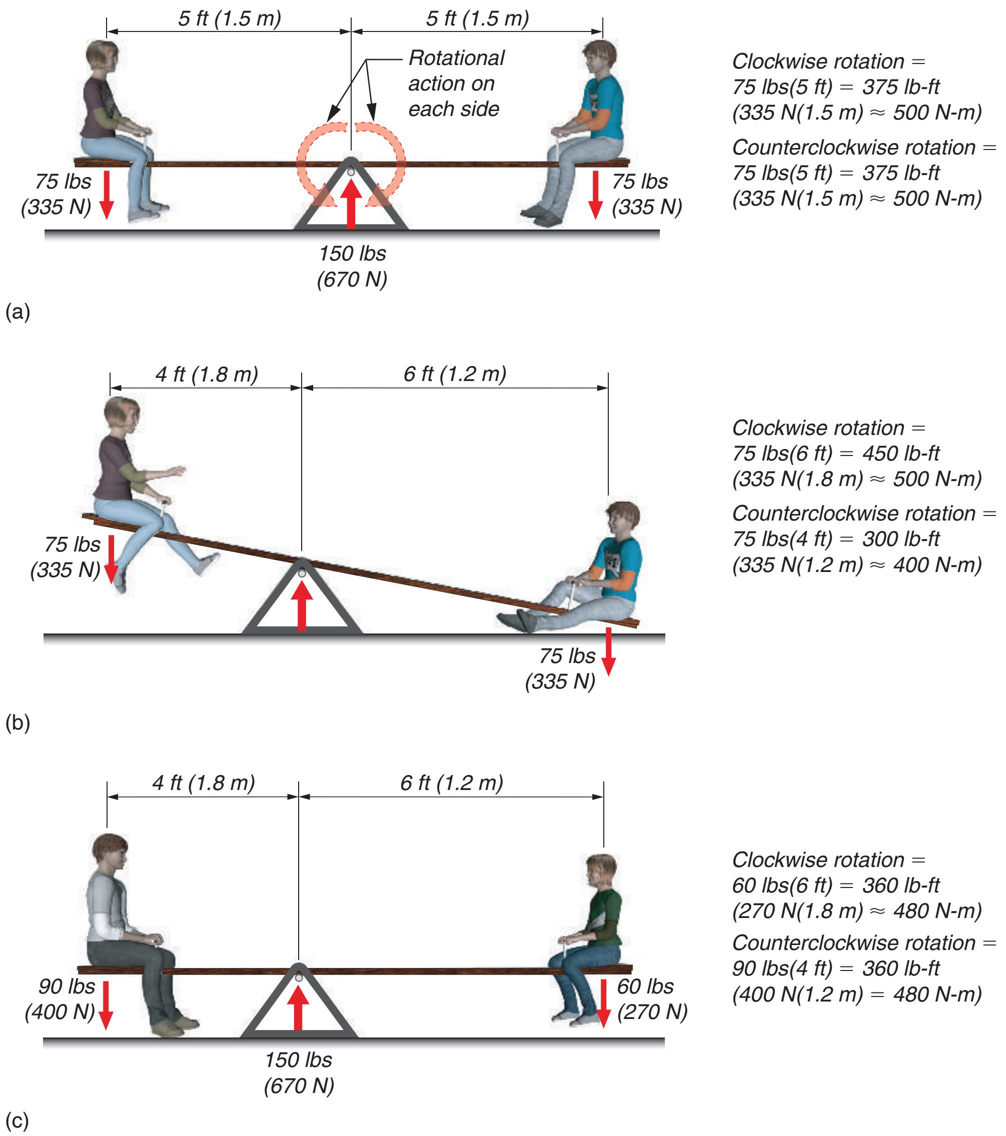


Figure 4.4 Rotational equilibrium

Two children on a see-saw can be seen as a system of rotational equilibrium—more conventionally known as *balance*. If the children weigh the same, then at equal distances they will have the same rotational tendency and thus balance out (4.4a). If one child sits farther away, rotational balance will be lost (4.4b). On the other hand, if an older/heavier child sits on the end, to achieve balance each child must sit at a different distance from the support, or the entire board must shift by the same amount to relocate the pivot off center (4.4c).