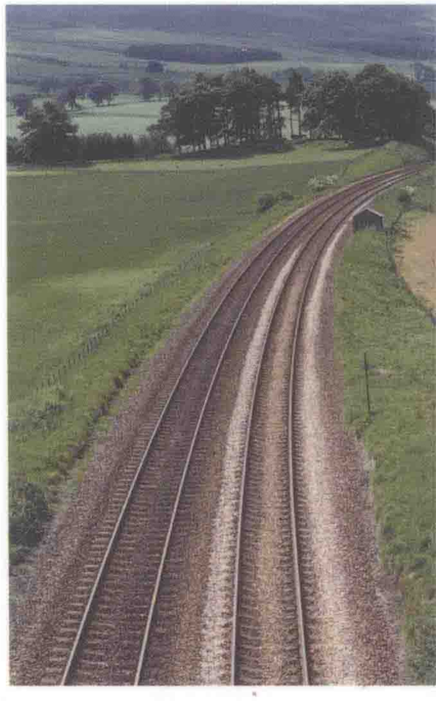
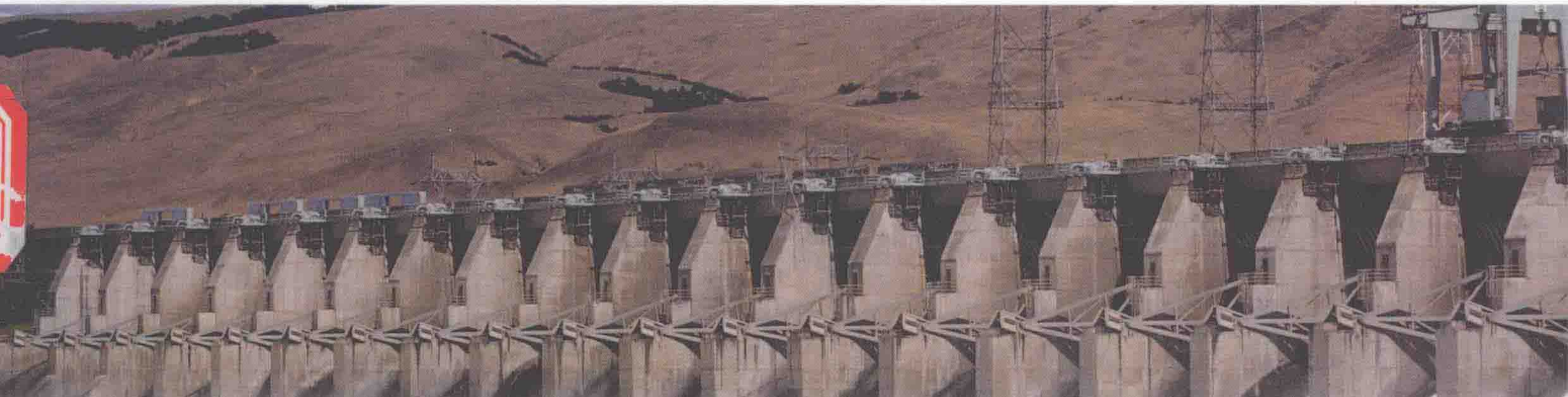



Pearson New International Edition

Statics and Strength of Materials for Architecture and Building Construction

Barry S. Onouye Kevin Kane

Fourth Edition

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Statics and Strength of Materials for
Architecture and Building Construction
Barry S. Onouye Kevin Kane
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ISBN 10: 1-292-02707-X
ISBN 13: 978-1-292-02707-4

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Printed in the United States of America

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Introduction

1 DEFINITION OF STRUCTURE

Structure is defined as something made up of interdependent parts in a definite pattern of organization (Figures 1 and 2)—an interrelation of parts as determined by the general character of the whole. Structure, particularly in the natural world, is a way of achieving the most strength from the least material through the most appropriate arrangement of elements within a form suitable for its intended use.

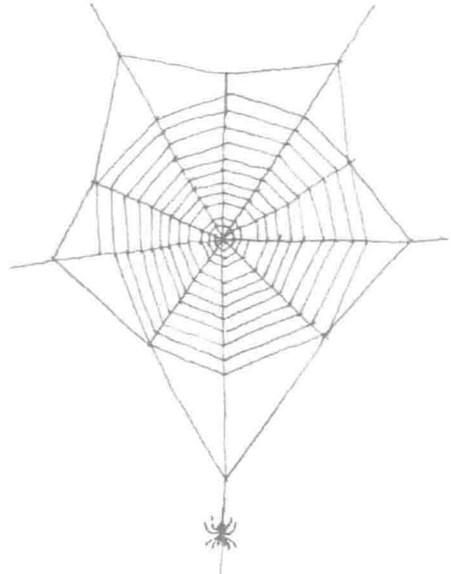


Figure 1 Radial, spiral pattern of the spider web.

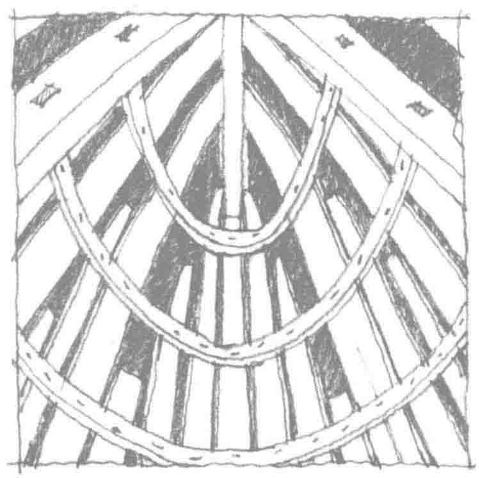


Figure 2 Bow and lattice structure of the currach, an Irish workboat. Stresses on the hull are evenly distributed through the longitudinal stringers, which are held together by steam-bent oak ribs.

The primary function of a building structure is to support and redirect loads and forces safely to the ground. Building structures are constantly withstanding the forces of wind, the effects of gravity, vibrations, and sometimes even earthquakes.

The subject of structure is all-encompassing; everything has its own unique form. A cloud, a seashell, a tree, a grain of sand, the human body—each is a miracle of structural design.

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 minimum means (Figure 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.*

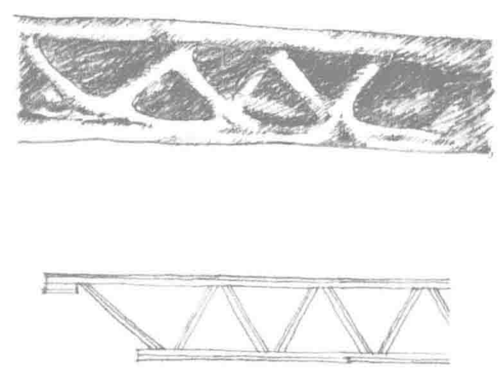


Figure 3 Metacarpal bone from a vulture wing and an open-web steel truss with web members in the configuration of a Warren Truss.

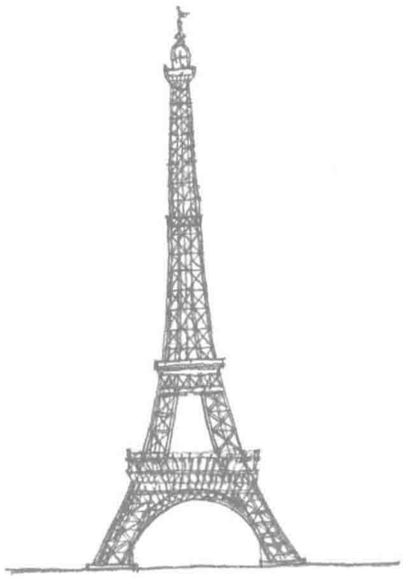


Figure 4 Eiffel Tower.

2 STRUCTURAL DESIGN

Structural design is essentially a process that involves 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.

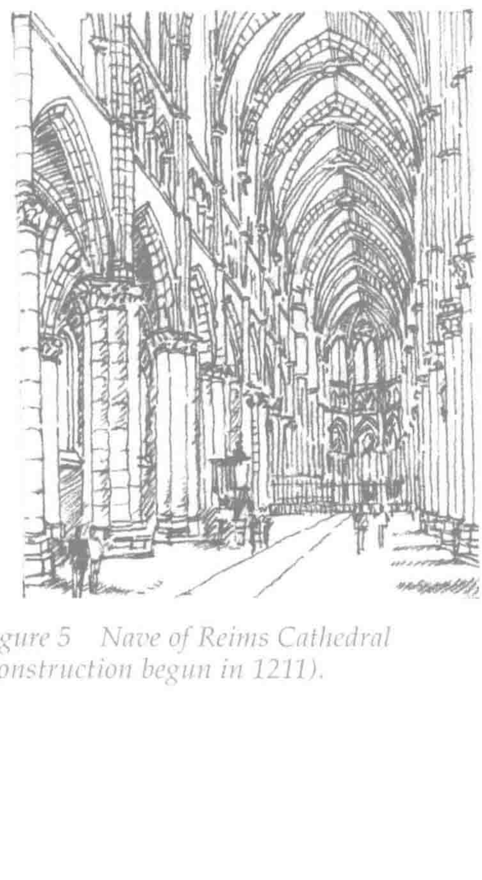


Figure 5 Nave of Reims Cathedral (construction begun in 1211).

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 a sufficient understanding of 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.

A structure need not actually collapse to be lacking in integrity. For example, a structure indiscriminately 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,* Harvard University Press; Cambridge, Massachusetts, 1966. (See Figures 4 and 5.)

Figure 6 Tree—a system of cantilevers.

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 constructability. The other "inherent" economy is dictated by the laws of nature (Figure 6).

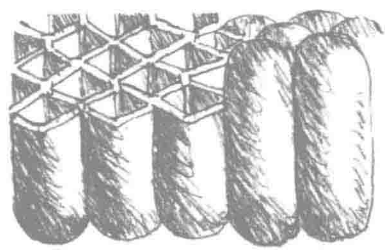


Figure 7 Beehive—cellular structure.

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, because survival of a species depends on it. An example of optimization is the honeycomb of the bee (Figure 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.

Galileo Galilei (16th 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

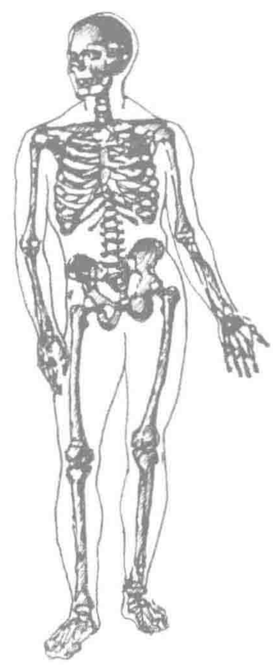


Figure 8 Human body and skeleton.

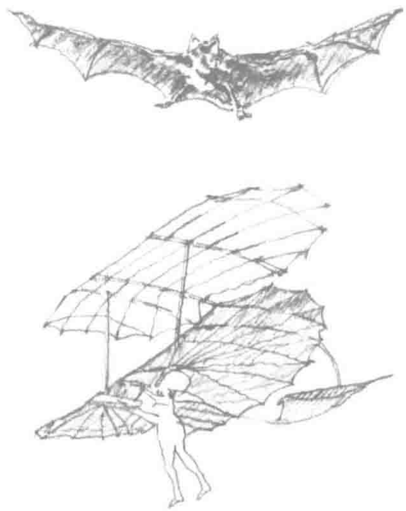


Figure 9 Flying structures—a bat and Otto Lilienthal's hang glider (1896).

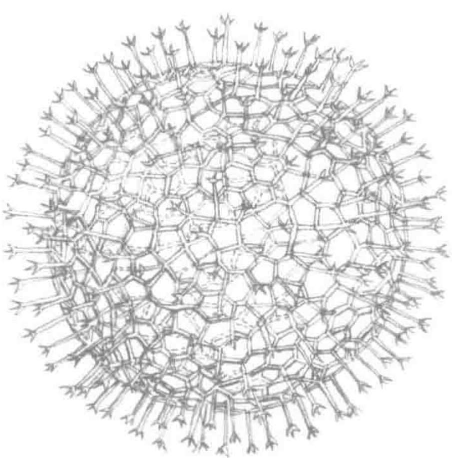


Figure 10 The skeletal latticework of the radiolarian (Aulasyrum triceros) consists of hexagonal prisms in a spherical form.

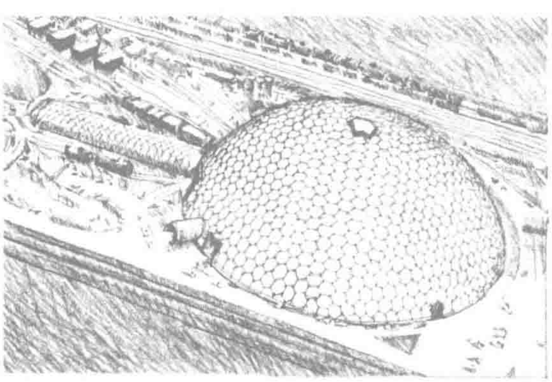


Figure 11 Buckminster Fuller's Union Tank Car dome, a 384-ft.-diameter geodesic dome.

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 (Figure 8).

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.

Historically, human development in the area of structural forms has also been slow (Figure 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. However, 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 and, therefore, that 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 10 and 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.

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, and so on.*

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 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 (Figure 12).

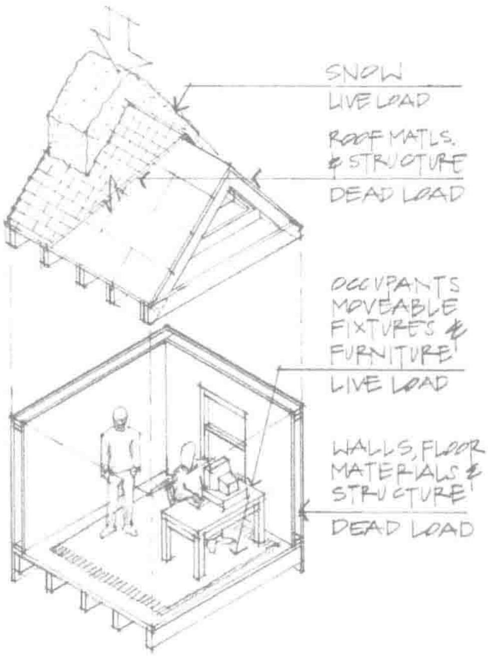


Figure 12 Typical building loads.

- **Dead Loads.** Loads resulting from the self-weight of the building or structure and of any permanently attached components, such as partition walls, flooring, framing elements, and fixed equipment, are classified as dead loads. Standard weights of commonly used materials for building are known, and a complete building's dead weight can be calculated with a high degree of certainty. However, the weight of structural elements must be estimated at the beginning of the design phase of the structure and then refined as the design process proceeds toward completion. A sampling of some standard building material weights used for the initial structural design process is:

  concrete = 150 pounds per cubic foot (pcf)
  timber = 35 pcf
  steel = 490 pcf
  built-up roofing = 6 pounds per square foot (psf)
  half-inch gypsum wallboard = 1.8 psf
  plywood, per inch of thickness = 3 psf
  suspended acoustical ceiling = 1 psf

  When activated by earthquake, static dead loads take on a dynamic nature in the form of horizontal inertial forces. Buildings with heavier dead loads generate higher inertial forces that are applied in a horizontal direction.

- **Live Loads.** Transient and moving loads that include occupancy loads, furnishings, and storage are classified as live loads. 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. These codes 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. (See Table 2 for an additional listing of common live loads for buildings.)

- **Snow Loads.** Snow loads represent a special type of live load because of the variability involved. Local building officials or applicable building codes prescribe the design snow for a specific geographical jurisdiction. Generally, snow loads are determined from a zone map reporting 50-year recurrence intervals of an extreme snow depth. Snow weights can vary from approximately 8 pcf for dry powder snow to 12 pcf for wet snow (Figure 13). Design loads can vary from 10 psf on a horizontal surface to 400 psf in some specific mountainous regions. In many areas of the United States, design snow loads can range from 20 to 40 psf.

  The accumulation depth of the snow depends on the slope of the roof. Steeper slopes have smaller accumulations. Special provisions must also be made for potential accumulation of snow at roof valleys, parapets, and other uneven roof configuration.


DB Auer/EPA/Newscom

Figure 13 Failure from snow load.

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 will be present at much lower magnitudes—or may never occur at all.

The structural efficiency of a building is often 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 Golden Gate Bridge in San Francisco, 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/live load ratio. In a traditional house, the live load is low, and much of the dead load not only supports itself but also serves as weather protection and space-defining systems. This represents a high dead/live load ratio. In contrast, in a large factory building, the dead load is nearly all structurally effective, and the dead/live load 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 to resist the increased bending effects. This added material weight itself adds further dead load and pronounced bending effects as spans increase. The dead/live load ratio not only increases but may eventually become extremely large.

- **Wind Loads.** Wind is essentially air in motion and creates a loading on buildings that is dynamic in nature. When buildings and structures become obstacles in the path of wind flow, the wind's kinetic energy is converted into potential energy of pressure on various parts of the building. Wind pressures, directions, and duration are constantly changing. However, for calculation purposes, most wind design assumes a static force condition for more conventional, lower rise buildings. The fluctuating pressure caused by a constantly blowing wind is approximated by a *mean pressure* that acts on the windward side (the side facing the wind) and leeward side (the side opposite the windward side) of the structure. The "static" or nonvarying external forces are applied to the building structure and simulate the actual varying wind forces.

  Direct 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. Wind pressure on a building varies as the square of the velocity (in miles per hour). This pressure is also referred to as the *stagnation pressure.*

  Buildings respond to wind forces in a variety of complex and dynamic ways. The wind creates a negative pressure, or suction, on both the leeward side of the building and on the side walls parallel to the wind direction (Figure 14). Uplift pressure occurs on horizontal or sloping roof surfaces. In addition, the corners, edges, and eave overhangs of

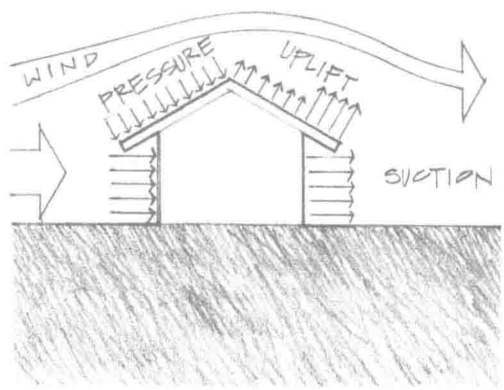


Figure 14 Wind loads on a structure.

a building are subjected to complicated forces as the wind passes these obstructions, causing higher localized suction forces than generally encountered on the building as a whole.

Wind is a fluid and acts like other fluids—a rough surface causes friction and slows the wind velocity near the ground. Wind speeds are measured at a standard height of 10 meters (33 feet) above the ground, and adjustments are made when calculating wind pressures at higher elevations. The wind pressure increases with the height of the building. Other buildings, trees, and topography affect how the wind will strike the building. Buildings in vast open areas are subject to larger wind forces than are those in sheltered areas or where a building is surrounded by other buildings. The size, shape, and surface texture of the building also impact the design wind forces. Resulting wind pressures are treated as lateral loading on walls and as downward pressure or uplift forces (suction) on roof planes.

- **Earthquake Loads** (*seismic*). Earthquakes, like wind, produce a dynamic force on a building. During an actual earthquake, there are continuous ground motions that cause the building structure to vibrate. The dynamic forces on the building are a result of the violent shaking of the ground generated by seismic shock waves emanating from the center of the fault (the *focus* or *hypocenter*) (Figure 15). The point directly above the *hypocenter* on the earth's surface is known as the *epicenter*. The rapidity, magnitude, and duration of these shakes depend on the intensity of the earthquake.

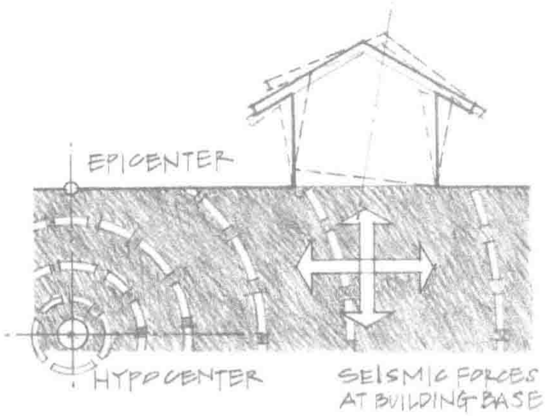


Figure 15 Earthquake loads on a structure.

During an earthquake, the ground mass suddenly moves both vertically and laterally. The lateral movements are of particular concern to building designers. Lateral forces developed in the structure are a function of the building's mass, configuration, building type, height, and geographic location. The force from an earthquake is initially assumed to develop at the base of the building; the force being known as the base shear (V_{base}). This base shear is then redistributed equal and opposite at each of the floor levels where the mass of the building is assumed concentrated.

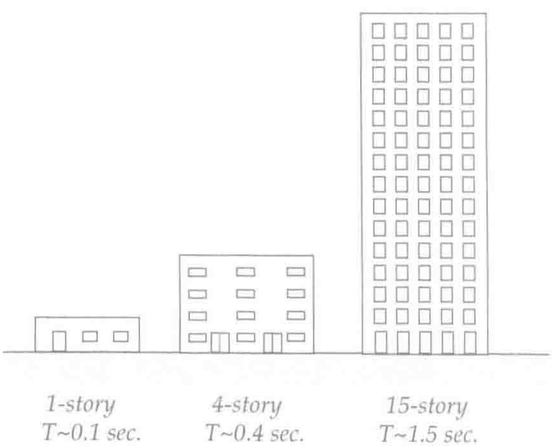


Figure 16 Approximate building periods of vibration.

All objects, including buildings, have a *natural or fundamental period of vibration*. It represents the time it takes an object or building to vibrate through one cycle of vibration (or sway) when subjected to an applied force. When an earthquake ground motion causes a building to start vibrating, the building begins to displace (sway) back and forth at its natural period of vibration. Shorter, lower buildings have very short periods of vibration (less than one second), while tall high rises can have periods of vibration that last several seconds (Figure 16). Fundamental periods are a function of a building's height. An approximate estimate of a building's period is equal to

$$T = 0.1N$$

where N represents the number of stories and T represents the period of vibration in seconds.

The ground also vibrates at its own natural period of vibration. Many of the soils in the United States have periods of vibration in the range of 0.4 to 1.5 seconds. Short periods are more characteristic of hard soils (rock), while soft ground (some clays) may have periods of up to two seconds.

Many common buildings can have periods within the range of the supporting soils, making it possible for the ground motion to transmit at the same natural frequency as that of the building. This may create a condition of resonance (where the vibrations increase dramatically), in which the inertial forces might become extremely large.

Inertial forces develop in the structure due to its weight, configuration, building type, and geographic location. Inertial forces are the product of mass and acceleration (Newton's second law: $F = m \times a$). Heavy, massive buildings will result in larger inertial forces; hence, there is a distinct advantage in using a lighter weight construction when seismic considerations are a key part of the design strategy.

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. Building codes are intended to safeguard against major failures and loss of life; they are not explicitly for the protection of property.

5 BASIC FUNCTIONAL REQUIREMENTS

The principal functional requirements of a building structure are:

1. Stability and equilibrium.
2. Strength and stiffness.
3. Continuity and redundancy.
4. Economy.
5. Functionality.
6. Aesthetics.

Primarily, structural design is intended to make the building "stand up" (Figure 17). In making a building "stand up,"

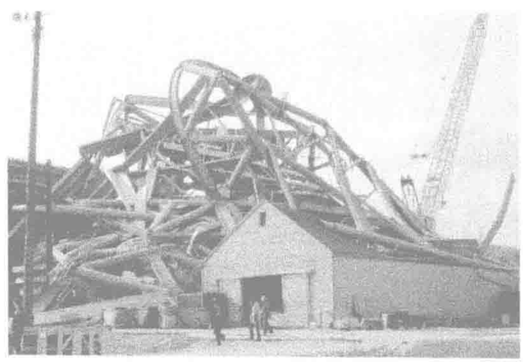


Figure 17 Stability and the strength of a structure—the collapse of a portion of the University of Washington Husky stadium during construction (1987) due to lack of adequate bracing to ensure stability. Photo by author.

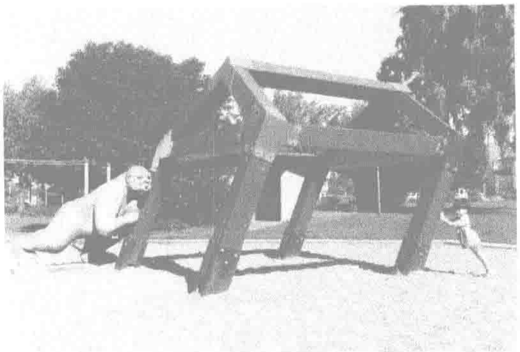
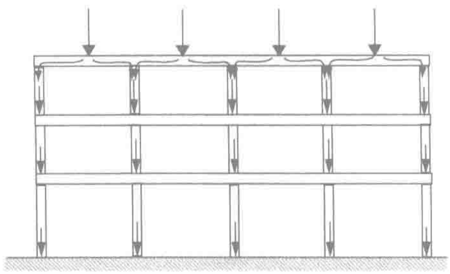
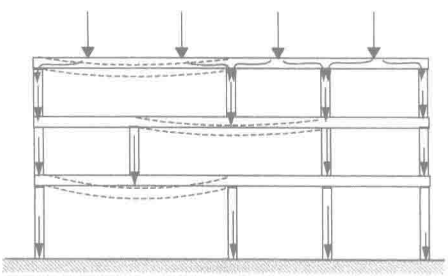


Figure 18 Equilibrium and Stability?—sculpture by Richard Byer. Photo by author.



(a) Continuity—loads from the roof beams are redistributed to the roof columns below. A continuous path is provided for the column loads to travel directly to the columns below and then on to the foundation.



(b) Discontinuity in the vertical elevation can result in very large beam bending moments and deflection. Structural efficiency is enhanced by aligning columns to provide a direct path to the foundation. Beam sizes can thus be reduced significantly. In this example, missing or damaged columns could also represent how structural frameworks can have the ability to redistribute loads to adjacent members without collapse. This is referred to as structural redundancy.

Figure 19 Examples of continuity and redundancy.

the principles governing the stability and equilibrium of buildings form the basis for all structural thinking. *Strength* and *stiffness* of materials are concerned with the stability of a building's component parts (beams, columns, walls), whereas *statics* deals with the theory of general stability. Statics and strength of materials are actually intertwined, because the laws that apply to the stability of the whole structure are also valid for the individual components.

The fundamental concept of *stability* and *equilibrium* is concerned with the balancing of forces to ensure that a building and its components will not move (Figure 18). In reality, all structures undergo some movement under load, but stable structures have deformations that remain relatively small. When loads are removed from the structure (or its components), internal forces restore the structure to its original, unloaded condition. A good structure is one that achieves a condition of equilibrium with a minimum of effort.

Strength of materials requires knowledge about building material properties, member cross-sections, and the ability of the material to resist breaking. Also of concern is that the structural elements resist excessive deflection and/or deformation.

Continuity in a structure refers to a direct, uninterrupted path for loads through the building structure—from the roof level down to the foundation. *Redundancy* is the concept of providing multiple load paths in a structural framework so that one system acts as a backup to another in the event of localized structural failure. Structural redundancy enables loads to seek alternate paths to bypass structural distress. A lack of redundancy is very hazardous when designing buildings in earthquake country (Figure 19).

On 9/11, both of the World Trade Center towers were able to withstand the impact of jetliners crashing into them and continue standing for some time, permitting many people to evacuate. The towers were designed with structural redundancy, which prevented an even larger loss of life. However, the process by which the collapse of the impacted story level led to the progressive collapse of the entire building may have led some investigators to hint that an inadequate degree of structural redundancy existed.

The requirements of *economy, functionality,* and *aesthetics* are usually not covered in a structures course and will not be dealt with in this text. Strength of materials is typically covered upon completion of a statics course.

6 ARCHITECTURAL ISSUES

A technically perfect work can be aesthetically inexpressive but there does not exist, either in the past or in the present, a work of architecture which is accepted and recognized as excellent from an aesthetic point of view which is not also excellent from the technical point of view. Good engineering seems to be a necessary though not sufficient condition for good architecture.

—Pier Luigi Nervi

The geometry and arrangement of the load-bearing members, the use of materials, and the crafting of joints all represent opportunities for buildings to express themselves. The best buildings are not designed by architects who, after resolving the formal and spatial issues, simply ask the structural engineer to make sure it does not fall down.

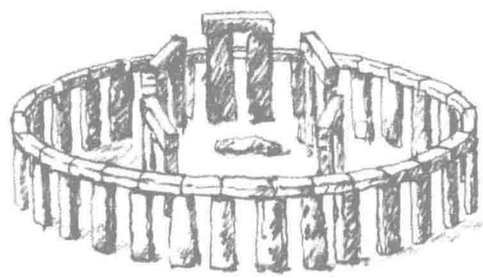


Figure 20 Stonehenge.

An Historical Overview

It is possible to trace the evolution of architectural space and form through parallel developments in structural engineering and material technology. Until the 19th century, this history was largely based on stone construction and the capability of this material to resist compressive forces. Less durable wood construction was generally reserved for small buildings or portions of buildings.

Neolithic builders used drystone techniques, such as coursed masonry walling and corbelling, to construct monuments, dwellings, tombs, and fortifications. These structures demonstrate an understanding of the material properties of the various stones employed (Figure 20).

Timber joining and dressed stonework were made possible by iron and bronze tools. Narrow openings in masonry building walls were achieved through corbelling and timber or stone lintels.

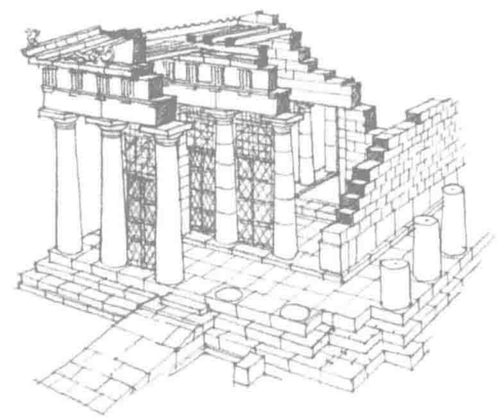


Figure 21 Construction of a Greek peristyle temple.

The earliest examples of voussoir arches and vaults in both stone and unfired brick construction have been found in Egypt and Greece (Figure 21). These materials and structural innovations were further developed and refined by the Romans. The ancient Roman architect Vitruvius, in his *Ten Books*, described timber trusses with horizontal tie members capable of resisting the outward thrust of sloping rafters.

Roman builders managed to place the semicircular arch atop piers or columns; the larger spans reduced the number of columns required to support the roof. Domes and barrel and groin vaults were improved through the use of modular fired brick, cement mortar, and hydraulic concrete. These innovations enabled Roman architects to create even larger unobstructed spaces (Figure 22).

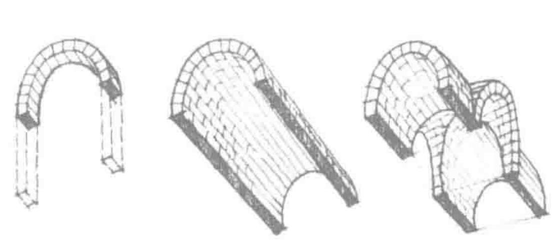


Figure 22 Stone arch, barrel vault, and groin vault.

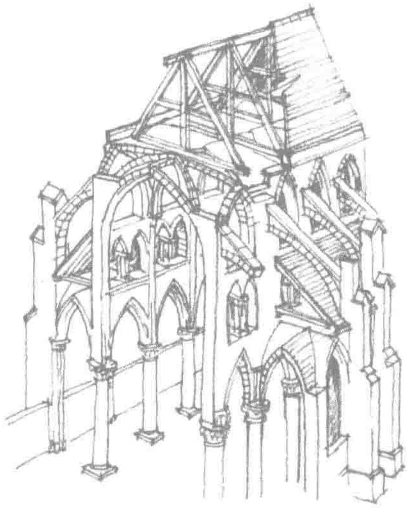


Figure 23 Construction of a Gothic cathedral.

Gradual refinements of this technology by Romanesque mason builders eventually led to the structurally daring and expressive Gothic cathedrals. The tall, slender nave walls with large stained glass openings, which characterize this architecture, are made possible by improvements in concrete foundation construction; the pointed arch, which reduces lateral forces; flying arches and buttresses, which resist the remaining lateral loads; and the ribbed vault, which reinforces the groin and creates a framework of arches and columns, keeping opaque walls to a minimum (Figure 23).

The medium of drawing allowed Renaissance architects to work on paper, removed from construction and the site. Existing technical developments were employed in the search for a classical ideal of beauty and proportion.

Structural cast iron and larger, stronger sheets of glass became available in the late 18^{th} century. These new materials were first employed in industrial and commercial buildings, train sheds, exhibition halls, and shopping arcades. Interior spaces were transformed by the delicate long-span trusses supported on tall, slender, hollow columns. The elements of structure and cladding were more clearly articulated, with daylight admitted in great quantities. Wrought iron and, later, structural steel provided excellent tensile strength and replaced brittle cast iron. Art Nouveau architects exploited the sculptural potential of iron and glass, while commercial interests capitalized on the long-span capabilities of rolled steel sections.

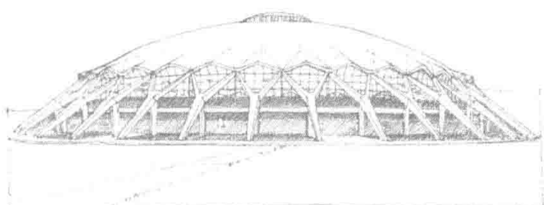


Figure 24 Sports Palace, reinforced concrete arena, by Pier Luigi Nervi.

The tensile properties of steel were combined with the high compressive strength of concrete, making a composite section with excellent weathering and fire-resistive properties that could be formed and cast in almost any shape (Figure 24). Steel and reinforced concrete structural frames enabled builders to make taller structures with more stories. The smaller floor area devoted to structure and the greater spatial flexibility led to the development of the modern skyscraper.

Today, pretensioned and posttensioned concrete, engineered wood products, tensile fabric, and pneumatic structures and other developments continue to expand the architectural and structural possibilities.

The relationship between the form of architectural space and structure is not deterministic. For example, the development of Buckminster Fuller's geodesic dome did not immediately result in a proliferation of domed churches or office buildings. As history has demonstrated, vastly different spatial configurations have been realized with the same materials and structural systems. Conversely, similar forms have been generated utilizing very different structural systems. Architects as well as builders must develop a sense of structure (Figure 25). Creative collaboration between architect, builder, and engineer is necessary to achieve the highest level of formal, spatial, and structural integration.

Criteria for the Selection of Structural Systems

Most building projects begin with a client program outlining the functional and spatial requirements to be accommodated. Architects typically interpret and prioritize this information, coordinating architectural design work with the work of other consultants on the project. The architect and structural engineer must satisfy a wide range of factors in determining the most appropriate structural system. Several of these factors are discussed here.

Nature and magnitude of loads

The weight of most building materials (Table 1) and the self-weight of structural elements (dead loads) can be calculated from reference tables listing the densities of various materials. Building codes establish design values for the weight of the occupants and furnishings—live loads (Table 2)—and other temporary loads, such as snow, wind, and earthquake.

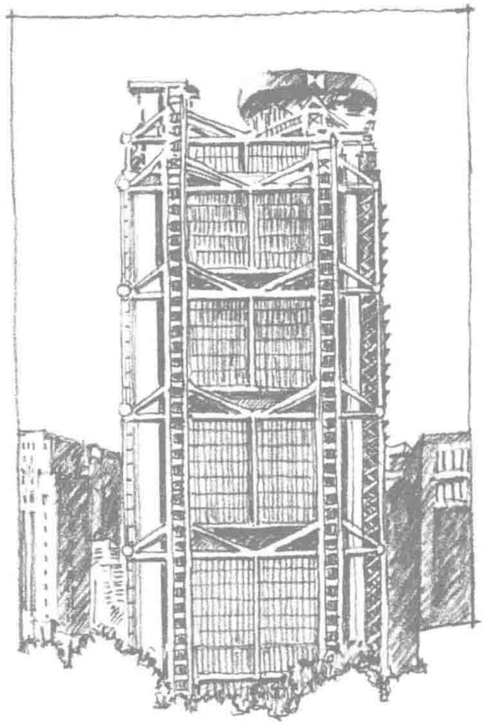


Figure 25 Hong Kong Bank, by Norman Foster.

Building use/function

Sports facilities (Figure 26) require long, clear span areas free of columns. Light wood framing is well suited to the relatively small rooms and spans found in residential construction.

Site conditions

Topography and soil conditions often determine the design of the foundation system, which in turn influences the way loads are transmitted though walls and columns. Low soil-bearing capacities or unstable slopes might suggest a series of piers loaded by columns instead of conventional spread footings. Climatic variables, such as wind speed and snowfall, affect design loads. Significant movement (thermal expansion and contraction) can result from extreme temperature fluctuations. Seismic forces, used to calculate building code design loads, vary in different parts of the country.

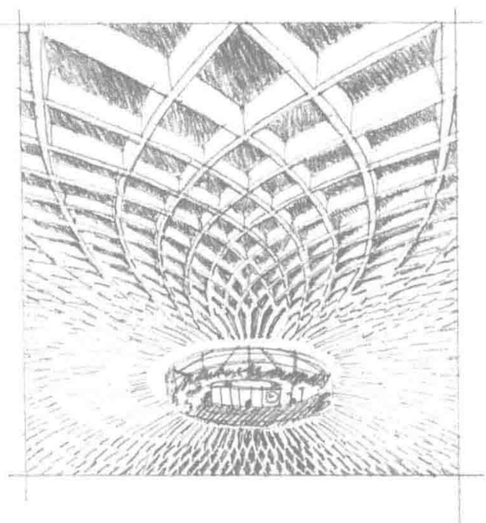


Figure 26 Sports Palace interior, by Pier Luigi Nervi (1955).

Building systems integration

All building systems (lighting, heating/cooling, ventilation, plumbing, fire sprinklers, electrical) have a rational basis that governs their arrangement. It is generally more elegant and cost-effective to coordinate these systems to avoid conflict and compromise in their performance. This is especially the case where the structure is exposed and dropped ceiling spaces are not available for duct and pipe runs.

Fire resistance

Building codes require that building components and structural systems meet minimum fire-resistance standards. The combustibility of materials and their ability to carry design loads when subjected to intense heat are tested to ensure that buildings involved in fires can be safely evacuated in a