CHAPTER

1

Basic Concepts

This chapter presents basic issues that affect the design of building structures and presents an overall view of the materials, products, and systems used to achieve them.

1.1 BASIC CONCERNS

All physical objects have structures. Consequently, the design of structures is part of the general problem of design for all physical objects. It is not possible to understand fully why buildings are built the way they are without some knowledge and understanding of the problems of their structures. Building designers cannot function in an intelligent manner in making decisions about the form and fabric of a building without some comprehension of basic concepts of structures.

Safety

Life safety is a major concern in the design of structures. Two critical considerations are for fire resistance and for a low likelihood of collapse under load. Major elements of fire resistance are:

Combustibility of the Structure. If structural materials are combustible, they will contribute fuel to the fire as well as hasten the collapse of the structure.

Loss of Strength at High Temperature. This consists of a race against time, from the moment of inception of the fire to the failure of the structure—a long interval increasing the chance for occupants to escape the building.

Containment of the Fire. Fires usually start at a single location, and preventing their spread is highly desirable. Walls, floors, and roofs should resist burn-through by the fire.

Major portions of building code regulations have to do with aspects of fire safety. Materials, systems, and details of construction are rated for fire resistance on the basis of experience and tests. These regulations constitute restraints on building design with regard to selection of materials and use of details for building construction.

Building fire safety involves much more than structural behavior. Clear exit paths, proper exits, detection and alarm systems, firefighting devices (sprinklers, hose cabinets, etc.), and lack of toxic or highly flammable materials are also important. All of these factors will contribute to the race against time, as illustrated in Figure 1.1.

The structure must also sustain loads. Safety in this case consists of having some margin of structural capacity beyond that strictly required for the actual task. This margin of safety is defined by the safety factor, SF, as follows:

$$SF = \frac{\text{actual capacity of the structure}}{\text{required capacity of the structure}}$$

Thus, if a structure is required to carry 40,000 lb and is actually able to carry 70,000 lb before collapsing, the safety factor is expressed as SF = 70,000/40,000 = 1.75. Desire for safety must be tempered by practical concerns. The user of a structure may take comfort in a safety factor as high as 10, but the cost or gross size of the structure may be undesirable. Building structures are generally designed with an average safety factor of about 2. There is no particular reason for this other than experience.

For many reasons, structural design is a highly imprecise undertaking. One should not assume, therefore, that the true safety factor in a given situation can be established with great accuracy. What the designer strives for is simply a general level of assurance of a reasonably adequate performance without incorporate this investigation into design work, the designer needs to develop a number of capabilities, including the following:

The ability to visualize and evaluate the sources that produce the loads on the structure
The ability to quantify the loads and the effects they produce on the structure
The ability to analyze the structure's response to the loads in terms of internal forces, stresses, and strains
The ability to determine the structure's limits of load-carrying capacity
The ability to manipulate the variables of material, form, and construction details for the structure in order to optimize its responses to loads

Although analysis of stresses and strains is necessary in the design process, there is a sort of chicken-and-egg relationship between analysis and design. To analyze some of the structure's responses, one needs to know some of its properties. However, these properties are not known until the designed object is established. In some simple cases it is possible to derive expressions for desired properties by simple inversion of analytical formulas. For example, a simple formula for stress in a compression member is

$$\text{Stress} = \frac{\text{total load on the member}}{\text{area of the member cross section}}$$

If the load is known and the stress limit for the material is established, this formula can be easily converted to one for finding the required area of the cross section, as follows:

$$\text{Required area} = \frac{\text{total load on the member}}{\text{stress limit for the material}}$$

Most structural situations are more complex, however, and involve variables and relationships that are not so simply converted for design use. In the case of the compression member, for example, if the member is a slender column, its load capacity will be limited to some degree by the tendency to buckle. The relative stiffness of the column in resisting buckling can be determined only after the geometry of its cross section is known. Therefore, the design of such an element is a hit-or-miss situation, consisting of guessing at a possible cross-sectional shape and size, analyzing for its performance, and refining the choice as necessary until a reasonable fit is established.

Professional designers use their experience together with various design aids, such as tabulations of capacities of common elements, to shorten the design process. Even so, final choices often require some progressive effort.

Investigation of Structural Behavior

Whether for design purposes, for research, or for study of structural behaviors as a learning experience, analysis of stresses and strains is important. Analysis may be performed as a testing procedure on the actual structure with a loading applied to simulate actual usage conditions. If carefully done, this is a highly reliable procedure. However, except for some of the widely used elements of construction, it is generally not feasible to perform destructive load testing on building structures built to full scale. The behavior of building structures must usually be anticipated speculatively on the basis of demonstrated performance of similar structures or on a modeling of the actions involved. The modeling can be done in the form of physical tests on scaled-down structures but is most often done mathematically using the current state of knowledge in the form of formulas for analysis. When the structure, the loading conditions, and the necessary formulizations are relatively simple, computations may be done by "hand." More commonly, however, computations of even routine nature are done by professional designers using computer-assisted techniques. While the computer is an extremely useful tool, it is imperative that the designer keep an upper hand in this process by knowing reasonably well what the computer is doing, a knowledge often gained from a lot of "hand" investigations and the follow-up to applications in design decision making. Otherwise, there is often the danger of garbage in, garbage out.

1.4 STRUCTURAL MATERIALS

All materials—solid, liquid, or gaseous—have some structural nature. The air we breathe has a structural nature: It resists compression when contained. Every time you ride in a car you are sitting on an air-supported structure. Water supports the largest human-made vehicles: huge ships. Oil resists compression so strongly that it is used as the resisting element in hydraulic presses and jacks capable of developing tremendous force.

In the design of building structures, use is made of the available structural materials and the products formed from them. The discussion in this section deals with common structural materials and their typical uses in contemporary construction.

General Considerations

Broad classifications of materials can be made, such as distinctions among animal, vegetable, and mineral; between organic and inorganic; and the physical states of solid, liquid, and gaseous. Various chemical and physical properties distinguish individual materials from others. In studying or designing structures, particular properties of materials are of concern. These may be split between essential structural properties and general properties.

Essential properties for building structures include the following:

Strength. May vary for different types of force, in different directions, at different ages, or at different amounts of temperature or of moisture content.

Deformation Resistance. Degree of rigidity, elasticity, ductility; variation with time, temperature, and so on.
Hardness. Resistance to surface indentation, scratching, abrasion, and general wear.
Fatigue Resistance. Time loss of strength, progressive fracture, and shape change with time.
Uniformity of Physical Structure. Grain and knots in wood, cracks in concrete, shear planes in stone, and effects of crystallization in metals.

Some general properties of interest in using and evaluating structural materials include the following:

Form. Natural, reshaped, reconstituted.
Weight. Contributing to gravity loads.
Fire Resistance. Combustibility, conductivity, melting or softening point, and general behavior at high temperature.
Thermal Expansion. Relating to dimensional change.
Availability and Cost.
Green Concerns. Toxicity, renewable source, energy use for production, potential for reuse.

In any given situation choices of materials must often be made on the basis of several properties—both structural and general. There is seldom a material that is superior in all respects, and the importance of various properties must often be ranked.

Wood

Technical innovations have overcome some of the long-standing limitations of wood. Size and form limits have been extended by various processes, including lamination and reconstitution as fiber products. Special fastenings have made some structures possible through better performing jointing. Combustibility, rot, and insect infestation can be retarded by chemical impregnations.

Dimensional movements from changes in temperature or moisture content remain a problem with wood. Although easily worked, wood elements are soft and readily damaged; thus damage during production, transportation, and construction and even some uses are a problem.

Although hundreds of species (different trees) exist, structural use is limited mostly to a few softwoods: Douglas fir, southern pine, northern white pine, spruce, redwood, cedar, and hemlock. Regional availability and cost are major concerns in selection of a particular species.

Economy is generally achieved by using the lowest grade (quality) of material suitable for the work. Grade is influenced by lack of knots, splits, and pitch pockets and by the particular grain character of individual pieces.

Fabricated products are increasingly used in place of solid-sawn wood pieces. Plywood and glued laminated timbers have been used for some time. More recently items fabricated from wood fibers and strands are being used to replace plywood panels and light framing elements.

Fabricated compound structural elements are also widely used. The light wood truss with wood top and bottom chords and metal interior members is in direct competition with the steel open web joist for medium- to long-span roof and floor structures. A newer product is the wood I-joist, composed of solid wood or laminated top and bottom pieces and a web of plywood or fiber board.

Because of its availability, low cost, and simple working possibilities, wood is used extensively for secondary and temporary construction. However, it is also widely used for permanent construction and is generally the material of choice for light construction unless its limitations preclude its use. It is a renewable resource, although the best wood comes from very slow-growth trees. However, the most extensive use of wood is as fiber for the paper industry, which has become a major commercial institution in the United States. The fiber users can use small, fast-growth trees and they routinely plant and harvest trees for quick turnover. This is a major factor in the rapid expansion of use of fiber products for building construction.

Steel

Steel is used in a variety of forms in nearly every building. From its use for huge towers to the smallest nails, steel is the most versatile of traditional materials. It is also one of the strongest, the most resistive to aging, and generally the most reliable in its quality control. Steel is a highly industrialized material and is subjected to tight control of its content and of the details of forming and fabrication. It has the additional desirable qualities of being noncombustible, nonrotting, and dimensionally stable with time and moisture change.

Although the bulk material is expensive, steel can be used in small quantities because of its high strength and its forming processes; thus the completed steel structure is competitive with structures produced with materials of much cheaper bulk cost. Economy can also be produced with mass production of standardized items. Choosing the parts for a steel structure is done mostly by picking items from standard documented references.

Two principal disadvantages of using steel for building construction are inherent in the basic material. These are its rapid heat gain and resultant loss of strength when exposed to fire and its rusting when exposed to moisture and air or to corrosive conditions (such as salty water). A variety of techniques can be used to overcome these limitations, two common ones being special coatings and the encasing of the steel in construction of a protective nature.

Concrete

The word *concrete* is used to describe a number of materials having something in common: the use of a binder to form a solid mass from a loose, inert aggregate. The three basic ingredients of ordinary structural concrete are water, a binder (cement), and a large volume of loose aggregate (sand and gravel). Variation of the end product is endless through the use of different binders and aggregates and with the use of chemical additives and air-producing foaming agents.

Ordinary cementitious concrete has several attributes, chief among which are its low bulk cost and its resistance to moisture, rot, insects, fire, and wear. Being formless in its initial mixed condition, it can be made to assume a large variety of forms.

One of concrete's chief shortcomings is its lack of tensile strength. The use of inert reinforcement or prestressing is imperative for any structural functions involving bending or torsion. Recent use of imbedded fibers is another means for enhancing resistance to tension. Because the material is formless, its forming and finishing are major expenses in its use. Precasting in permanent forms is one means for reducing forming cost.

Aluminum

In alloyed form, aluminum is used for a large variety of structural, decorative, and hardware elements in building construction. Principal advantages are its light weight (one-third that of steel) and its high resistance to corrosion. Some disadvantages are its softness, its low stiffness, its high rate of thermal expansion, its low resistance to fire, and its relatively high cost.

Large-scale structural use in buildings is limited by cost and its increased dimensional distortion due to its lack of stiffness. Low stiffness also reduces its resistance to buckling. Minor structural use is considerable, however, for window and door frames, wall panels, trim, and various hardware items.

Masonry

The term *masonry* is used to describe a variety of formations consisting of separate, inert objects bonded together by some binding joint filler. Elements may be rough or cut stone, fired clay tile or bricks, or cast units of concrete. The binder is usually a cement and lime mortar. The resulting assemblage is similar in weight and bulkiness to concrete construction and possesses many of the same properties. Assemblage typically involves considerable hand labor, making it highly subject to the skill of individual craftspersons. Reinforcing can be used to increase strength, as is commonly done for increased resistance to windstorms and earthquakes. Shrinkage of the mortar and thermal-expansion cracking are two major concerns that necessitate care in detailing, material quality control, and field inspection during construction.

Plastics

Plastic elements represent the widest variety of usage in building construction. The great variation of material content, properties, and formation processes yields an unlimited field for the designer's imagination. Some of the principal problems with plastics are lack of fire resistance, low stiffness, high rate of thermal expansion, and some cases of chemical or physical instability with time.

Some of the uses in building construction are:

Glazing. For windowpanes, skylights, and sheet-form or corrugated panels.

Coatings and Laminates. Sprayed, painted, or rolled on or applied as laminates in composite panels.

Formed elements. For frames, trim, and hardware.

Foamed. In preformed or foamed-in-place applications, as insulation and filler for various purposes.

Design developments in recent years include pneumatic and tension-sustained surface structures using various plastic membranes and fabric products. Small structures may use thin plastic membranes, but for larger structures the surface material is usually a coated fabric with enhanced resistance to tension and tearing. The plastic-surfaced structure can also be created by using plastic elements on a framework.

Miscellaneous Materials

Glass

Ordinary glass possesses considerable strength but has the undesirable characteristic of being brittle and subject to shattering under shock. Special glass products are produced with higher strength, but a more widely used technique is to produce laminated panels with alternating layers of plastic and glass—like good old "safety glass," which has been in use for car windows for a long time.

Fiber-Reinforced Products

Glass fiber and other stranded elements are used to strengthen paper, plastic membranes, and various panel materials. This notably increases tension and tear resistance.

Paper

Paper—that is, sheet material of basically rag or wood fiber content—is used considerably in building construction, although for some uses it has been replaced by plastics. Various coatings, laminations, impregnations, and reinforcing can be used to produce a tougher or more moisture-resisting material. A widely used product is the "drywall" panel, consisting of a thin slab of plaster sandwiched between two thick paper sheets.

Mixed Materials

Buildings use a large mixture of materials for their construction. This also applies to building structures. Just about every building has concrete foundations, regardless of the materials of the rest of the structure. For structures of wood, concrete, and masonry, many steel elements will be used for fastenings, reinforcement, and other purposes. Nevertheless, despite the typical material mixture that designers must use, the industries that produce structural products are very material specific. Thus major concentrations exist in terms of primary structural materials: wood, steel, concrete, and masonry. Information for design comes primarily from these sources.

1.5 STRUCTURAL SYSTEMS

The materials, products, and systems available for the construction of building structures constitute a vast inventory through which the designer must sift carefully for the appropriate selection in each case. The material in this section presents some of the issues relating to this inventory and its applications.

Attributes of Structural Systems

A specific structural system derives its unique character from any number of considerations—and probably from many of them simultaneously. Considered separately, some of these factors are the following:

Structural Functions or Tasks. These include support in compression (piers, footings, columns); support in tension (vertical hangers, guy wires, suspended cables); spanning—horizontally (beams, arches), vertically (window glass, basement walls), or inclined (rafters); cantilevering—vertically (flagpoles) or horizontally (balconies, canopies). A single element or system may be required to perform more than one of these functions, simultaneously or for different loading conditions.

Geometric Form or Orientation. Note the difference between the flat beam and the curved arch, both of which can be used for the same basic task of spanning horizontally. The difference is one of structural form. Also compare the arch and the suspended cable—similar in form but different in orientation to the loads.

Material of Elements. May possibly be all the same or of different materials in complex systems.

Manner of Joining of Elements. A major concern for systems with many assembled parts.

Loading Conditions. Sources, static or dynamic, in various combinations.

Usage. Structures usually serve some purpose (wall, roof, floor, bridge, etc.) and must be appropriate to the task.

Limits of Form and Scale. Many factors establish both upper and lower limits of size. These may have to do with material sources, with joining methods, or with inherent performance characteristics of particular systems or elements.

Special Requirements. Performance may be conditioned by need for light weight, visual exposure, demountability, portability, multifunctions, and so on.

Structural systems occur in almost endless variety. The designer, in attempting to find the ideal structure for a specific purpose, is faced with an exhaustive process of comparative "shopping." The ideal solution is mostly illusive, but careful shopping can narrow the field of acceptable solutions. For shopping, a checklist can be used to rate the available known systems for a given purpose. Items to be considered are as follows:

Economy. This includes the cost of the structure itself as well as its influence on the total cost of construction. Some special considerations may be required for factors such as slow construction time, adaptability to modifications, and first cost versus maintenance cost over the life of the structure.

Special Structural Requirements. These may include unique aspects of the structure's action, details required for development of its strength and stability, adaptability to special loadings, and need for symmetry or modular development. Thus arches require horizontal restraints at their bases; tension elements must be hung from something. Structures with very thin parts must be braced or stiffened against buckling, and domes must have some degree of symmetry and a concentric continuity.

Problems of Design. Possible concerns include difficulty of performing reliable investigation of behaviors, ease of detailing of the structure, and ease of integrating the structure with the other elements of the complete building.

Problems of Construction. Possible issues include availability of materials—especially ones that are difficult to transport, availability of skilled labor or equipment, speed of erection, requirements for temporary bracing or forming, and need for on-site storage of large inventories of parts.

Material and Scale Limitations. There are feasible ranges of size for most systems; for example, beams cannot span nearly as far as trusses, arches, or cables.

Form Constraints. Arches and domes produce curved shapes, which may or may not be acceptable for the building form. Cables sag and produce low points at the center of their spans. For efficient performance, trusses need some significant height of the truss structure itself, generating space that may not be usable on the building interior.

Historic Precedent. Many structural systems have been developed over long periods of time and are so classical in both their structural performance and their accommodation of desired architectural forms that they well may be considered as permanent features of construction. However, materials and construction processes change, and the means for achieving some classic forms are often not the same as they were in previous times. Figure 1.25 shows a centuries-old structure (Santa Ines Mission Church in Santa Ynez, California) with construction primarily of adobe bricks and hand-hewn timbers. Neither of these construction methods is likely to be possible today, there being no hand-hewers and seismic design criteria pretty much ruling out the unreinforced adobe. While it might be desirable to recapture the charm of the old building, it would have to be faked.