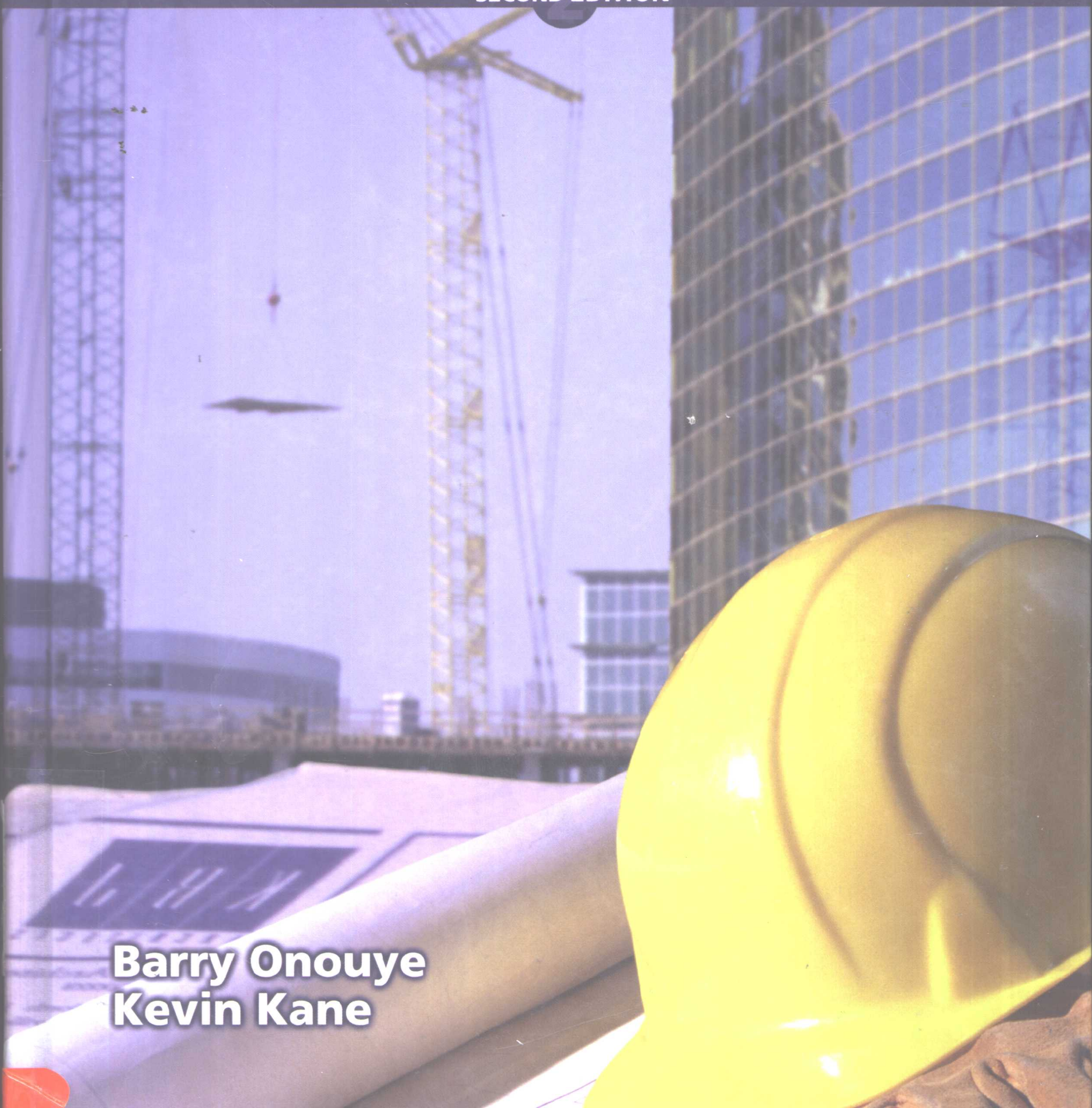
Statics and Strength of Materials for Architecture and Building Construction

SECOND EDITION



Barry Onouye
Kevin Kane

Statics and Strength of Materials for Architecture and Building Construction

Second Edition

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Foreword

I have had the privilege of teaching with Barry Onouye in a design studio setting for 12 years. From the outset, it was obvious that he had a sound knowledge of structures, but what also became apparent over time was his profound understanding of architectural structures—the structural systems that play a critical role in the planning, design, and making of buildings. He is an exceptional teacher, not only extremely knowledgeable but also able to explain principles and concepts in an articulate manner and to relate his reasoning to the problems and opportunities in architectural design and building construction. In the pages of this book, he has managed, along with Kevin Kane, to convey this same extraordinary teaching ability.

Statics and Strength of Materials for Architecture and Building Construction is a refreshing treatment of an enduring topic in architectural education. It combines in a single text the related fields of statics—the external force systems acting on structural elements—and strength of materials—the internal forces and deformations that result from external forces. Together, these classic areas of inquiry give rise to the size and shape of structural elements and the configuration of these elements into systems that unite and support the components and contents of a building.

Such systems underlie all buildings, from the monuments of the past to the most humble structures of the present. Whether visible to the eye or concealed by elements of enclosure, these three-dimensional frameworks occupy space and establish the nature and composition of the spaces within buildings. Even when obscured by the more discernible faces of floors, walls, and ceilings, their presence can often be sensed by the mind's eye. Thus, an understanding of structural theory and systems remains an essential component of architectural education.

Over the last century, numerous texts on building structures have been written for students of architecture and building construction. What distinguishes this work is its effective weaving of word and image. The problem for anyone teaching structures has always been to explain structural theories and concepts to design students, for whom graphic material can be more meaningful than numbers. The danger in a purely graphic approach, however, is the omission of the mathematical models necessary for a realistic and rigorous treatment of the science of structures. This text instead adopts the classical method of teaching of building structures and integrates visual information with the necessary mathematical models and essential structural principles and relates these concepts to real-world examples of architectural design in a coherent and illuminating manner. This wise and balanced approach to the subject of statics and strength of material should serve well both teachers and students of architectural structures.

Frank Ching

Preface

A primary aim of this book has been to develop and present basic structural concepts in an easily understood manner using "building" examples and illustrations to supplement the text. Much of this material has been field tested, revised, and modified over a course of 25 years of teaching.

Introducing structural theory, without relying on a predominantly mathematical treatment, has been challenging to say the least—and a non-calculus engineering alternative to the topic seemed essential if the target audience (students of architecture, building construction, and some engineering technology programs) were to remain interested. Early on it was decided that a heavily illustrated, visual approach was essential in connecting and linking structural theory to real buildings and components. Using examples and problems that are commonly found in buildings and structures around us seemed to be a logical way of introducing mathematically based material in a nonthreatening way.

This text is organized along the lines of traditional textbooks on statics and strength of materials because it seems to be the most logical approach. A sound understanding of statics and strength of materials establishes a theoretical and scientific basis for understanding structural theory. Numerical calculations are included as a way of explaining and testing one's understanding of the principles involved. Many fully worked example problems are included, with additional problems for student practice. An interesting, descriptive narrative of structural concepts may stimulate the student's interest in the subject matter, but it does not engage the student enough to ensure understanding.

This text is intended as the next step following a basic introductory course on structural principles (for example, Salvadori and Heller's *Structure in Architecture—The Building of Buildings*). Organizationally, the book consists of two parts: Statics in Chapters 2 through 4, and Strength of Materials covered in Chapters 5 through 10. Load Tracing in Chapter 4 is not customarily covered in statics, but was intentionally included to illustrate the power of the basic principle of mechanics and the use of free-body diagrams. Gravity and lateral load tracing are often covered in subsequent structures courses, but the fundamentals can be introduced at this stage without much anxiety on the student's part. Chapter 11 is included as a synthesis of the prior topics and summarizes some of the overall architectural, structural, and constructional issues outlined in the introduction to Chapter 1.

A heavy emphasis is placed on the use of free-body diagrams in understanding the forces acting on a structural member. All problems begin with a pictorial representation of a structural component or assembly and are accompanied by a free-body diagram. Illustrations are used extensively to ensure that the student sees the connection between the real object and its abstraction. Chapter 3 uses the principles discussed in the previous chapter to solve an array of determinate structural frameworks. Load tracing in Chapter 4 attempts to examine the overall structural condition with regard to gravity and lateral loads. This chapter illustrates the interaction of one member with other members and introduces the concept of load paths that develop within a building.

Chapter 5 introduces the concepts of stress and strain and material properties as they relate to materials commonly used in the building industry. The text would be greatly complemented by a course on the methods and materials of construction taken concurrently or before the strength of materials portion. Cross-sectional properties are covered in Chapter 6, again with an emphasis on commonly used beam and column shapes. Chapters 7, 8, and 9 develop the basis for beam and column analysis and design. Chapter 10 on steel connections has been added to this second edition to emphasize the importance of the interconnection of parts in creating a stable, functional, and economical structure. Elastic theory has been utilized throughout, and the allowable stress method has been employed for the design of beams and columns. Some simplifications have been introduced to beam and column design equations to eliminate the complexity unwarranted for preliminary design purposes. Sizing of beams and columns is well within the range of a final, closely engineered element sized by the more complex formulas. It is assumed that students will take subsequent courses in timber, steel, and concrete. Therefore, building code equations and criteria have not been incorporated in these chapters.

No attempt was made to include the study of indeterminate beams and frames since it would require substantial development beyond the purview of statics and strength of materials. Indeterminate structures is probably one of the more important structural topics for building designers since most of the commercial and institutional buildings of moderate size are of this type. Indeterminate structural behavior using one of the many available structural analysis software packages is emerging as a critical area of study for all future building designers.

This text is intended to be used for a one-semester (15-week) class or two 10-week quarters in architectural, building construction, and engineering technology programs. Chapters 4 and 10 might be of interest and use to the civil engineering student who wants to better understand building components in a larger context. Also, Chapters 8 and 9 might be useful for quick preliminary methods of sizing beams and columns. Although this text might be used for self-study, its real benefit is to supplement the instruction received in class.

Many of the topics covered in the text can be demonstrated in model form in class. Slides of actual buildings representing the subject being covered help to reinforce the idea through visual images. Previous teaching experience has been convincing about the need to use a variety of media and techniques to illustrate a concept. Structures should by no means be a "dry" subject.

Computers and the availability of powerful structural software for desktop and laptop computers have revolutionized the field of structural analysis and design. Most students enrolled in our programs are generally quite computer literate and expect extensive use of structural software in solving statics and strength of materials problems. However, it is this author's belief that the basic principles and numerical techniques used in this book are easily within the grasp and understanding of our students. A sound, fundamental working knowledge of free-body diagrams, equations of equilibrium, stress, strain, and bending equations are key to developing a mental framework for the understanding of structural behavior. Basic equations of equilibrium, although quantitative in nature, still evokes a qualitative, intuitive sense about a structure. Matrix-based computer programs are highly abstract and mathematical with little connectivity to real structures, except perhaps for the exceptionally gifted student.

Computers can certainly be used to supplement these early foundation structures courses and add to the student's understanding of structural behavior through the generation of graphically displayed output. Although there are many excellent structural analysis/design software packages available for purchase, reference will be made in selected sections of this book to *free* structural software of a limited nature accessible on the Internet.

As part of an ongoing effort by the United States to convert from the U.S. customary system of units to the international system of units (SI metric units), some example and practice problems in this text use the SI units. A table defining both the U.S. customary system of units and the SI metric units is included on page vii.

ACKNOWLEDGMENTS

I am indebted and grateful to a vast number of students over many years who have used the earlier versions of this text and generously given suggestions for changes and improvements.

In particular, this book would not be possible without the shared authorship of Kevin Kane and his skill and insightfulness illustrating the structural concepts. Kevin's major contributions, along with drawing and coordinating all of the illustrations, are evident in Chapters 4 and 10. Additional thanks to Cynthia Esselman, Murray Hutchins, and Gail Wong for drawing assistance that helped us meet deadlines.

Special acknowledgment and appreciation is given to Tim Williams and Loren Brandford for scanning and typing assistance; Robert Albrecht for reviewing the earlier manuscript; Ed Lebert for some of the practice problems; Chris Countryman for proofreading the problems and solutions; Bert Gregory and Jay Taylor for providing information pertinent to Chapter 10; and Elga Gemst, a teaching assistant from long ago, for helping me prepare the original strength of materials sections and the biographies of famous thinkers of the past. Thanks also go to the reviewers of this edition: Robert W. Aderholdt, Auburn University; David Bilbo, Texas A&M University; and Madan Mehta, University of Texas, Arlington; and our senior editor at Prentice Hall, Ed Francis. Finally, thanks to a friend and colleague, Frank Ching, who encouraged us to pursue this project. He has served as a mentor and role model for many of us who teach here at the University of Washington.

A warm and sincere thanks to our families for their support and sacrifice throughout this process. Thank you Yvonne, Jacob, Qingyu, Jake, Amia, and Aidan.

Barry Onouye

Definition of Terms

Measurement	U.S. Units	Metric (SI)
a measure of length	inch (in. or ″)	millimeter (mm)
	feet (ft. or ′)	meter (m)
a measure of area	square inches (in.^{2})	square millimeters (mm^2)
	square feet (ft.^{2})	square meters (m^2)
a measure of mass	pound mass (lbm)	kilogram (kg)
a measure of force	pound (lb. or #)	newton (N)
	kilopound = 1,000 lb. (k)	kilonewton = 1,000 N (kN)
a measure of stress (force/area)	psi (lb./in.^{2} or #/in.^{2})	pascal (N/m^2)
	ksi (k/in.^{2})	
a measure of pressure	psf (lb./ft.^{2} or #/ft.^{2})	kilopascal = 1,000 Pa
moment (force × distance)	pound-feet (lb.-ft. or #-ft.)	newton-meter (N-m)
	kip-feet (k-ft.)	kilonewton-meter (kN-m)
a load distributed over length	ω (lb./ft., #/ft., or plf)	ω (kN/m)
density (weight/volume)	γ (lb./ft.^{3} or #/ft.^{3})	γ (kN/m^3)

force = (mass) × (acceleration); acceleration due to gravity: 32.17 ft./sec.^{2} = 9.807 m/sec.^{2}

Conversions

1 m = 39.37 in.	1 ft. = 0.3048 m
1 m^2 = 10.76 ft.^{2}	1 ft.^{2} = 92.9 × 10^{-3} m^2
1 kg = 2.205 lb.-mass	1 lbm = 0.4536 kg
1 kN = 224.8 lb.-force	1 lb. = 4.448 N
1 kPa = 20.89 lb./ft.^{2}	1 lb./ft.^{2} = 47.88 Pa
1 MPa = 145 lb./in.^{2}	1 lb./in.^{2} = 6.895 kPa
1 kg/m = 0.672 lbm/ft.	1 lbm/ft. = 1.488 kg/m
1 kN/m = 68.52 lb./ft.	1 lb./ft = 14.59 N/m

Prefix	**Symbol**	**Factor**
giga	G	10^9 or 1,000,000,000
mega	M	10^6 or 1,000,000
kilo	k	10^3 or 1,000
milli	m	10^{-3} or 0.001

Contents

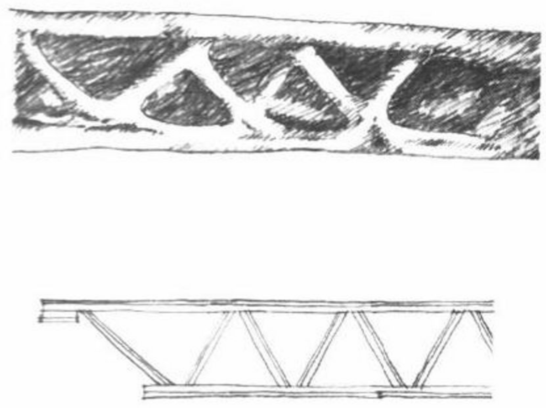

Figure 1.3 *Metacarpal bone from a vulture wing and an open-web steel truss with web members in the configuration of a Warren Truss.*

Buildings, like any other physical entity, require structural frameworks to maintain their existence in a recognizable physical form.

To structure also means *to build*—to make use of solid materials (timber, masonry, steel, concrete) in such a way as to assemble an interconnected whole that creates space suitable to a particular function or functions and to protect the internal space from undesirable external elements.

A structure, whether large or small, must be stable and durable, must satisfy the intended function(s) for which it was built, and must achieve an economy or efficiency—that is, maximum results with the minimum means (see Figure 1.3). As stated in Sir Isaac Newton's *Principia*:

> *Nature does nothing in vain, and more is in vain when less will serve; for Nature is pleased with simplicity, and affects not the pomp of superfluous causes.*

1.2 STRUCTURAL DESIGN

Structural design is essentially a process involving the balancing between applied forces and the materials that resist these forces. Structurally, a building must never collapse under the action of assumed loads, whatever they may be. Furthermore, tolerable deformation of the structure or its elements should not cause material distress or psychological harm. Good structural design is more related to correct intuitive sense than to sets of complex mathematical equations. Mathematics should be merely a convenient and validating tool by which the designer determines the physical sizes and proportions of the elements to be used in the intended structure.

The general procedure of designing a structural system (called *structural planning*) consists of the following phases:

- Conceiving of the basic structural form.
- Devising the gravity and lateral force resisting strategy.
- Roughly proportioning the component parts.
- Developing a foundation scheme.
- Determining the structural materials to be used.
- Detailed proportioning of the component parts.
- Devising a construction methodology.

After all of the separate phases have been examined and modified in an iterative manner, the structural elements within the system are then checked mathematically by the structural consultant to ensure the safety and economy of the structure. The process of conceiving and visualizing a structure is truly an art.

There are no sets of rules one can follow in a linear manner to achieve a so-called "good design." The iterative approach is most often employed to arrive at a design solution. Nowadays, with the design of any large structure involving a team of designers working jointly with specialists and consultants, the architect is required to function as a coordinator and still maintain a leadership role even in the initial structural scheme. The architect needs to have a broad general understanding of the structure with its various problems and must also sufficiently understand the fundamental principles of structural behavior to provide useful approximations of member sizes. The structural principles influence the form of the building, and a logical solution (often an economical one as well) is always based on a correct interpretation of these principles. A responsibility of the builder (constructor) is to have the knowledge, experience, and inventiveness to resolve complex structural and constructional issues without losing sight of the spirit of the design.

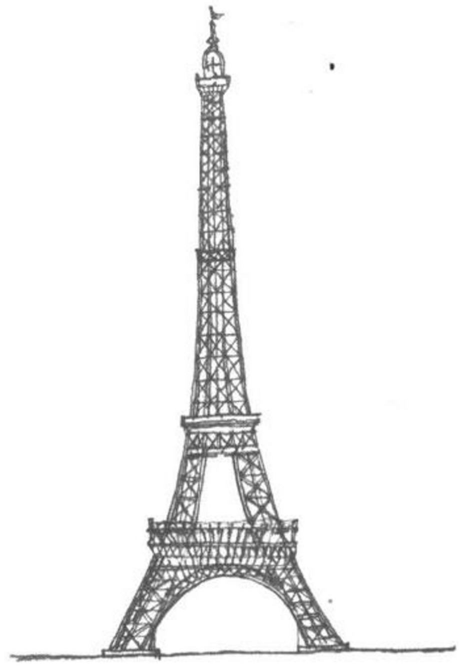

Figure 1.4 Eiffel Tower.

A structure need not actually collapse to be lacking in integrity. For example, a structure indiscriminantly employing inappropriate materials or an unsuitable size and proportion of elements would reflect disorganization and a sense of chaos. Similarly, a structure carelessly overdesigned would lack truthfulness and reflect a wastefulness that seems highly questionable in our current world situation of rapidly diminishing resources.

> *It can be said that in these works (Gothic Cathedrals, Eiffel Tower, Firth of Forth Bridge), forerunners of the great architecture of tomorrow, the relationship between technology and aesthetics that we found in the great buildings of the past has remained intact. It seems to me that this relationship can be defined in the following manner: the objective data of the problem, technology and* **statics** *(empirical or scientific), suggest the solutions and forms; the aesthetic sensitivity of the designer, who understands the intrinsic beauty and validity, welcomes the suggestion and models it, emphasizes it, proportions it, in a personal manner which constitutes the artistic element in architecture.*

Quote from Pier Luigi Nervi, *Aesthetics and Technology in Architecture*, MIT Press. (See Figures 1.4 and 1.5.)

Figure 1.5 Nave of Reims Cathedral, construction begun in 1211.

1.3 PARALLELS IN NATURE

There is a fundamental "rightness" in the structurally correct concept, leading to an economy of means. Two kinds of "economy" are present in buildings. One such economy is based on expediency, availability of materials, cost, and constructibility. The other "inherent" economy is dictated by the laws of nature. (See Figure 1.6.)

Figure 1.6 Tree—a system of cantilevers.

In his wonderful book *On Growth and Form*, D'Arcy Wentworth Thompson describes how Nature, as a response to the action of forces, creates a great diversity of forms from an inventory of basic principles. Thompson says that

> *. . . in short, the form of an object is a diagram of forces; in this sense, at least, that from it we can judge of or deduce the forces that are acting or have acted upon it; in this strict and particular sense, it is a diagram.*

The form as a diagram is an important governing idea in the application of the principle of *optimization* (maximum output for minimum energy). Nature is a wonderful venue to observe this principle, since survival of a species depends on it. An example of optimization is the honeycomb of the bee (Figure 1.7). This system, an arrangement of hexagonal cells, contains the greatest amount of honey with the least amount of beeswax and is the structure that requires the least energy for the bees to construct.

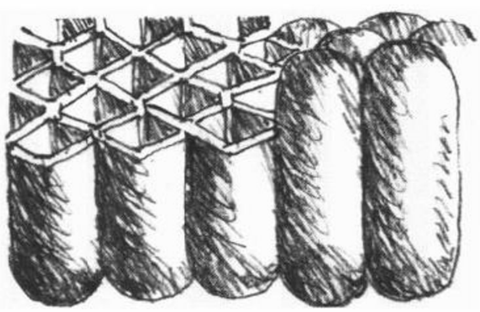

Figure 1.7 Beehive—cellular structure.

Galileo Galilei (sixteenth century), in his observation of animals and trees, postulated that growth was maintained within a relatively tight range—that problems with the organism would occur if it were too small or too large. In his *Dialogues Concerning Two New Sciences*, Galileo hypothesizes that:

> *. . . it would be impossible to build up the bony structures of men, horses, or other animals so as to hold together and perform their normal functions if these animals were to be increased enormously in height; for this increase in height can be accomplished only by employing a material which is harder and stronger than usual, or by enlarging the size of the bones, thus changing their shape until the form and appearance of the animals suggest monstrosity. . . . If the size of a body be diminished, the strength of that body is not diminished in the same proportion; indeed, the smaller the body the greater its relative strength. Thus a small dog could probably carry on its back two or three dogs of his own size; but I believe that a horse could not carry even one of his own size.*

Economy in structure does not just mean frugality. Without the economy of structure, neither a bird nor an airplane could fly, for their sheer weight would crash them to earth. Without economy of materials, the dead weight of a bridge could not be supported. Reduction in dead weight of a structure in nature involves two factors. Nature uses materials of fibrous cellular structure (as in most plants and animals) to create incredible strength-to-weight ratios. In inert granular material such as an eggshell, it is often used with maximum economy in relation to the forces that the structure must resist. Also, structural forms (like a palm leaf, a nautilus shell, or a human skeleton) are designed in cross section so that the minimum of material is used to develop the maximum resistance to forces (see Figure 1.8).

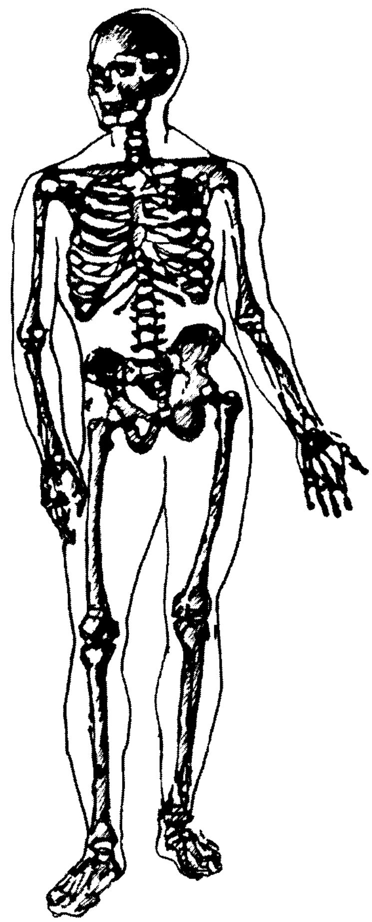

Figure 1.8 Human body and skeleton.

Nature creates slowly through a process of trial and error. Living organisms respond to problems and a changing environment through adaptations over a long period of time. Those that do not respond appropriately to the environmental changes simply perish.

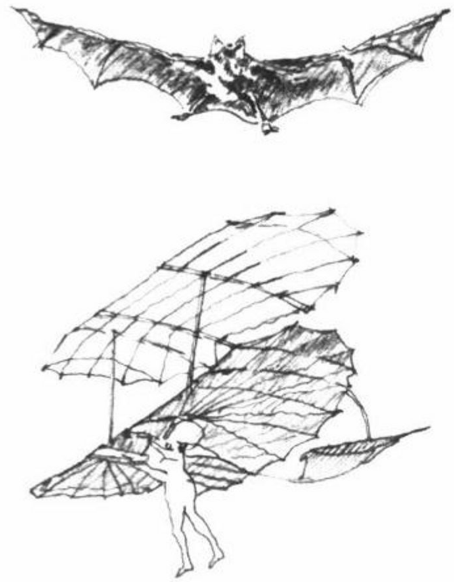

Figure 1.9 Flying structures—a bat and Otto Lilienthal's hang glider (1896).

Historically, human development in the area of structural forms has also been slow (Figure 1.9). For the most part, limited materials and knowledge restricted the development of new structural elements or systems. Even within the last 150 years or so new structural materials for buildings have been relatively scarce—steel, reinforced concrete, prestressed concrete, composite wood materials, and aluminum alloys. These materials have brought about a revolution in structural design and are currently being tested to their material limit by engineers and architects. Some engineers believe that most of the significant structural systems are known. Therefore, the future lies in the development of new materials and the exploitation of known materials in new ways.

Advances in structural analysis techniques, especially with the advent of the computer, have enabled designers to explore very complex structures (Figures 1.10 and 1.11) under an array of loading conditions much more rapidly and accurately than in the past. However, the computer is still being used as a tool to validate the intent of the designer and is not yet capable of actual "design." A human designer's knowledge, creativity, and understanding of how a building structure is to be configured are still essential for a successful project.

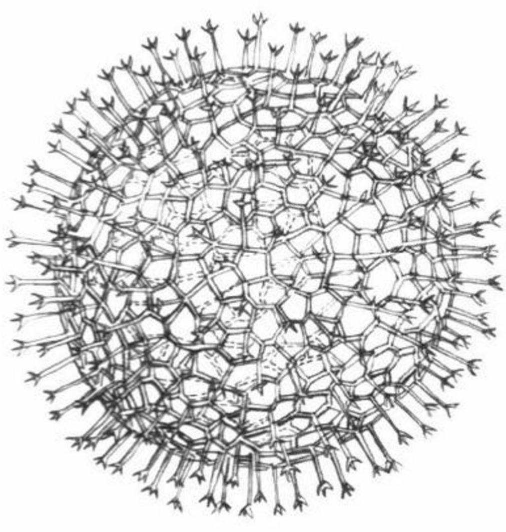

Figure 1.10 The skeletal latticework of the radiolarian (aulasyrum triceros) *consists of hexagonal prisms in a spherical form.*

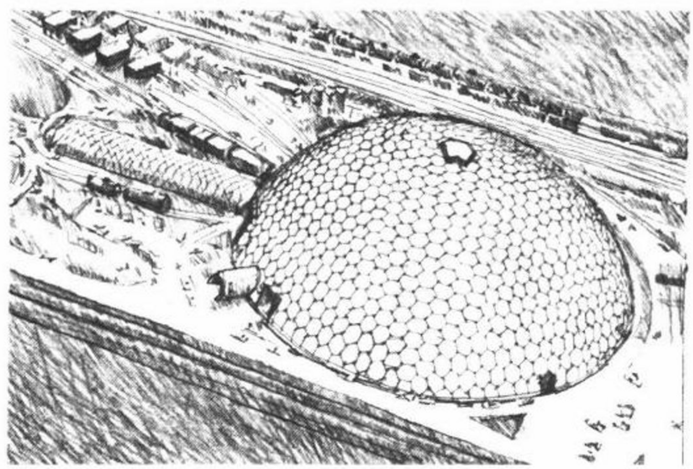

Figure 1.11 Buckminster Fuller's Union Tank Car dome, a 384-ft.-diameter geodesic dome.

1.4 LOADS ON STRUCTURES

Structural systems, aside from their form-defining function, essentially exist to resist forces that result from two general classifications of loads:

1. **Static.** This classification refers to gravity-type forces.
2. **Dynamic.** This classification is due to inertia or momentum of the mass of the structure (like earthquakes). The more sudden the starting or stopping of the structure, the greater the force will be.

***Note:** Other dynamic forces are produced by wave action, landslides, falling objects, shocks, blasts, vibration from heavy machinery, etc.*

A light, steel frame building may be very strong in resisting static forces, but a dynamic force may cause large distortions to occur because of the frame's flexible nature. On the other hand, a heavily reinforced concrete building may be as strong as the steel building in carrying static loads but may have considerable stiffness and sheer dead weight, which may absorb the energy of dynamic forces with less distortion (*deformation*).

All of the following forces must be considered in the design of a building structure (see Figure 1.12).

- **Dead loads.** Static, fixed loads that include building structure weight, exterior and interior cladding, flooring, and fixed equipment. When activated by earthquake, static dead loads take on a dynamic nature in the form of inertial forces.
- **Live loads.** Transient and moving loads that include occupancy loads, furnishings, and storage. Live loads are extremely variable by nature and normally change during a structure's lifetime as occupancy changes. Building codes specify minimum uniform live loads for the design of roof and floor systems based on a history of many buildings and types of occupancy conditions. They incorporate safety provisions for overload protection, allowance for construction loads, and serviceability considerations (such as vibration and deflection behavior). Minimum roof live loads include allowance for minor snowfall and construction loads. Snow load is often considered a special type of live load because it is so variable. To determine snow loads, local building officials or building codes must be consulted.

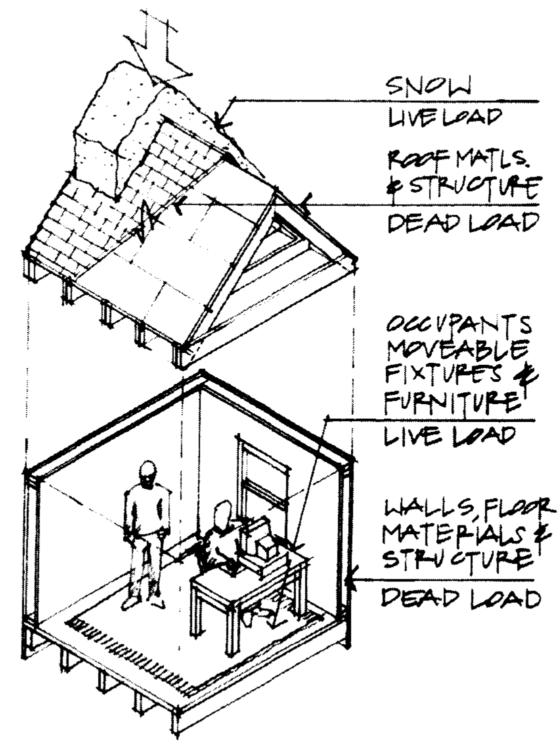

Figure 1.12 Typical building loads.

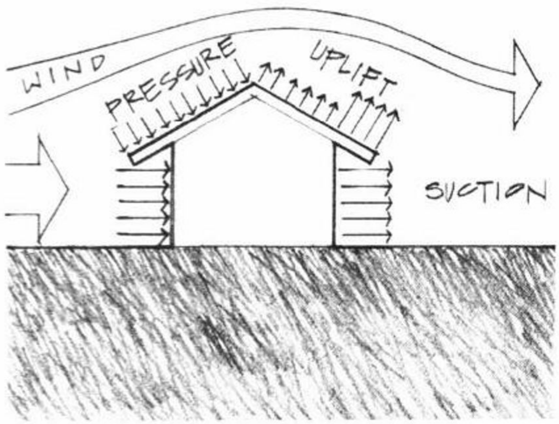

Figure 1.13 Wind loads on a structure.

- **Wind loads.** Wind loading on buildings is dynamic in nature. Wind pressures, directions, and duration are constantly changing. However, for calculation purposes, most wind design assumes a static force condition. Resulting wind pressures are treated as lateral loading on walls and in downward pressure or uplift forces on roof planes. Design wind pressures depend on several variables: wind velocity, height of the wind above ground (wind velocities are lower near the ground), and the nature of the building's surroundings. Other buildings, trees, and topography affect how the wind will strike the building. (See Figure 1.13.)

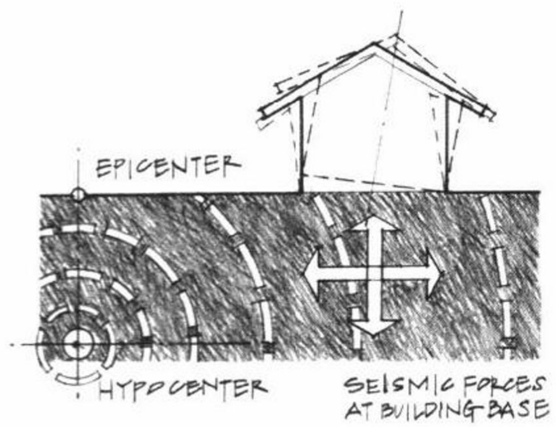

Figure 1.14 Earthquake loads on a structure.

- **Earthquake loads** *(seismic).* Inertial forces develop in the structure due to its weight, configuration, building type, and geographic location. Earthquake, like wind, produces a dynamic force on a building. Inertial forces developed in the structure are a function of the building's mass, configuration, building type, height, and geographic location. During an earthquake, the ground mass moves suddenly both vertically and laterally. The lateral movements are of particular concern to building designers. For some tall buildings or structures with complex configurations or unusual massing, a dynamic structural analysis is required. Computers are used to simulate earthquakes on the building to study how the forces are developed and the response of the structure to these forces. In most cases, however, building codes allow an equivalent static analysis of the loads produced, greatly simplifying the structural design for more conventional structures. (See Figure 1.14.) For a comprehensive resource of information regarding earthquakes and the damage to structures caused by earthquakes, see:

  http://www.eerc.berkeley.edu/

Except for a building's dead load, which is fixed, the other forces listed above can vary in duration, magnitude, and point of application. A building structure must nevertheless be designed for these possibilities. Unfortunately, a large portion of a building structure exists for loads that may never occur or will be present at much lower magnitudes.

Dead loading represents the weight of materials required in the building. The structural efficiency of a building is measured by its dead load weight in comparison to the live load carried.

Building designers have always strived to reduce the ratio of dead to live load. New methods of design, new and lighter materials, and old materials used in new ways have contributed to the dead/live load reduction.

The size of the structure has an influence on the ratio of dead to live load. A small bridge over a creek, for example, can carry a heavy vehicle—a live load representing a large portion of the dead/live load ratio. The San Francisco Golden Gate Bridge, on the other hand, spans a long distance, and the material of which it is composed is used chiefly in carrying its own weight. The live load of the vehicular traffic has a relatively small effect on the bridge's internal stresses.

With the use of modern materials and construction methods, it is often the smaller rather than the larger buildings that show a high dead-to-live load ratio. In a traditional house, the live load (LL) is low, and much of the dead load (DL) not only supports itself but also serves as weather protection and space-defining systems. This represents a high DL/LL ratio. In contrast, in a large factory building, the dead load is nearly all structurally effective, and the DL/LL ratio is low.

The dead/live load ratio has considerable influence on the choice of structure and especially on the choice of beam types. As spans increase, so do the bending effects caused by dead and live loads; therefore, more material must be introduced into the beam in order to resist the increased bending effects. This added material weight itself adds further dead load and pronounced bending effects as spans increase. The DL/LL ratio not only increases but may eventually become extremely large.