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

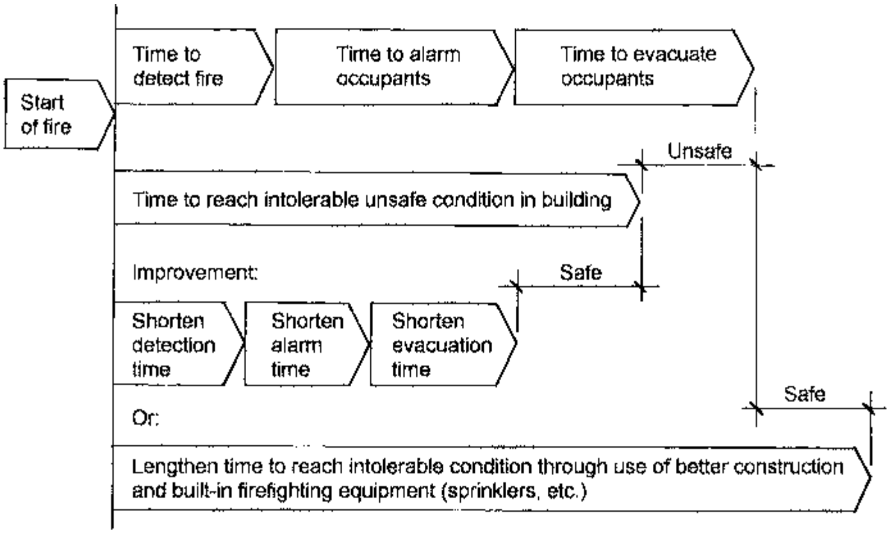


Figure 1.1 Concept of fire safety.

pushing the limits of the structure too close to the edge of failure.

There are two basic techniques for assuring the margin of safety. The method once used most widely is called the *allowable stress design* or *service load method.* With this method stress conditions under actual usage (with service loads) are determined and limits for stresses are set at some percentage of the predetermined ultimate capacity of the materials. The margin of safety is inferred from the specific percentage used for the allowable stresses.

A problem encountered with the allowable stress method is that many materials do not behave in the same manner near their ultimate failure limits as they do at service load levels. Thus prediction of failure from a stress evaluation cannot be made on the basis of only a simple linear proportionality; thus using an allowable stress of one-half the ultimate stress limit does not truly guarantee a safety factor of 2.

The other principal method for assuring safety is called the *strength design* or *load and resistance factor* (LRFD) method. The basis of this method is simple. The total load capacity of the structure at failure is determined and its design resistance is established as a percentage (factored) of the ultimate resistance. This factored resistance is then compared to an ultimate design failure loading, determined as a magnified (factored) value of the service load. In this case the margin of safety is inferred by the selected design factors.

Although life safety is certainly important, the structural designer must also deal with many other concerns in establishing a satisfactory solution for any building structure.

General Concerns

Feasibility

Structures are real and thus must use materials and products that are available and can be handled by existing craftspeople and production organizations. Building designers must have a reasonable grasp of the current inventory of available materials and products and of the usual processes for building construction. Keeping abreast of this body of knowledge is a challenge in the face of the growth of knowledge, the ever-changing state of technology, and the market competition among suppliers and builders.

Feasibility is not just a matter of present technological possibilities but relates to the overall practicality of a structure. Just because something *can* be built is no reason that it *should* be built. Consideration must be given to the complexity of the design, dollar cost, construction time, acceptability by code-enforcing agencies, and so on.

Economy

Buildings cost a lot of money, and investors are seldom carefree, especially about the cost of the structure. Except for the condition of a highly exposed structure that constitutes a major design feature, structures are usually appreciated as little as the buried piping, wiring, and other mundane hidden service elements. Expensive structures do not often add value in the way that expensive hardware or carpet may. What is usually desired is simple adequacy, and the hard-working, low-cost structure is much appreciated.

However vital, the building structure usually represents a minor part of the total construction cost. When comparing alternative structures, the cost of the structure itself may be less important than the effects of the structure on other building costs.

Optimization

Building designers often are motivated by desires for originality and individual expression. However, they are also usually pressured to produce a practical design in terms of function and feasibility. In many instances this requires making decisions that constitute compromises between conflicting or opposing considerations. The best or optimal solution is often elusive. Obvious conflicts are those between desires for safety, quality of finishes, grandeur of spaces, and general sumptuousness on the one hand and practical feasibility and economy on the other. All of these attributes may be important, but often changes that tend to improve one factor work to degrade others. Some rank ordering of the various attributes is generally necessary, with dollar cost usually ending up high on the list.

Integration

Good structural design requires integration of the structure into the whole physical system of the building. It is necessary to recognize the potential influences of the structural design decisions on the general architectural design and on the development of the systems for power, lighting, thermal control, ventilation, water supply, waste handling, vertical transportation, firefighting, and so on. The most popular structural systems have become so in many cases largely because of their ability to accommodate the other subsystems of the building and to facilitate popular architectural forms and details.

1.2 ARCHITECTURAL CONSIDERATIONS

Primary architectural functions that relate to the structure are:

Need for shelter and enclosure
Need for spatial definition, subdivision, and separation
Need for unobstructed interior space

In addition to its basic force-resistive purpose, the structure must serve to generate the forms that relate to these basic usage functions.

Shelter and Enclosure

Exterior building surfaces usually form a barrier between the building interior and the exterior environment. This is generally required for security and privacy and often in order to protect against various hostile external conditions (thermal, acoustic, air quality, precipitation, etc.). Figure 1.2 shows many potential requirements of the building skin. The skin is viewed as a selective filter that must block some things while permitting the passage of others.

In some instances, elements that serve a structural purpose must also fulfill some of the filter functions of the building skin, and properties other than strictly structural ones must be considered in the choice of the materials and details of the structure. Basic structural requirements cannot be ignored but frequently can be relatively minor as final decision criteria.

When need exists for complete enclosure, the structure must either provide it directly or facilitate the addition of other elements to provide it. Solid masonry walls, shell domes, and tents are examples of structures that provide naturally closed surfaces. It may be necessary to enhance the bare structure with insulation, waterproofing, and so on, to generate all the required skin functions, but the enclosure function is inherent in the structural system.

Frame systems, however, generate open structures that must be provided with separate skin elements to develop the enclosure function. In some cases, the skin may interact with the frame; in other cases it may add little to the basic structural

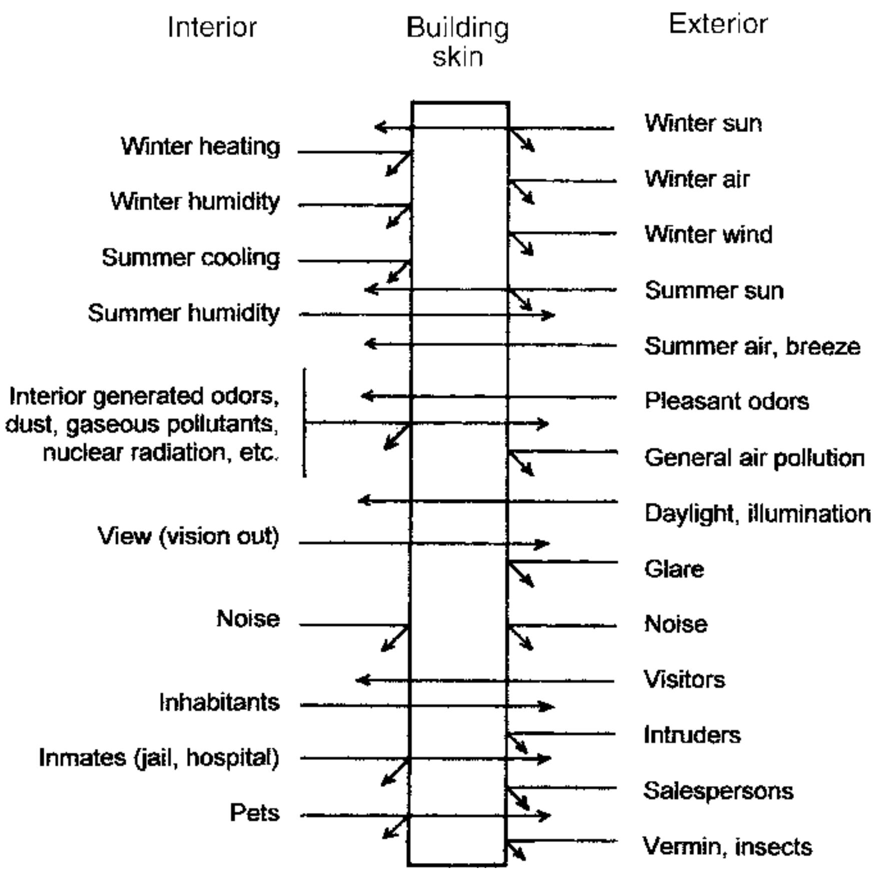


Figure 1.2 Functions of the building skin as a selective filter.

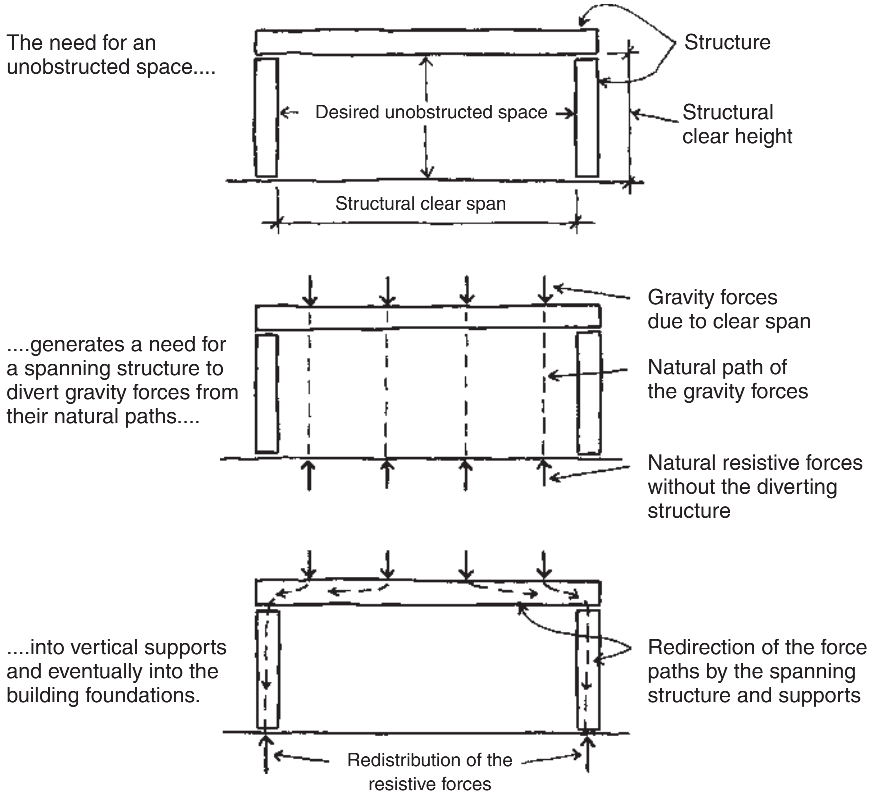


Figure 1.3 Structural task of generating unobstructed interior space.

behavior. An example of the latter is a highrise building with a thin curtain wall of light metal and glass elements.

Interior Space Division

Most buildings have interior space division with separate rooms and often separate levels. Structural elements used to develop the interior must relate to the usage requirements of the individual spaces and to the needs for separation and privacy. In multistory buildings structural systems that form the floor for one level may simultaneously form the ceiling for the space below. These two functions generate separate form restrictions, surface treatments, attachments, or incorporation of elements such as light fixtures, air ducts, power outlets, and plumbing pipes and fixtures. In addition, the floor–ceiling structure must provide a barrier to the transmission of sound and fire. As in the case of the building skin, the choice of construction must be made with all necessary functions in mind.

Generating Unobstructed Space

Housing of activities typically creates the need for producing open, unobstructed interior spaces. The spaces may be very small (for bathrooms) or very large (for sports arenas). Generating open space involves the structural task of spanning for overhead roofs or floors, as illustrated in Figure 1.3. The magnitude of the spanning problem is determined by the loads and the span. As the length of the span increases, the required structural effort increases rapidly, and options for the structural system narrow.

A particularly difficult problem is that of developing a large open space in the lower portion of a multistory building.

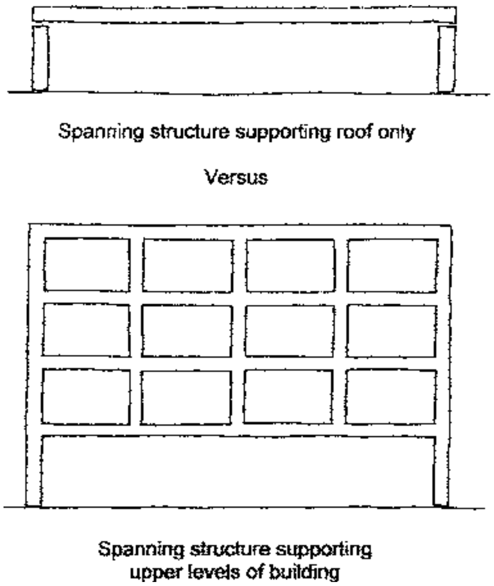


Figure 1.4 Load conditions for the spanning structure.

As shown in Figure 1.4, this generates a major load on the transitional spanning structure. This situation is unusual, however, and most large spanning structures consist only of roofs, for which the loads are relatively light.

Architectural Elements

Most buildings consist of combinations of three basic elements: walls, roofs, and floors. These elements are arranged to create both space division and unobstructed space.

Walls

Walls are usually vertical and potentially lend themselves to the task of supporting roofs and floors. Even when they do not serve as supports, they often incorporate the columns that do serve this function. Thus the design development of the spanning roof and floor systems must begin with consideration of the locations of wall systems over which they span.

Walls may be classified on the basis of their functions, which affects many of the design conditions regarding materials and details. Some basic categories are:

Structural Walls. These serve one or both of two functions in the general building structural system. *Bearing walls* support roofs, floors, and other walls. *Shear walls* brace the building against horizontal forces, utilizing the stiffness of the wall in its own plane, as shown in Figure 1.5.

Nonstructural Walls. Actually, there is no such thing as a nonstructural wall, since the least that any wall must do is hold itself up. However, the term *nonstructural* is used to describe walls that do not contribute to the general structural system of the building. When they occur on the exterior, they are called *curtain walls*; on the interior they are called *partitions*.

Exterior Walls. As part of the building skin, exterior walls have a number of required functions, including the barrier and filter functions described previously. Wind produces both inward and outward pressures that the wall surface must transmit to the bracing system. Exterior walls are usually permanent, as opposed to interior walls that can be relocated if they are nonstructural.

Interior Walls. Although some barrier functions are required of any wall, interior walls need not separate interior and exterior environments or resist wind. They may be permanent, as when they enclose stairs, elevators, or toilets, but are often essentially only partitions and can be built as such.

Many walls must incorporate doors or windows or provide space for wiring, pipes, or ducts. Walls of hollow construction provide convenient hiding places, whereas those of solid construction can present problems in this regard. Walls that are not flat and vertical can create problems with hanging objects. Walls that are not straight in plan and walls that intersect at other than right angles can also present problems. (See Figure 1.6.)

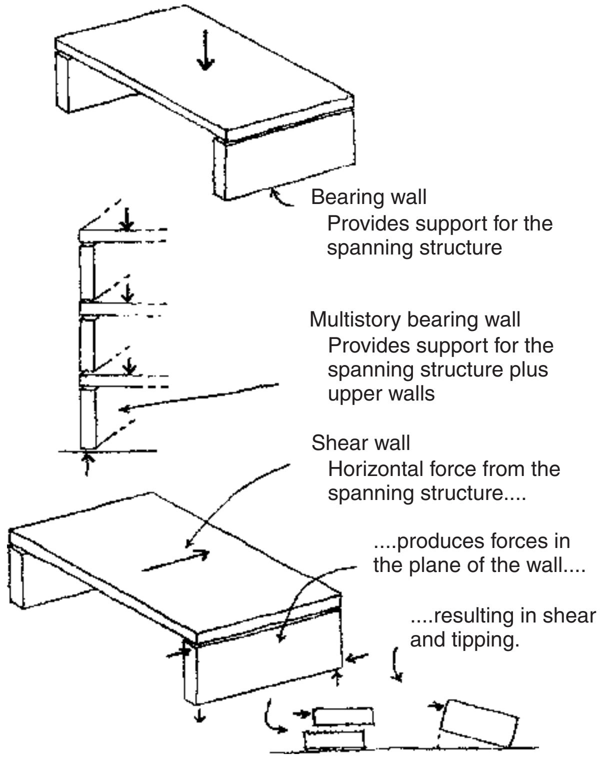


Figure 1.5 Structural functions of walls.

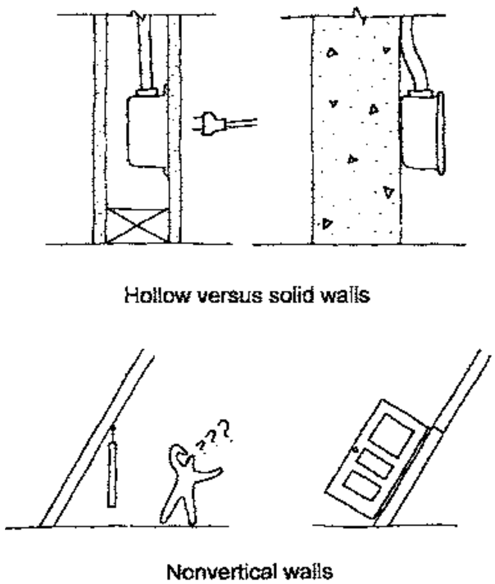


Figure 1.6 Problems of wall form.

Roofs

Roofs have two primary functions: They must serve as skin elements and must facilitate the runoff of water from precipitation. Barrier functions must be met and the roof geometry and surface must relate to the drainage problem. Whereas floors must generally be flat, roofs generally must not be, as some slope is required for drainage. The so-called flat roof must actually have some slope, typically a minimum of 1/4 inch per foot, or approximately 2%. In addition, the complete drainage operation must be controlled so that runoff water is collected and removed from the roof.

Floors are meant to be walked on; roofs generally are not. Thus, in addition to not being horizontal, roofs may be constructed of materials or systems that are not rigid, the ultimate possibility being a fabric or membrane surface held in position by tension.

Because of the freedom of geometry and lack of need for rigidity or solidity, the structural options for roofs are more numerous than those for floors. The largest enclosed, unobstructed spaces are those spanned only by roofs. Thus most of the dramatic and exotic spanning structures for buildings are roof structures.

Floors

Floor structures may serve as both a floor for upper spaces and a ceiling for lower spaces. Floors usually require a flat, horizontal form, limiting the choice to a flat-spanning system. Barrier requirements derive from the needs for separation of the spaces above and below.

Most floor structures are relatively short in span, since flat-spanning systems are relatively inefficient and load magnitudes for floors are generally higher than those for roofs. Achieving large open spaces under floors is considerably more difficult than achieving such spaces under roofs.

Form–Scale Relationships

There is a great variety of types of architectural space and associated structural problems. Figure 1.7 illustrates variables in terms of interior space division and of scale in terms of span and clear height. Other variables include the number of levels or adjacent spaces. The following discussion deals with some of the structural problems inherent in the situations represented in Figure 1.7.

Single Space

This ordinarily represents the greatest degree of freedom in the choice of the structural system. The building basically requires only walls and a roof, although a floor structure other than a paving slab may be required if the building is elevated above the ground. Some possible uses for such buildings and the potential structural systems follow.

Small Scale (10 ft high, 15 ft-span). This includes small sheds, cabins, and residential garages. The range of possible structural systems is considerable, including tents, air-inflated bubbles, ice block igloos, and mud huts, as well as more ordinary construction.

Medium Scale (15 ft high, 30 ft-span). This includes small stores, classrooms, and commercial or industrial buildings. The 15-ft wall height is just above the limit for 2 × 4 wood studs and the 30-ft span is beyond the limit of solid wood rafters on a horizontal span. Use of a truss, gabled frame, or some other efficient spanning system becomes feasible at this scale, although flat deck and beam systems are also possible.

Large Scale (30 ft high, 100+-ft span). This includes gyms, theaters, and large showrooms. The 30-ft wall height represents a significant structural problem, usually requiring braced construction of some form. The 100-ft span is generally beyond the feasible limit for a flat-spanning beam system, and the use of a truss, arch, or some other system is usually required. Because of the size of the spanning elements, they are usually widely spaced, requiring a secondary spanning system to fill in between the major spanning elements. Loads from the major spanning elements place heavy concentrated forces on walls, often requiring columns or piers. If the columns or piers are incorporated in the wall construction, they may serve the dual function of bracing the tall walls.

Super Large Scale (50 ft high, 300+-ft span). This includes large convention centers and sports arenas. Walls become major structural elements, requiring considerable bracing. The spanning structure itself requires considerable height in the form of spacing of truss elements, rise of arches, or sag of cables. Use of superefficient spanning systems becomes a necessity.

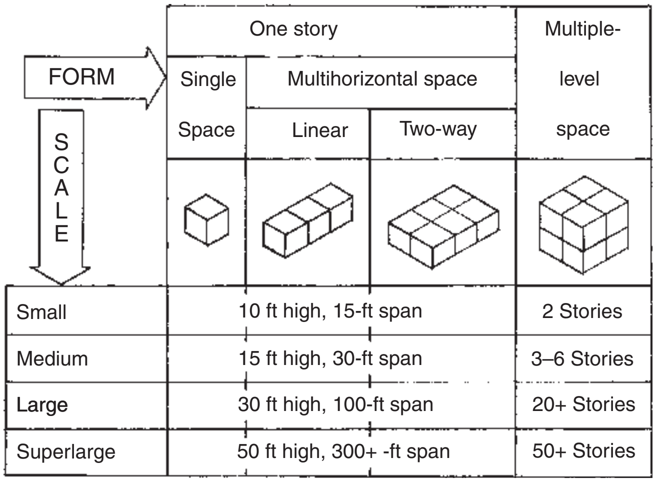


Figure 1.7 Form–scale relationships.

Multiple Horizontal Spaces—Linear Array

This category includes motels, small shopping centers, and school classroom wings. Multiplication may be done with walls that serve the dual function of supporting the roof and separating interior spaces, or it may be done only with multiples of the roof system with the possibility of no interior supports. The roof system has somewhat less geometric freedom than that for the single-space building, and a modular system of some kind may be indicated. (See Figure 1.8.)

Although space utilization and construction simplicity generally will be obtained with the linear multiplication of rectangular plan units, there are some other possibilities, as shown in Figure 1.9. If units are spaced by separate connecting links, more freedom can be obtained for the roof geometry of the individual units.

Structural options remain essentially the same as for the single-space building. If adjacent spaces are significantly different in height or span, it may be desirable to change the system of construction using systems appropriate to the scale of the individual spaces.

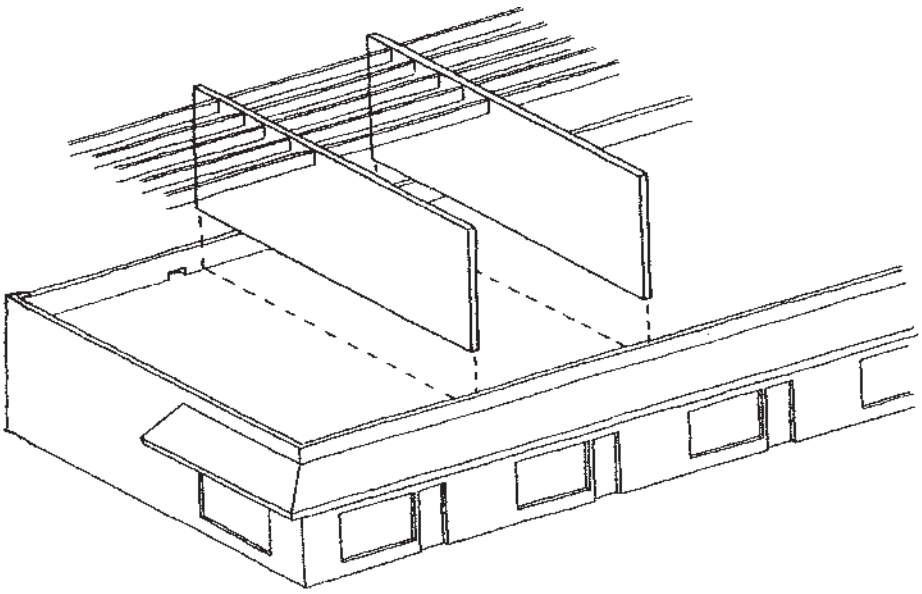


Figure 1.8 Multiple horizontal spaces in a linear array can be produced by a large number of optional structural modules, one of the simplest being the repetition of ordinary bearing walls and rafters.

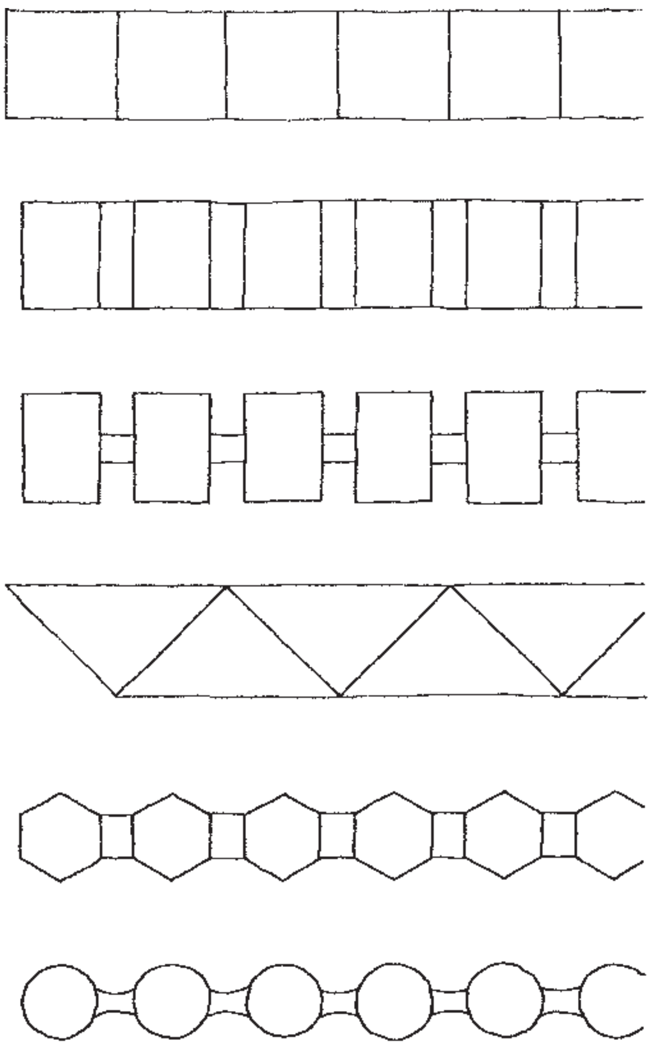


Figure 1.9 Linear plan multiplication.

Multiple Horizontal Spaces—Two-Way Array

This category includes factories, stores, warehouses, and large single-story offices. As with linear multiplication, the unit repetition may be done with or without interior walls, utilizing columns as supporting elements (see Figure 1.10).

Constraints on geometry are greater here than with linear unit multiplication. Modular organization and coordination become increasingly logical for the structure.

Although still possible using linear multiplication, roof structures that are other than flat and horizontal become increasingly less feasible for two-way multiplication. Roof drainage becomes a major problem when the distance from the center to the edge of the building is great. The pitch required for water runoff to an edge is often not feasible, in which case more costly and complex interior roof drains are required.

Multilevel Spaces

The jump from single to multiple levels has significant structural implications.

Need for a Framed Floor Structure. This is a spanning, separating element, not inherently required for the single-story building.

Need for Stacking of Support Elements. Lower elements (bearing walls and columns) must support upper elements as well as the spanning elements immediately above them. This works best if support elements are aligned vertically and imposes a need to coordinate the building plans at the various levels.

Increased Concern for Lateral Loads. As the building becomes taller, wind and earthquake loads impose greater overturning effects as well as greater horizontal forces in general, and the design of lateral bracing becomes a major problem.

Figure 1.10 Two-way multiplication of structural units in a single-story building. The structure is achieved here at a medium scale with a common system: steel posts and beams, light steel truss rafters, and a light-gauge formed sheet steel deck.

Vertical Penetration of the Structure. Elevators, stairs, ducts, chimneys, piping, and wiring must be carried upward through the horizontal structure at each level, and spanning systems must accommodate the penetrations.

Increased Foundation Loads. As building height increases without an increase in plan size, the total vertical gravity load for each unit of the plan area increases, eventually creating a need for a very strong foundation.

The existence of many levels also creates a problem involving the depth or thickness of the spanning structure at each floor level. As shown in Figure 1.11, the depth of the structure (*A* in the figure) is the distance from top to bottom of the complete structure, including structural decking and fireproofing. In many buildings a ceiling is hung below the floor structure, and the space between the ceiling and the underside of the floor contains various items, such as ducts, wiring, sprinkler piping, and recessed light fixtures. Architecturally, the critical depth dimension is the total distance from the top of the floor finish to the underside of the ceiling (*B* in the figure).

The floor-to-floor height, from finish floor level to finish floor level, is the total construction depth (*B*) plus the clear floor-to-ceiling height in each story. Repeated as required, the sum of these dimensions equals the total building height and volume, although only the clear space is of real value to the occupants. There is thus an efficiency ratio of clear height to total story height that works to constrain the depth allowed for the floor construction. While structural efficiency and reduced cost for the structure are generally obtained with increased structural depth, they are often compromised in favor of other cost considerations. Reduction of the building height and allowance for the air-handling ducts will probably push structural efficiency aside. Thus the net dimension allowed for the structure itself—dimension *C* in Figure 1.11—is a hard-fought one.

Sometimes it is possible to avoid placing the largest of the contained elements (usually air ducts) under the largest of the spanning structure's elements. Some techniques for accomplishing this are shown in Figure 1.12.

An important aspect of the multilevel building is the plan of the vertical supporting elements, since these represent fixed objects around which interior spaces must be arranged.

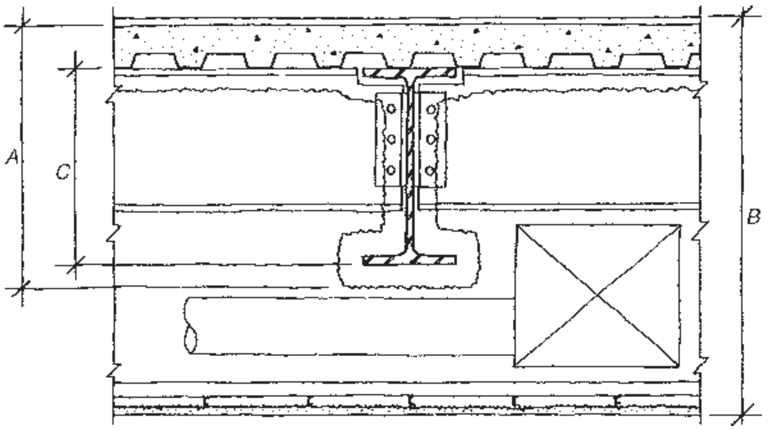


Figure 1.11 Dimensional relationships in the floor–ceiling systems for multistory buildings.

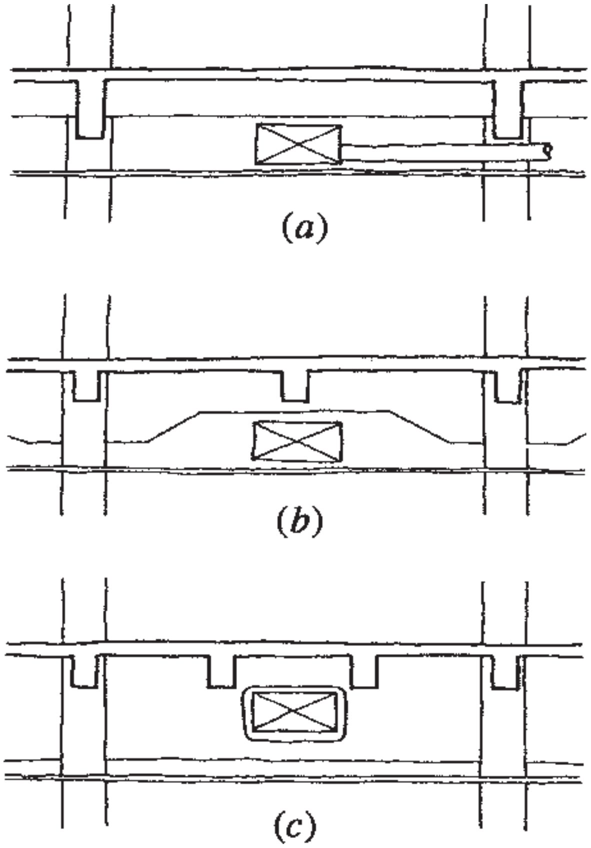


Figure 1.12 Accommodation of air ducts in the floor–ceiling construction: (*a*) by running major ducts parallel to major beams; (*b*) by varying beam depth; (*c*) by penetrating exceptionally deep beams.

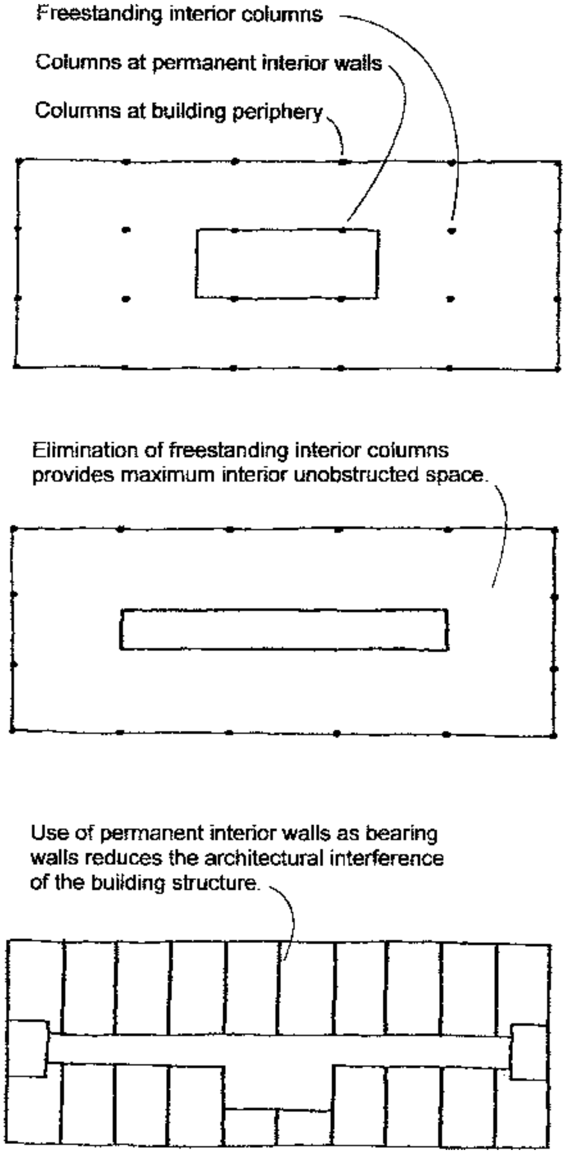


Figure 1.13 Development of vertical supports in multistory buildings.

Because of the stacking required, vertical structural elements are often a constant plan condition for each level, despite possible changes in architectural requirements at the various levels. An apartment building with parking in basement levels presents the problem of developing plans containing fixed locations of vertical structural elements that accommodate both the multiple parking spaces and the rooms of the apartments.

Vertical structural elements are usually walls or columns situated in one of three possible ways, as shown in Figure 1.13:

1. As isolated and freestanding columns or wall units in the interior of the building
2. As columns or walls at the location of permanent features such as stairs, elevators, toilets, or duct shafts
3. As columns or walls at the building periphery

Freestanding interior columns tend to be annoying for planning, because they restrict placement of doors and walls and are usually not desired within rooms. They are clumsy to incorporate into thin walls, as shown in Figure 1.14. This annoyance has motivated some designers to plan buildings with very few, if any, freestanding interior columns. The middle plan in Figure 1.13 shows such a solution, with interior supports only at the location of permanent construction. For buildings with fixed plan modules, such as hotels, dormitories, and jails, a plan with fixed interior bearing walls may be possible, as shown in the lower figure in Figure 1.13.

When columns are placed at the building periphery, their relationship to the building skin has a great bearing on the exterior appearance as well as interior planning. Figure 1.15 shows various locations for columns relative to the building skin wall.

Although freestanding columns (Figure 1.15*a*) are usually the least desirable, they may be tolerated if they are small (as in a low-rise building) and are of an unobtrusive shape (round, octagonal, etc.). The cantilevered edge of the horizontal structure is difficult to achieve with wood or steel framing but may actually be an advantage with some concrete systems.

Placing columns totally outside the wall (Figure 1.15*e*) eliminates both the interior planning intrusion and the

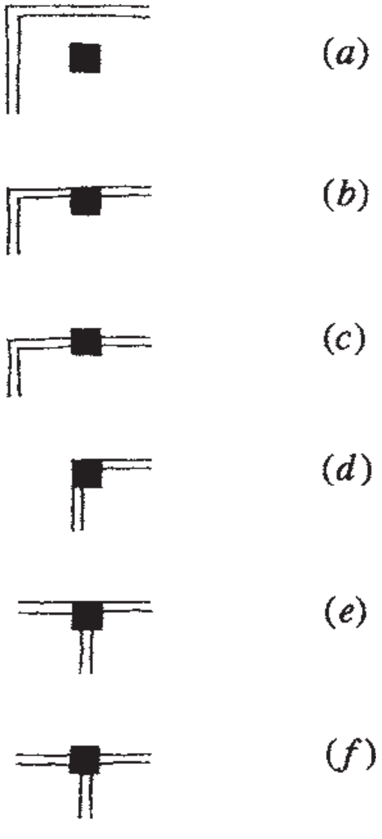


Figure 1.14 Interior column–wall relationships.

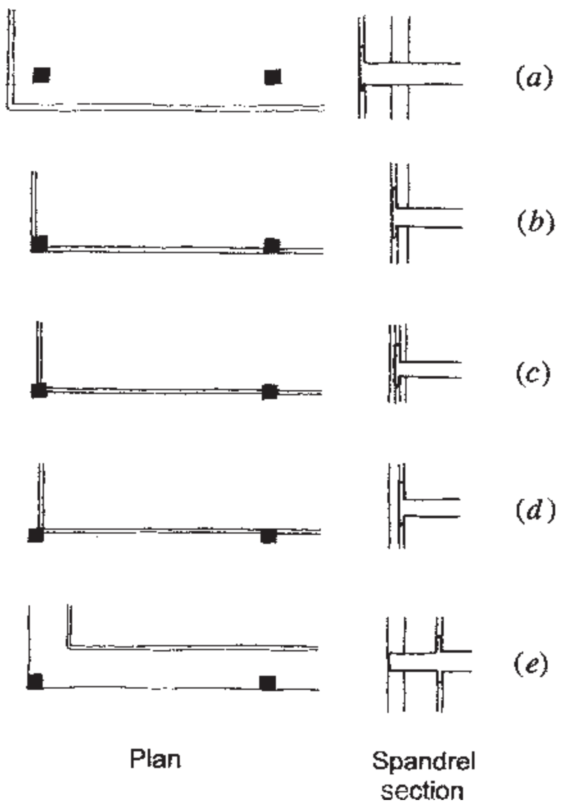


Figure 1.15 Relation of the structure to the building skin.

cantilevered edge. A continuous exterior ledge is produced and may be used as a sun shield, for window washing, as a balcony, or as an exterior balcony corridor. However, unless some such use justifies it, the ledge may be a nuisance, creating water runoff and dirt accumulation problems. The totally exterior columns also create a potential problem with thermal expansion.

If the wall and column are joined, three possibilities exist for the usually thick columns and usually thin wall, as shown in Figures 1.15*b*–*d*. For a smooth exterior surface, the column may be flush with the outside of the wall, although the interior lump may interfere with space use. If the wall is aligned with the interior edge of the column, the interior surface will be smooth (for ease of interior planning) but the outside will be dominated by the strong vertical ridges of the columns. The least useful scheme would seem to be to place the column midway in the wall plane (Figure 1.15*c*). Another solution, of course, is to thicken the wall sufficiently to accommodate the column—a neat architectural trick, but generally resulting in considerable wasted space in the building plan.

In tall buildings, column sizes usually vary from top to bottom of the building, although it is possible to achieve considerable range of strength within a fixed dimension, as shown in Figure 1.16. Although some designers prefer the more honest expression of function represented by varying column size, planning is often simplified by the use of a constant column size.

Planning problems usually make it desirable to reduce column size as much as possible. If size changes for interior columns are required, the usual procedure is to have the column grow concentrically, as shown in Figure 1.17. Exceptions are columns at the edges of stairwells or elevator shafts, where it is usually desirable to keep the inside surface of the shaft aligned vertically, as shown for the corner exterior columns in Figure 1.17.

For exterior columns, size changes relate to the column-to-skin relationship. If the wall is aligned with the inside of the column, there are several ways to let it grow in size without changing this alignment.

In very tall buildings, lateral bracing often constitutes a major concern. In regions of high risk for earthquakes or windstorms, this issue may dominate planning even for small and low-rise buildings.

Building–Ground Relationship

As shown in Figure 1.18, there are five variations of this relationship.

Subterranean Building

Figure 1.18*a* illustrates a situation that includes subway stations, underground parking structures, and bomb shelters. The insulating effect of the ground can be useful in extreme climates. Building surfaces must deal with soil pressures, water, and deterioration in general. Constant contact with the soil limits choices for construction materials.

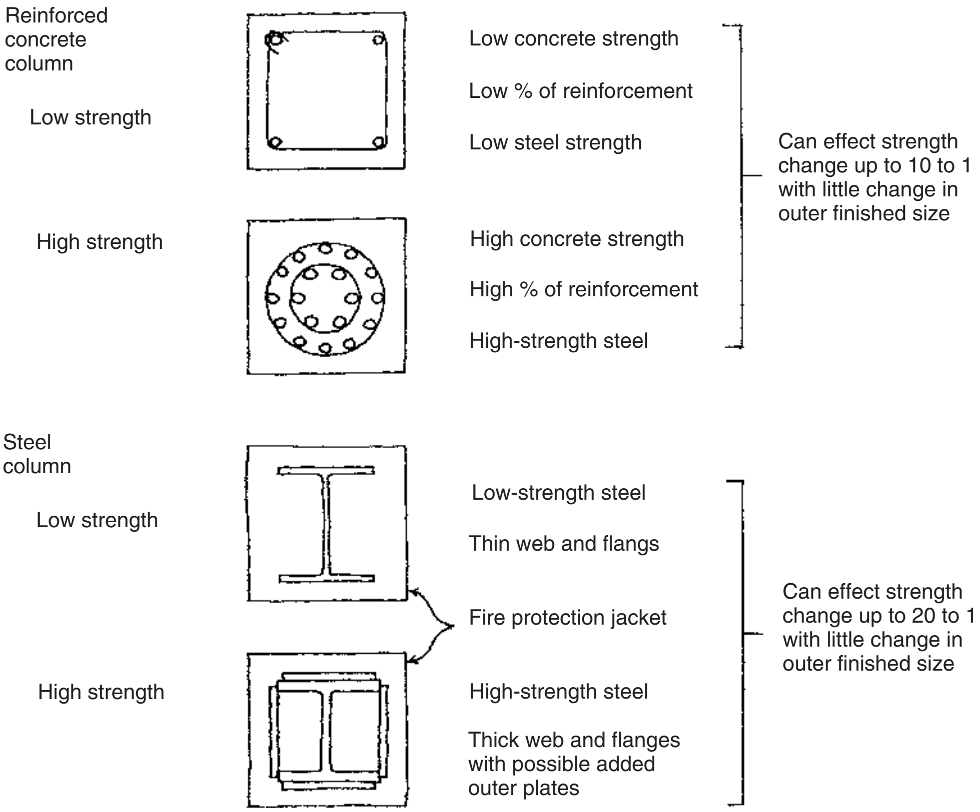


Figure 1.16 Variation in column strength without change in architectural finished size.

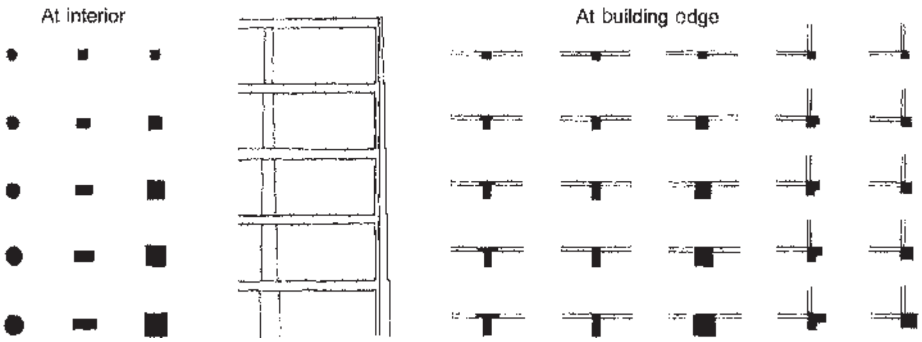


Figure 1.17 Patterns of size increase for columns in multistory buildings.

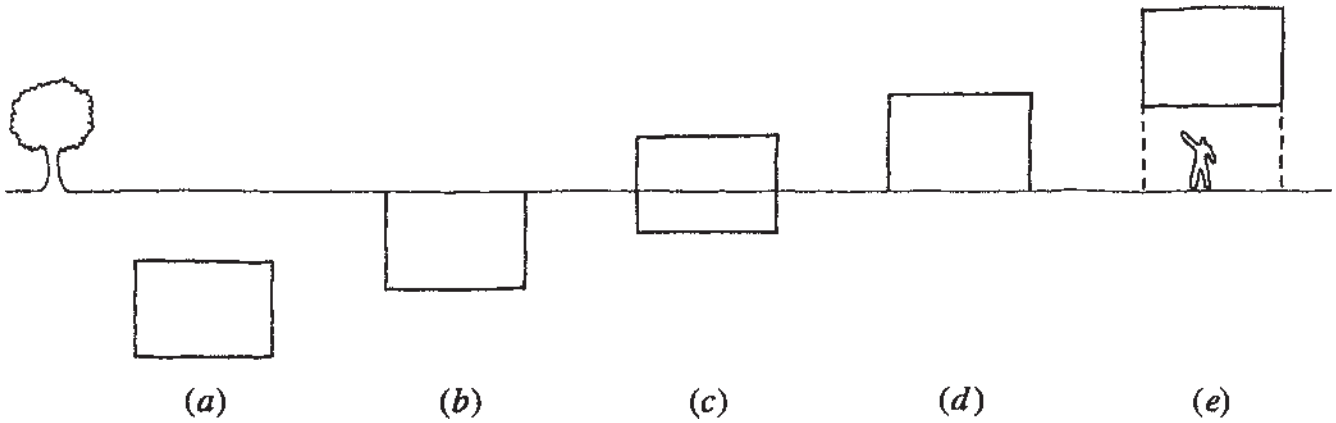


Figure 1.18 Building–ground relationships.

Ground-Level Roof

Figure 1.18*b* illustrates a situation similar to that of the submerged building, except that the exposed top offers some possibilities for light and air. Roof loading is less critical, although some traffic is likely and paving may be required. Some possibilities of opening up the building to dissipate the buried feeling are shown in Figure 1.19.

Partially Submerged Building

In this case the building often consists of two structural elements: the superstructure (above ground) and the substructure (below ground). The structure below ground has all the problems of the submerged building and in addition must support the superstructure. For very tall buildings the loads on the substructure will be very large. Horizontal wind and earthquake forces must also be resolved by the substructure. The superstructure is highly visible, whereas the substructure is not; thus the form of the superstructure is usually of much greater concern in architectural design.

Grade-Level Floor

Years ago basements were common, often required for gravity heating systems and storage of fuel. They were also useful for food storage before refrigeration and for general storage of junk. The advent of forced air heating systems and refrigeration and the high cost of construction have limited the use of basements unless they are needed for parking or housing of equipment.

If there is no basement, the building is reduced to a superstructure and a foundation, with the first floor often consisting of a simple paving slab. A building with no basement and only a shallow foundation system may have a problem regarding anchorage by the substructure for wind and earthquakes.

Above-Ground Building

As shown in Figure 1.20, buildings are sometimes built on legs, are cantilevered, or are suspended so that they are literally in midair. The support structures must be built into the ground, but the building proper may have little or no contact with the ground. The bottom floor of such a building must be designed for the barrier and filter functions usually associated only with roofs and exterior walls. If the floor underside is visible, it becomes an architectural design feature.

1.3 STRUCTURAL FUNCTIONS

Understanding of the work performed by structures requires the consideration of various issues; basic questions involve the following:

- Load sources and their effects
- What the structure actually does in performing its tasks of supporting, spanning, or bracing
- What happens internally in the structure
- What are the specific needs of the parts of the structure

Load Sources

The term *load* refers to any effect that results in a need for some resistive effort on the part of the structure. There are many sources for loads and many ways in which they can be classified. The principal kinds and sources of loads on building structures are discussed below.

Gravity

Source. Weight of the structure and other parts of the building, of occupants and contents, and of ice, snow, or water on the roof.

Computation. By determining the volume, density, and type of dispersion of items.

Application. Vertically downward and constant in magnitude.

Wind

Source. Moving air, in fluid flow action.

Computation. From anticipated maximum wind velocities as established by local weather history.

Application. As pressure perpendicular to exterior surfaces or as frictional drag parallel to surfaces. As a total horizontal force on the building or as action on any single surface.

Earthquakes (Seismic Shock)

Source. Movement or acceleration of the ground as a result of violent subterranean faults, volcanic eruptions, underground blasts, and so on.

Computation. By prediction of the probability of occurrence on the basis of the history of the region

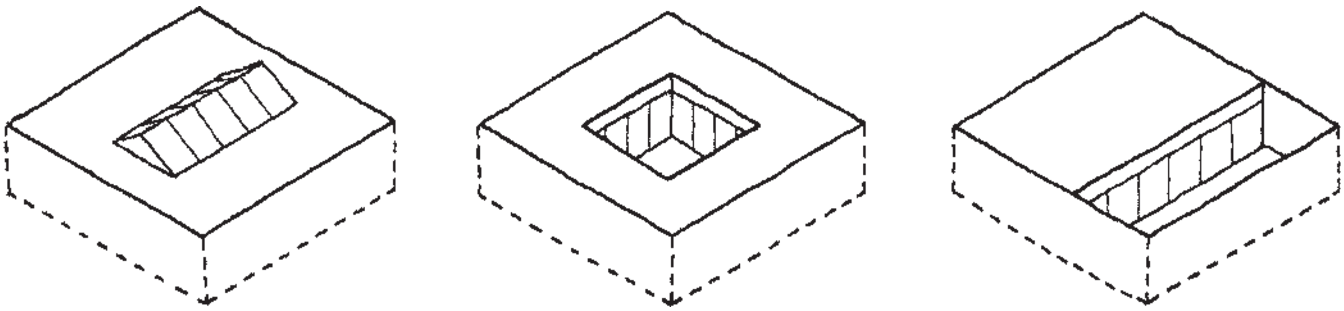


Figure 1.19 Opening up a building with a ground-level roof.

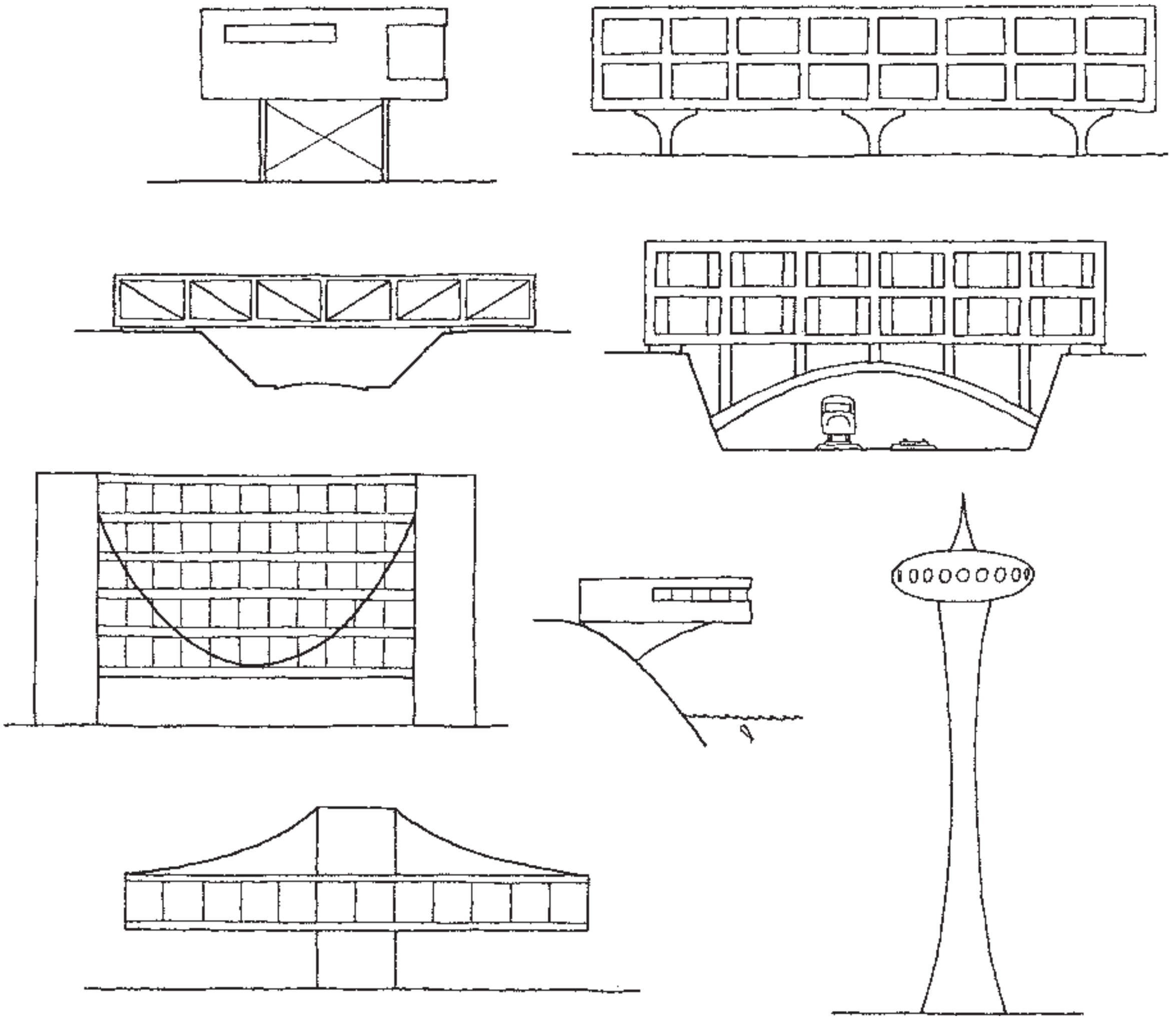


Figure 1.20 Buildings above ground.

and records of previous seismic activity. A principal force on the building structure is generated by the momentum of the building mass once it is moved.

Application. Consideration of the building mass as a horizontal or vertical force with the necessary resistance of the building's bracing system.

Hydraulic Pressure

Source. Principally from groundwater when the free water level in the soil is above the bottom of the building basement floor.

Computation. As fluid pressure proportional to the depth of the fluid.

Application. As horizontal pressure on walls or upward pressure on floors.

Soil Pressure

Source. Action of soil as a semifluid exerting pressure on buried objects or vertical retaining structures.

Computation. By considering the soil as a fluid with the typical hydraulic action of the fluid pressures.

Application. As for hydraulic pressure; horizontally on walls.

Thermal Change

Source. Temperature variations in building materials from fluctuations in outdoor temperature.

Computation. From weather histories, indoor design temperatures, and the coefficients of expansion of the materials.

Application. Forces on the structure if free movement due to expansion or contraction is prevented; stresses within the structure if connected parts have different temperatures or different rates of thermal expansion.

Other Potential Load Sources

Shrinkage. Volume reduction in concrete, plaster, stucco, or mortar in masonry joints as the materials dry out and harden. Dimensional and form changes in large timber members as the wood dries out from the green, freshly cut condition.

Vibration. Oscillations caused by machinery, vehicles, high-intensity sounds, and people walking.

Internal Actions. Movements within the structure due to settlement of supports, slippage of connections, warping of materials, and so on.

Secondary Structural Actions. Horizontal force effects from arches, gabled rafters, or tension structures. Soil pressures from nearby loads on the ground.

Handling of Construction. Forces generated during production, transportation, and erection of structural elements and extra loads from stored materials during construction.

Live and Dead Loads

A distinction is made between *live* and *dead loads.* A dead load is a permanent load, such as the weight of the building construction. A live load is anything that is not permanent, although the term is usually used to refer to loads on building floors.

Static versus Dynamic Loads

A distinction is also made between static and dynamic loads. This has to do with the time-dependent character of the load. As shown in Figure 1.21*a*, the weight of an object is considered static (essentially not moving); however, if the object is impelled, its weight becomes a potential dynamic effect. Dynamic effects include those from ocean waves, wind gusts, and seismic shocks.

The effects of dynamic loads are different for the building and the structure. A steel frame may adequately resist a dynamic load, but the distortion of the frame may result in cracked finishes or perception of movement by the building occupants (see Figure 1.21*b*). A masonry structure, although possibly not as strong as the steel frame, has considerable mass and resistance and may absorb a dynamic load with little perceptible movement.

Load Dispersion

Forces from loads may be distinguished by the manner of their dispersion. Gas under pressure in a container exerts a pressure effect that is uniform in all directions at all points. The dead load of roofing, the weight of snow, and the weight of water on the bottom of a tank are all loads that are

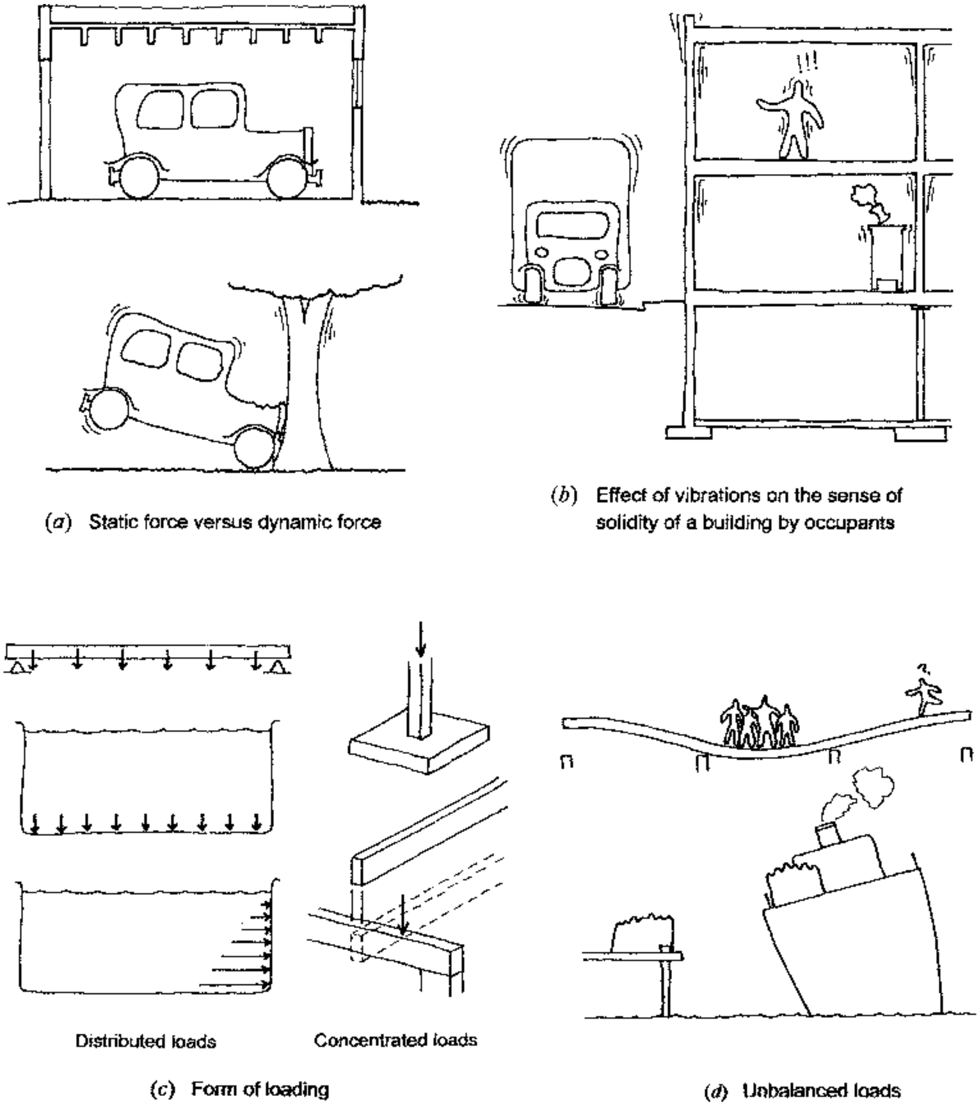


Figure 1.21 Load effects: (*a, b*) static and dynamic effects; (*c*) dispersion of loads; (*d*) unbalanced loads.

uniformly distributed on a surface. The weight of a beam is a load that is uniformly distributed along a line. The foot of a column or the end of a beam represents loads that are concentrated at a relatively small location. (See Figure 1.21*c*.)

Randomly dispersed live loads may result in unbalanced conditions or in reversals of internal conditions in the structure (see Figure 1.21*d*). The shifting of all the passengers to one side of a ship can cause the ship to capsize. A large load in one span of a beam that is continuous through several spans may result in upward deflection in other spans and possibly lifting of the beam from some supports. Because live loads are generally variable in occurrence, magnitude, location, and even direction, several different combinations of them must often be considered in order to determine the worst effects on a structure. Directions for performance of such investigations are given by building design codes.

Load Combinations

A difficult judgment for the designer is that of the likelihood of the simultaneous occurrence of various force effects. Combinations must be considered carefully to determine those that cause critical situations and that have some reasonable possibility of simultaneous occurrence. In most cases, directions for required combinations given by design codes are used, but many designers use their own judgment for other possible concerns.

Reactions

Successful functioning of a structure in resisting various loads involves two considerations. The structure must have sufficient internal strength and stiffness to redirect the loads to the supports without developing undue stress on the materials or an undesirable amount of deformation. In addition, the supports must develop the necessary forces—called *reactions*—to keep the structure from moving or collapsing.

The balancing of the loads from the structure and the reaction forces produces the necessary static condition for the structure. This condition is described as one of *static equilibrium*. Both the magnitudes and form of the support reactions must provide for this balanced condition. The form of the structure is one factor in establishing the character required for the reactions.

For the column in Figure 1.22, the reaction force generated by the support must be aligned with and be equal to the column load and must act upward in response to the downward column load.

Figure 1.22 also shows the reaction forces required for various spanning structures. For the beam with two supports, the two reaction forces must combine to develop a total force equal in magnitude to the beam load and must act upward. For the gable frame, the reactions must also develop vertical forces equal to the loads; however, the supports must also develop horizontal forces to keep the bottoms of the rafters from moving sideways. The net effect for the gabled frame is to have reactions that are not simply directed vertically.

Horizontal-force reaction components are also required for arches and cables. The means for achieving these horizontal reactions becomes more challenging when the spanning structure is supported on the top of tall columns or walls. Options for these supports are discussed in the next section.

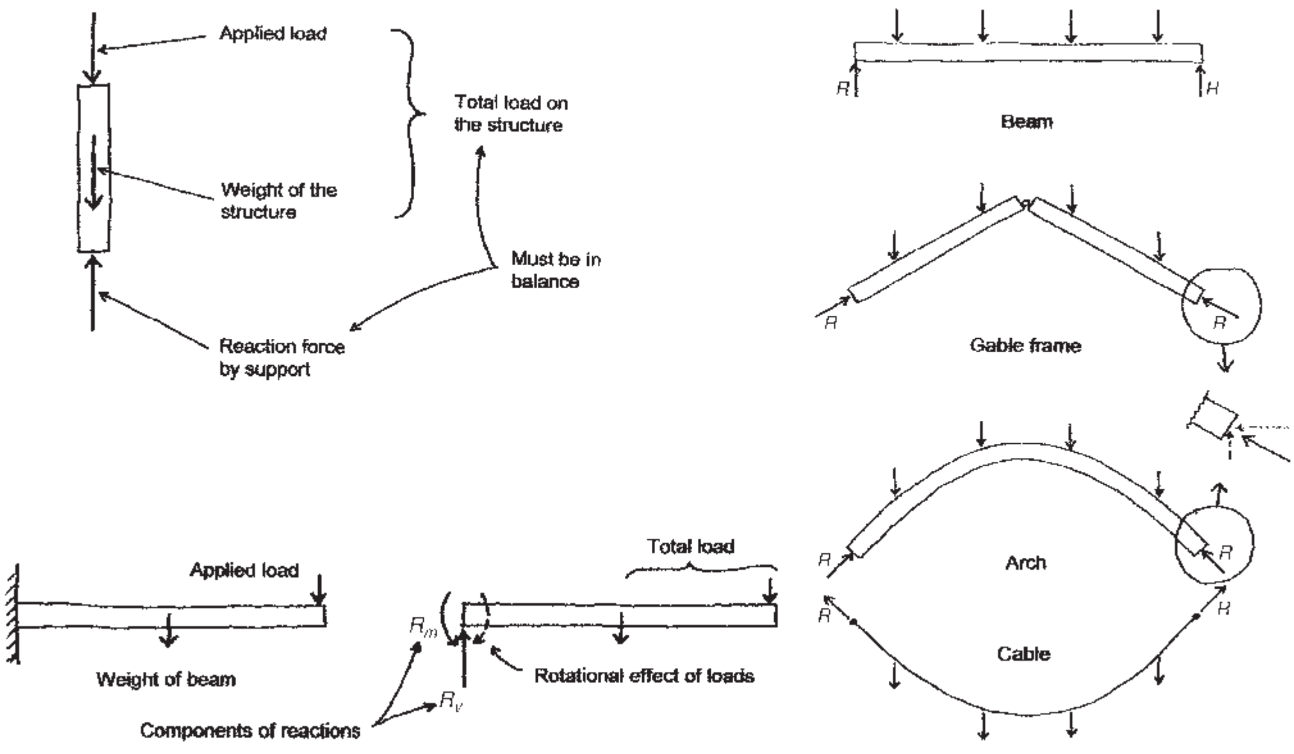


Figure 1.22 Development of reactions.

Another type of reaction force is required for the supported end of a cantilever beam. In this case, it is not sufficient to have simple, direct forces; another effort is required to keep the supported end of the cantilever from rotating. Thus the complete reaction system consists of a vertical force and a rotational resistance—called a *moment*. This combination may be developed for other structures, such as a flagpole.

For the rigidly connected frame shown in Figure 1.23 there are three possible components of the reactions. If vertical force alone is resisted, the bottoms of the columns will rotate and move outward, as shown in Figure 1.23*a*. If horizontal resistance is developed, the column bottoms can be pushed back to their original locations but will still rotate, as shown in Figure 1.23*b*. If a moment resistance is developed

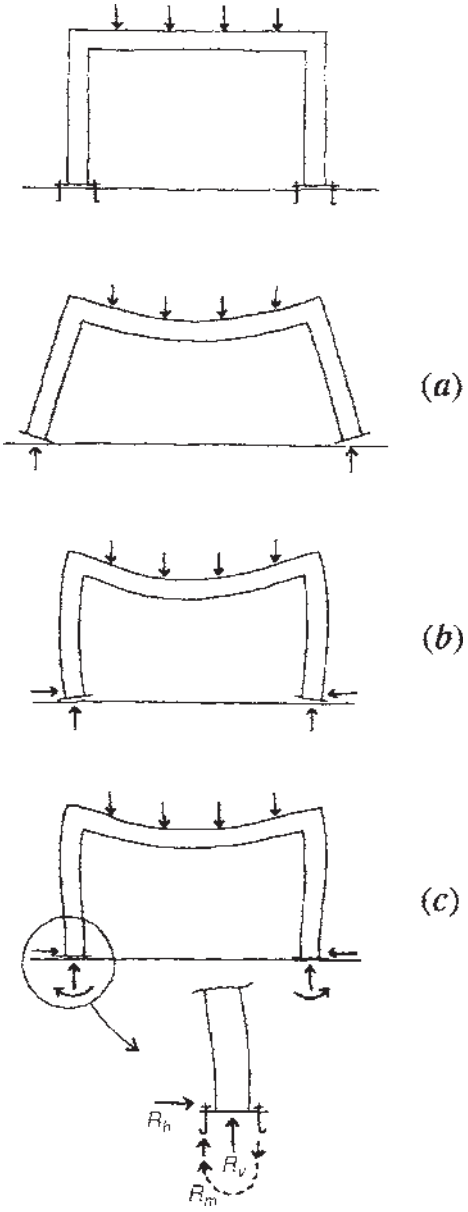


Figure 1.23 Reactions for a rigid frame.

at the supports, the column bottoms can be held entirely in their original position, as shown in Figure 1.23*c*.

The applied loads and support reactions for a structure constitute the external forces on the structure. This system of forces is in some ways independent of the structure's ability to respond. That is, the external forces must be in equilibrium if the structure is to be functional, regardless of the materials, strength, stiffness, and so on, of the structure itself. However, as has been shown, the form of the structure may affect the nature of the required reactions.

Internal Forces

In response to the external effects of loads and reactions, certain internal forces are generated within a structure as the material of the structure strives to resist the deformations induced by the external effects. These internal forces are generated by *stresses* in the material. The stresses are actually incremental forces within the material, and they result in incremental deformations, called *strains.*

When subjected to external forces, a structure sags, twists, stretches, shortens, and so on; or, to be more technical, it stresses and strains. It thus assumes some new shape as the incremental strains accumulate into overall dimensional changes. Whereas stresses are not visually apparent, their accompanying strains often are.

As shown in Figure 1.24, a person standing on a wooden plank that spans two supports will cause the plank to sag downward and assume a curved profile. The sag may be visualized as the manifestation of a strain phenomenon accompanying a stress phenomenon. In this example the principal cause of the structure's deformation is bending resistance, called *internal bending moment*. The stresses associated with this internal force action are horizontally directed compression in the upper portion of the plank and horizontally directed tension in the lower portion. Anyone could have predicted that the plank would assume a sagged profile when the person stepped on it. However, we can also predict the deformation as an accumulation of the strains, resulting in the shortening of the upper portion and the lengthening of the lower portion of the plank.

We would not, of course, want a building floor to sag like the example plank. However, it is useful for investigations to understand internal force actions by the device of visualizing exaggerated deformations.

Because stress and strain are inseparable, it is possible to infer one from the other. This allows us to visualize the nature of internal force effects by imagining the exaggerated form of the deformed structure under load. Thus, although stresses cannot be seen, strains can, and the nature of the accompanying stresses can be inferred. This relationship can be used in simple visualization or it can be used in laboratory tests where quantified stresses are determined by careful measurement of observed strains.

Any structure must have certain characteristics in order to function. It must have adequate strength for an acceptable margin of safety and must have reasonable

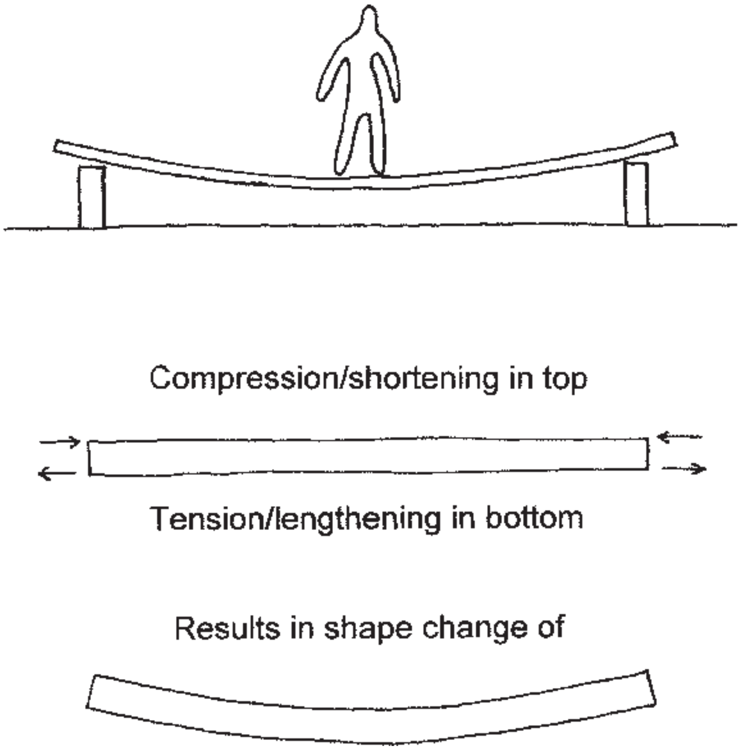


Figure 1.24 Development of bending.

resistance to dimensional deformation. It must also be inherently stable, both internally and externally. These three characteristics—strength, stiffness, and stability—are the principal functional requirements of structures.

Stresses and Strains

There are three basic types of stress: tension, compression, and shear. Tension and compression are similar in nature although opposite in sign or direction. Both tension and compression produce a linear type of strain and can be visualized as pressure effects perpendicular to the surface of a stressed cross section. Because of these similarities, tension and compression are referred to as *direct stresses*; one is considered positive and the other negative.

Shear stress occurring in the plane of a cross section is similar to the frictional sliding effect. Strain due to shear takes the form of angular distortion, rather than the lengthening or shortening due to direct stress.

Dynamic Effects

Vibrations, moving loads, and sudden changes in the state of motion, such as the jolt of braking or rapid acceleration of vehicles, cause force effects that result in stresses and strains in structures. The study of dynamic forces and their effects is complex, although some of the basic concepts can be illustrated simply.

For structural investigation and design the significant distinction between static and dynamic effects has to do with response of the structure to the loading. If the principal response of the structure can be effectively evaluated in static terms (force, stress, linear deformation, etc.), the effect on the structure is essentially static. If, however, the structure's response can be evaluated effectively only in terms such as energy capacity, work accomplished, cyclic movement, and so on, the effect of the loading is of a true dynamic character. Judgments made in this regard must be made in consideration of the adequate performance of the structure in its role in the building system. Performance relates to both structural responses and effects on the building and its occupants.

A critical factor in the evaluation of a structure's response to dynamic loads is the *fundamental period* of the structure's cyclic motion or vibration. This is the time required for one full cycle of motion, in the form of a bounce or a continuing vibration. The relation of this time to the time of buildup of the load is a major factor in the determination of the relative degree of the dynamic effect on the structure. A structure's fundamental period may vary from a fraction of a second to several seconds, depending on the size, shape, mass, materials, stiffness, support conditions, and possible presence of damping effects.

Design for dynamic effects begins with an evaluation of possible dynamic load sources and their potential actions. The response of the structure is then considered using the variables of its dynamic character. Once the dynamic behavior is understood, the designer can consider how to manipulate the variables to improve the structure's behavior or to reduce the load effects.

Design for Structural Behavior

In professional design practice the investigation of structural behavior is an important part of the design process. To 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.

Figure 1.25 Historic construction with hand-hewn timbers and adobe brick walls and arcades.

Categorization of Structural Systems

Structural systems can be categorized in a variety of ways. One broad differentiation is that made between solid structures, framed structures, and surface structures.

Solid Structures

Solid structures are structures in which strength and stability are achieved through mass, even though the structure is not completely solid (Figure 1.26*a*). Large piers, abutments, dams and seawalls, retaining walls, and ancient burial pyramids are examples. These are highly resistive to forces such as those created by blasts, violent winds, wave actions, and intense vibrations. Although exact analysis is usually highly indeterminate, distribution of stresses may be diffuse enough to allow simple approximations with a reasonable assurance of safety.

Framed Structures

Framed structures consist of networks of assembled elements (Figure 1.26*b*). Construction is completed by filling in the voids as required between the spaced frame members. Although the infilling elements may also have a structural character—often serving to brace the frame members, for example—they do not serve as essential components of the frame itself. Animal skeletons, beam and column systems, and trussed towers are examples.

These structures are generally very adaptable to variations in form, dissymmetry of layouts, and the carrying of special loads. They can be cumbersome, however, if the complexity of their assembly becomes excessive. Attachment of infilling elements must also be accommodated. Construction can be achieved in wood, steel, or concrete, and a great range of scale is possible, from the most modest light wood frames (2 by 4s, etc.) to the tallest high-rise structures.

Surface Structures

Surface structures can be very efficient because of their simultaneous twofold function as structure and enclosure (Figure 1.26*c*). They may also be very stable and strong, especially in the case of three-dimensional forms. They are, however, somewhat limited in resisting most concentrated loads and in facilitating any sudden discontinuities such as openings. They are also quite dominant as building form givers, which may be useful or not for the building's functions.

Other categorizations can be made for particular types of construction or configuration of the structure. Thus we describe certain family groups such as structural walls, post and beam, arch, suspension, pneumatic, trussed folded plate,

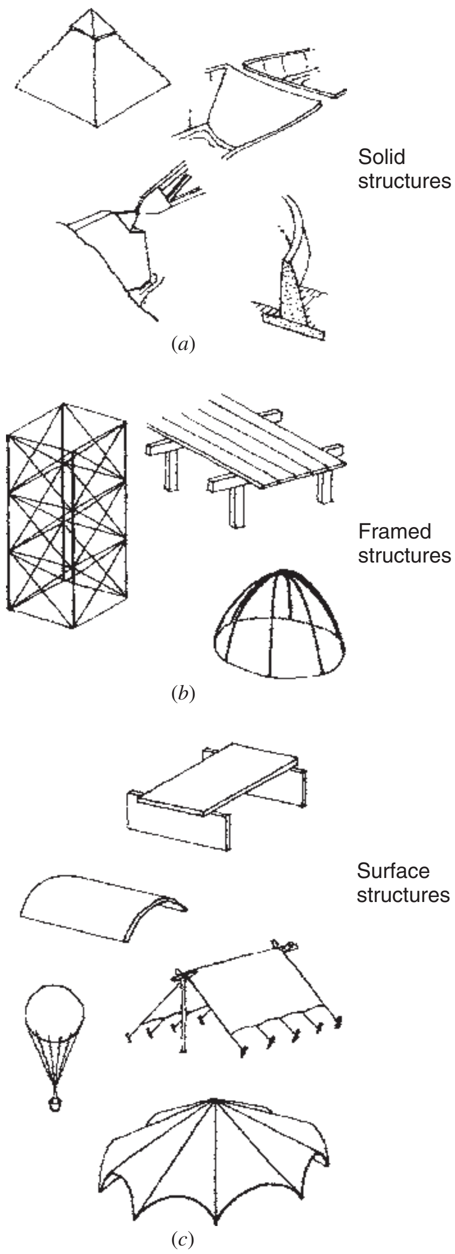


Figure 1.26 Categorization of structures by basic constructive nature.

or thin shell systems. Each of these has certain characteristics and is subject to specific material–scale limitations. Each lends itself most aptly to certain uses. A knowledge of the specific attributes of the various systems is essential to the designer but can be gained only by exhaustive study and some design experience. The inventive designer can, of course, consider new variations of the basic systems and possibly invent systems with no existing categorical identification.

A complete presentation of all structural materials and systems and a discussion of their relative merits, potentialities, and limitations would undoubtedly fill a volume several times the size of this book. Nevertheless, a short survey of traditional systems with some commentary follows. The categorization used—for example, post and beam—has no particular significance; it is merely a convenient one for discussion.

Structural Walls

It seems to be a direct structural development to use the enclosing and dividing walls of a building for support and bracing. When this system is utilized, there are usually two distinct elements in the total building structure:

Walls. Used to provide lateral stability for the building as well as to support the spanning elements.

Spanning Elements. Functioning as roofs and floors and as definers of clear-span interior spaces.

The spanning elements are usually structurally distinct from the walls and can be considered separately. They may consist of a variety of assemblies, from simple wooden joists and decks to complex precast concrete or trussed systems. The flat-spanning system is discussed as a separate category. However, if either the supporting walls or the spanning systems have some modular, repeating dimension or form, some codependent relations must be considered for the two systems. They will be joined, and the joining must be considered.

Bearing walls are essentially compression elements. They may be of monolithic form (like a brick wall) or may actually be frameworks assembled of many pieces (like a wood stud wall). They may be uninterrupted, or they may be pierced in a variety of ways (see Figure 1.27). Holes for windows and doors may be punched in the solid wall, and as long as their heads are framed and they are arranged so as not to destroy the structural potential of the wall, the structure remains intact.

Even when not used for support of vertical loads, walls are often used to provide lateral stability for the building. This can be achieved by having the wall acting independently or in combined interaction with the structural frame. An example of the latter is a plywood sheet surfacing attached to wooden studs. Even if it does not share in vertical-load development, the plywood attached to the studs will prevent collapse of the studs in the direction of the wall plane. This lateral bracing potential of the rigid wall plane (called *shear wall action*) is extensively used in bracing wood frame structures against wind and earthquake forces.

Consider the simple structure shown in Figure 1.28, which consists of a single space bounded by four walls and a flat roof. The two end walls in the upper illustration are capable of resisting horizontal forces in a direction parallel to the plane of the walls. However, horizontal forces in a direction perpendicular to the plane of the walls would not be resisted easily. If the other two walls of the building are also rigid, they may, of course, function to resist forces parallel to their planes. However, if these walls lack the structural capacity to function as shear walls, one device that may be used is to turn the ends of the end walls slightly around the

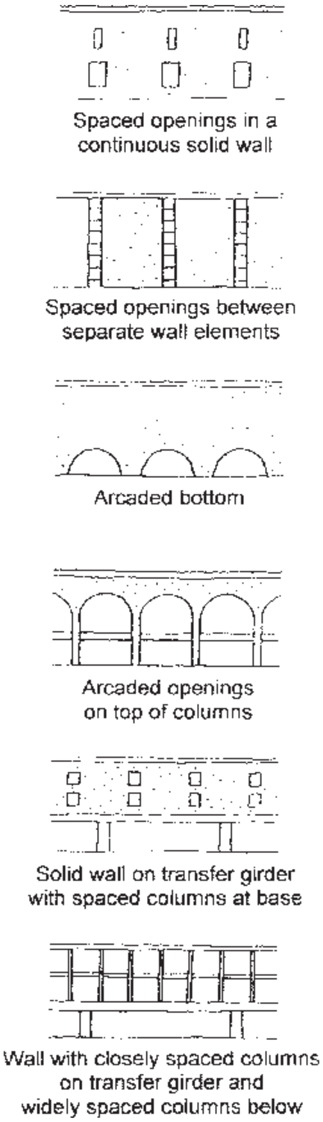


Figure 1.27 Opening up the structural wall.

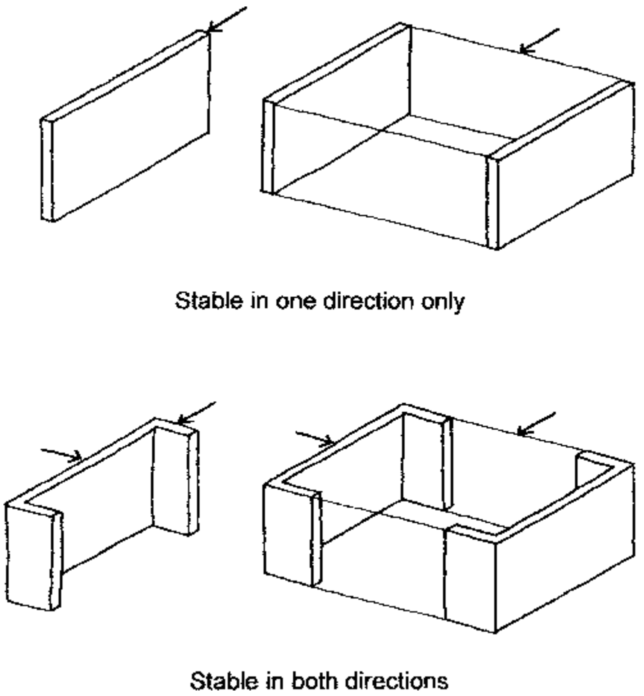


Figure 1.28 Lateral stability of walls.

corners, as shown in the lower illustration. This makes the walls independently stable against horizontal forces from all direction.

The device just illustrated is one technique for stabilizing the flat wall against horizontal forces perpendicular to the wall. It may also be necessary to stabilize the wall against buckling under vertical loads if it is very tall and thin. In addition to folding or curving the wall in plan, some other means for achieving transverse resistance are as follows (see Figure 1.29):

Spreading the Base. This can be done by thickening the wall toward its base, as with a gravity dam, or by attaching the wall rigidly to a broad footing.

Stiffening the Wall with Ribs. This is done most often to brace tall walls against buckling or to provide localized strength for heavy concentrated loads on top of the wall.

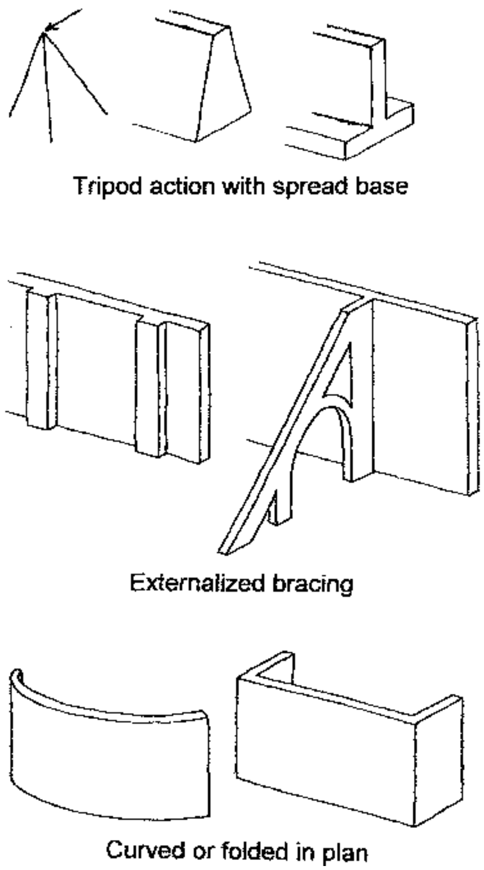


Figure 1.29 Means of stabilizing walls.

Figure 1.30 Simply detailed wood framing produces a structure with a clear lineage of historical development. Close inspection, however, reveals quite evidently that the elements are of contemporary industrialized origin, as opposed to the rough-hewn elements seen in Figure 1.25.

Providing Externalized Bracing. In addition to large vertical ribs, various bracing may be provided for the walls in the direction perpendicular to their planes. An example, as shown in Figure 1.29, is the flying buttress, extended at some distance outside the wall plane.

Exterior walls may also be braced by interior walls that intersect them, a common situation in buildings with multiple interior spaces.

Post and Beam Systems

Primitive cultures' use of tree trunks as building elements was the origin of this basic system. Later expansion of the vocabulary of construction materials into stone, masonry, concrete, and metals carried over the experience and tradition of form and detail established with wood. This same tradition, plus the real potentialities inherent in the system, keeps this building technique a major part of our structural repertoire. (See Figure 1.30.)

The two basic elements of the system are the post (column) and beam (lintel):

Post. Essentially a linear compression member subject to crushing or to lateral buckling depending on its relative slenderness.

Beam. Essentially a linear member subjected to transverse loading; must develop resistance to shear, bending, and excessive deflection (sag).

Critical aspects of the system are the ratio of height to thickness of the post and the ratio of span to depth of the beam. Efficiency of the beam cross-sectional shape in resisting bending is also critical.

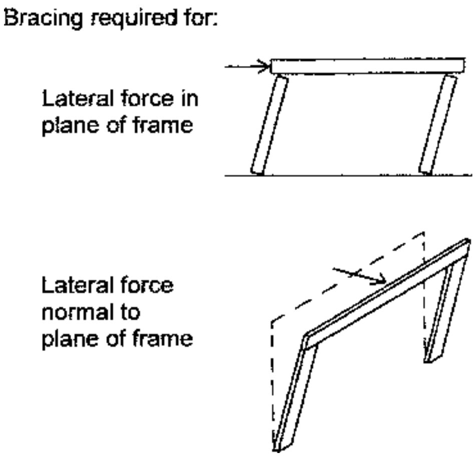


Figure 1.31 Bracing of framed structures against horizontal forces. See also the considerations for walls as shown in Figures 1.28 and 1.29.

The stability of the system under horizontal load is critical in two different ways (see Figure 1.31). Consider first the resistance to horizontal force in the same plane as the frame. This resistance can be provided in a number of ways, for instance, by fixing the posts rigidly to the base supports, connecting the posts rigidly to the beams, or using trussing or a shear wall paneling.

Stability against horizontal force perpendicular to the plane of the frame is a slightly different situation. This is similar in many ways to the wall in the same situation. In real design of whole building structures, horizontal forces (especially those due to wind or earthquakes) must be considered by studying the entire, three-dimensional building structure. In buildings of very complex form this is no small task.

A critical design problem with all framework systems is that of generating the infilling systems that turn the frame into a building. Thus, the development of wall, roof, and floor surfaces must be considered as an addition to the frame design itself. Many possible combinations must be considered. Design criteria and performance needs vary for the many elements of the whole building construction.

As with the situation illustrated in Figure 1.30, parts of frame systems are often exposed to view, adding additional design concerns regarding architectural issues to those of the structural design. Choice of materials, details of frame connections, and shape of individual elements will be given much consideration beyond simple structural performance.

Since walls provide only vertical elements of the building construction, various other elements must be considered for completion of the building roof and floors. Thus, since walls need some framing for completion of the system, and frames need infilling walls, many negotiated solutions are offered.

Some variation on the basic post and beam system are the following (see Figure 1.32):

Use of Extended Beam Ends. Produces beam overhangs, or cantilevers. This serves to reduce the degree of bending and sag at the center of the span, thus increasing the relative efficiency of the spanning element.

Rigid Attachment of Beam and Posts. One device for producing stability in the plane of the frame. It achieves some reduction of bending and sag at the center of the beam span but does so at the expense of the post—in contrast with the extended beam ends. It also produces an outward kick at the base of the posts.

Rigid Attachment with Extended Beams. Combines the two previous variations; also reduces the outward kick of the post bases.

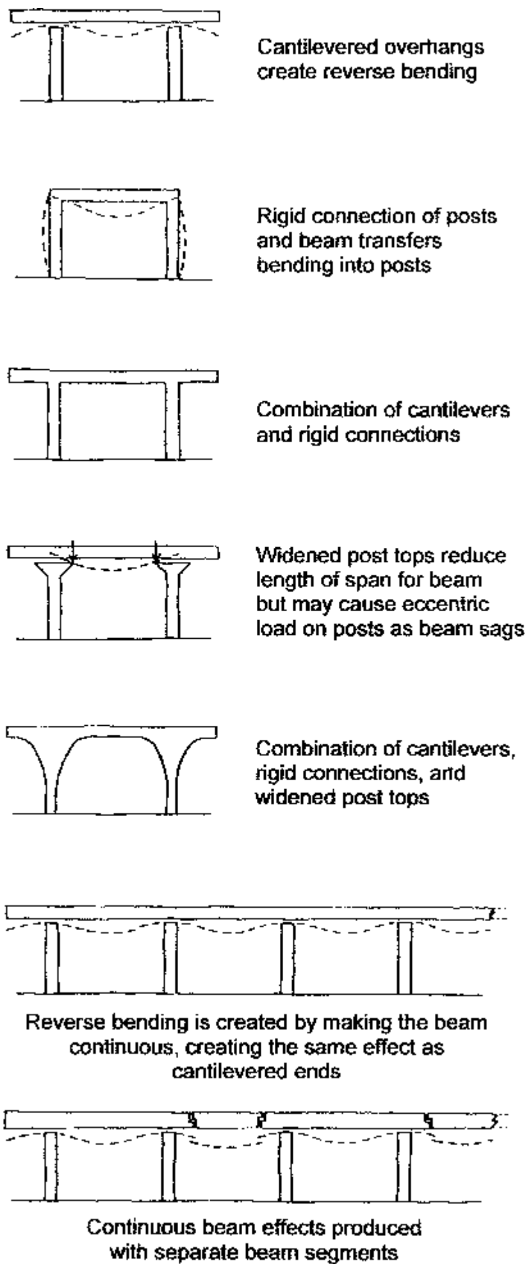


Figure 1.32 Variations of the post and beam.

Widened Top of Post. Serves to reduce the span of the beam. As the beam deflects, however, its load becomes concentrated at the edge of the widened top of the post, thus causing bending in the post. V-shaped or Y-shaped posts are possible variations.

Widened Post Top with Rigid Attachment and Extended Beam Ends. Combines the advantages of all three techniques.

Continuous Beams. Produces beneficial effects similar to those gained by the extended ends of the single span beam.

Additional gain is in the tying together of the system. A variation in which internal beam joints are placed off the columns preserves the advantages of the continuous beam but allows shorter beam segments. The latter is an advantage with beams of wood, steel, and precast concrete. Poured-in-place concrete can achieve virtually any length in a single piece form, although practical limits exist.

As with the framed wall-bearing structure, the post-and-beam frame requires the use of secondary systems for infilling to produce solid surfaces of walls, roofs, and floors (see Figure 1.33). A great variety is possible for these systems, as described in the discussion of structural walls. One possible variation with masonry or cast concrete systems is to combine the post and wall monolithically, producing a series of pilasters. Similarly, the beam and flat deck may be combined monolithically, producing a continuous ribbed deck or a series of T-shaped beams.

The post-and-beam system suggests the development of rectilinear architectural forms and spaces. The beams may, however, be curved in plan, tilted from the horizontal (as commonly done with roof rafters), or have other than a flat top or bottom. Posts can be T-shaped, Y-shaped, V-shaped, or multitiered. The system, in fact, lends itself to a greater degree of variation than practically any other system, which is one reason for its continuing widespread use (see Figure 1.34).

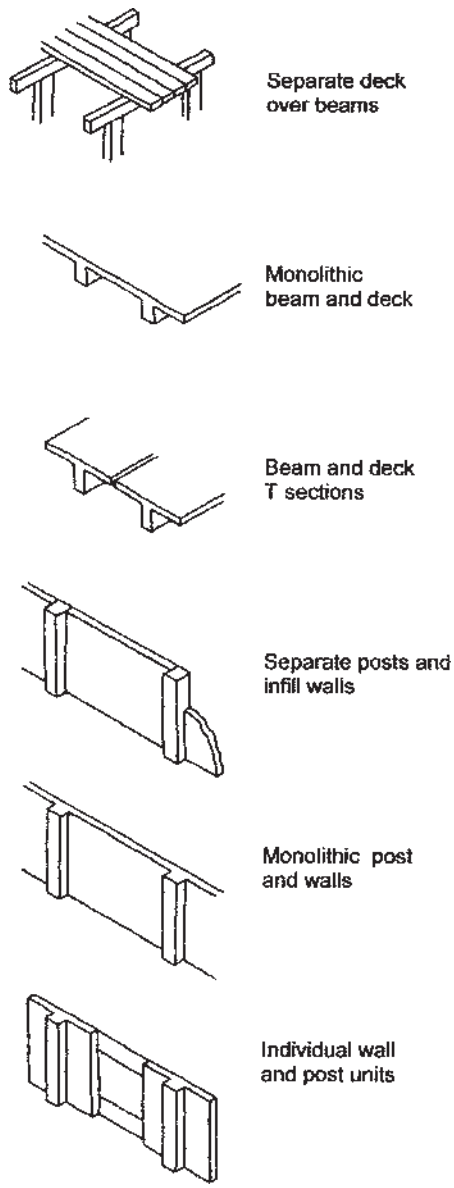


Figure 1.33 Infilling the post-and-beam system.

Rigid Frames

When the members of a linear framework are rigidly attached—that is, when the joints are capable of transferring bending between members—the system assumes a particular character. If all joints are rigid, it is impossible to load any one member transversely without causing bending in all members. This property and the inherent stability and redundancy of the system are its unique aspects in comparison to the simple post-and-beam system. The rigid-frame action may be restricted to a single plane or it may be extended in all directions in the three-dimensional framework. (See Figure 1.35.)

The joints take on a high degree of importance in this system. In fact, in the usual case, the highest magnitude of stresses and internal forces are concentrated at the joints. If the frame is assembled from separate members, the jointing must be developed carefully for structural function and feasibility.

A popular form of rigid frame is the gabled frame, in which two slanted elements are joined at the peak. When the slanted members sit on top of columns, one method for preventing the tops of the columns from spreading outward is to make one column and one sloping member into a single piece. This simple rigid frame can be executed in steel, laminated wood timber, or precast concrete.

Occasionally, the rigid-frame action is objectionable—for instance, when the beam transfers major bending to a small column or causes large curvature or an outward movement at the base of the column. It is sometimes necessary to avoid the rigid-frame action deliberately or to control it by using special joint detailing that controls the magnitude of bending or turning of the joints.

Flat-Spanning Systems

Compared to the arch, the dome, or the draped cable, the flat-spanning structure is very hardworking. In fact, it is exceeded only by the cantilever in this respect. Consequently,

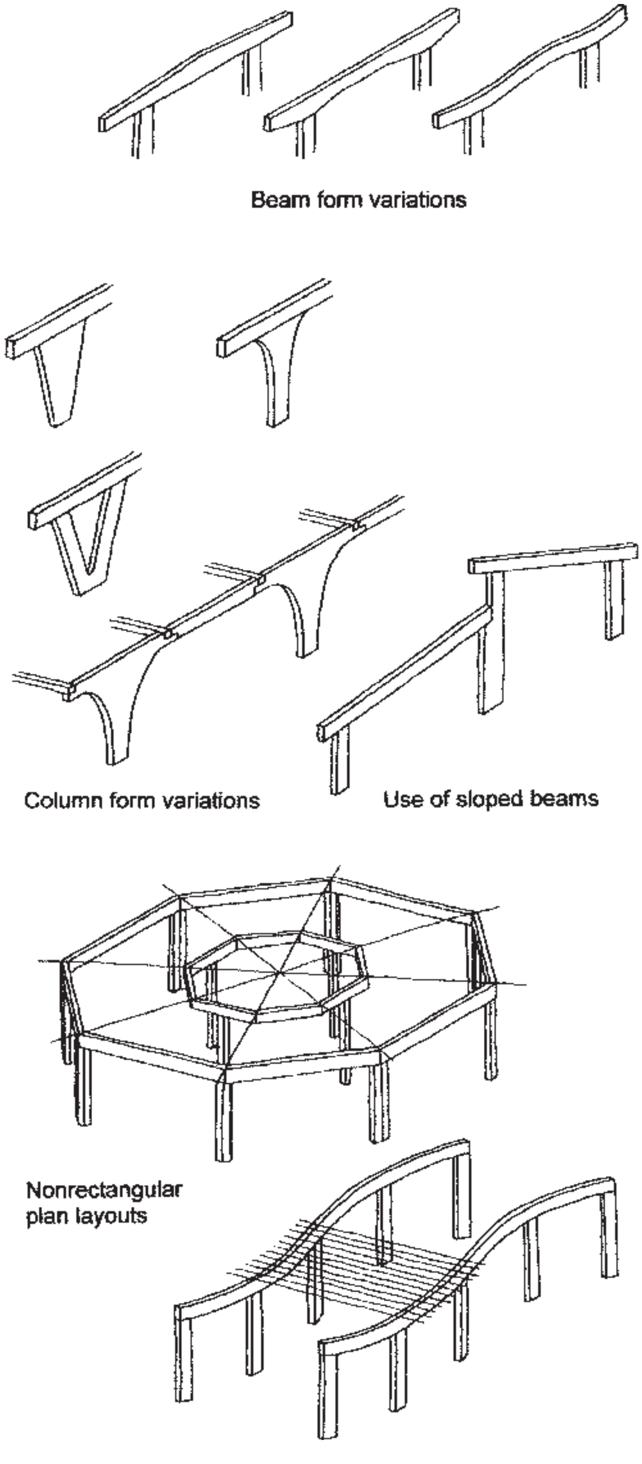


Figure 1.34 Form variations with the post-and-beam system.

scale limits for spans can be overcome by various techniques that improve the efficiency of the spanning elements. One of these is to develop the system as a two-way rather than a one-way spanning system (see Figure 1.36). This sharing of the spanning effort reduces the magnitude of bending as well as the deflection of the system.

Maximum benefit is derived from two-way spanning if the spans are equal. The more different they become, the less the work accomplished in the longer span. At a 2 : 1 ratio, less than 10% of the resistance will be offered by the longer span.

The other chief device for increasing efficiency is to improve the bending character of the spanning elements. A simple example is the difference in effectiveness illustrated by a flat sheet of paper and one that has been pleated or corrugated. The concept involved is that of increasing the depth of the element. A critical relationship in the flat span is the ratio of the span to the depth. Load capacity falls off rapidly as this ratio is pushed to its limits. Resistance to deflection is often more critical than bending stress in this situation.

Efficiency can also be increased by extending the elements beyond their supports, by using monolithic elements continuous over several supports, or by developing bending transfer between the elements and the supports.

Trussed Systems

A framework of linear elements connected by joints can be stabilized independently by guys, struts, rigid infilling, or rigid-frame action. Another means of achieving stability is through the arrangement of the elements in triangular forms (see Figure 1.37). This is called *trussing*, and when the structural element produced is a flat-spanning form, it is called simply a *truss*.

The triangulated frame can also be used to produce other structural forms, such as towers, rigid frames, arches, and two-way flat-spanning systems. Or, virtually any form of structure can be produced, such as the Statue of Liberty in New York Harbor.

There are two basic principles that work to make the truss an efficient system. The first is the self-stabilizing nature of the triangle, which cannot be changed in form without changing the length of a side. The other is the high efficiency of placing interacting elements at the greatest distance apart.

The multiplicity of joints in trussed systems makes their detailing a major item in truss design. The logic of form of the linear truss members derives as much, if not more, from the jointing as from their function as tension-resistive or compression-resistive elements. The elimination of bending and shear in the truss members is, by the way, another basic concept for the truss and is actually or essentially achieved in most trusses. One design aim in truss design is to avoid loading truss members directly; instead, loads and supports are located at truss joints. However, in developing roof, floor, or ceiling infill systems, it is sometimes necessary to make attachments to the top or bottom members directly. In the latter case, the members have a dual function—first as truss members and then as beams, with the two functions occurring at the same time.

An almost infinite variety of truss configurations is possible. The particular configuration, the loads sustained, the dimensional scale, the truss materials, member forms, and jointing methods are all design considerations.

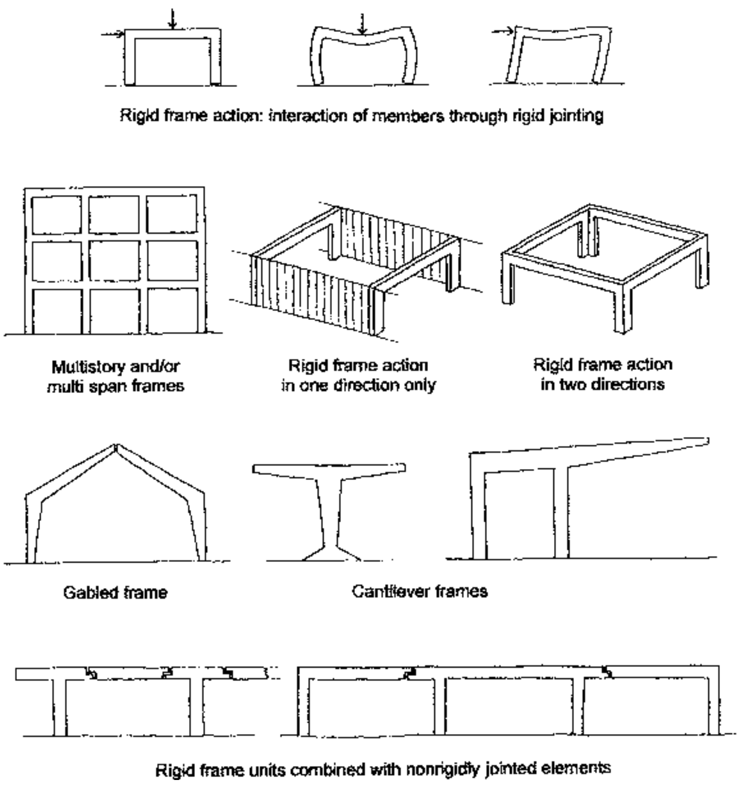


Figure 1.35 Rigid frames.

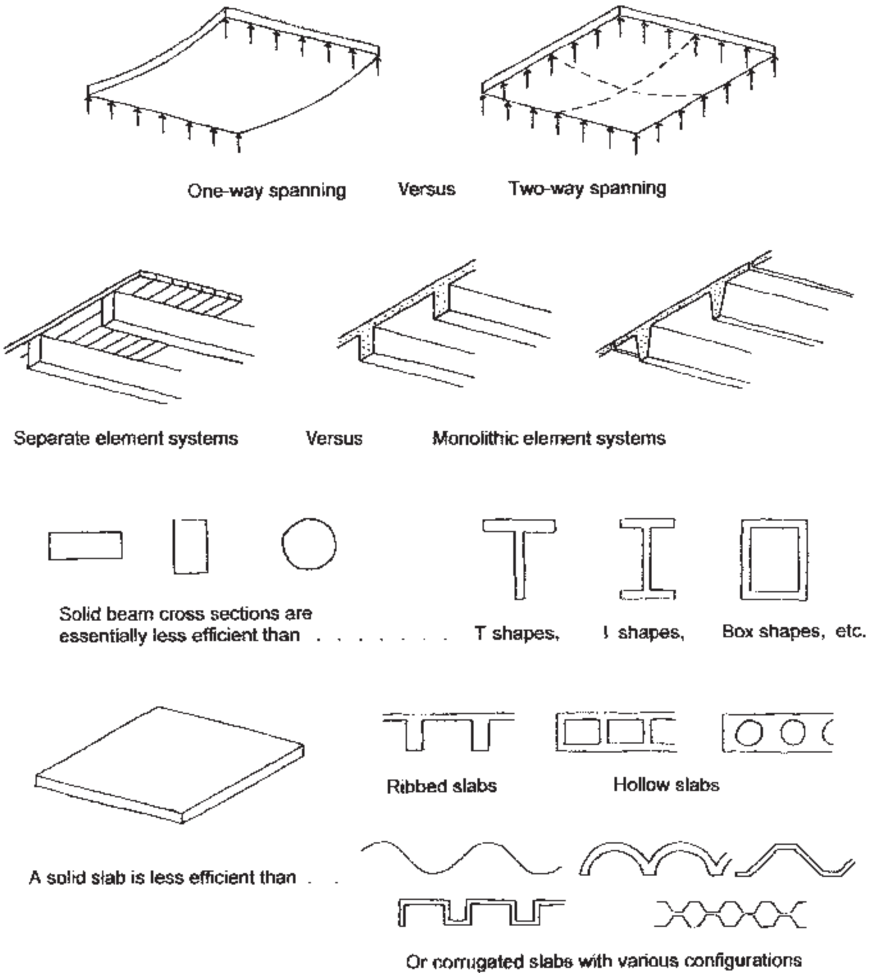


Figure 1.36 Basic aspects of flat-spanning systems.

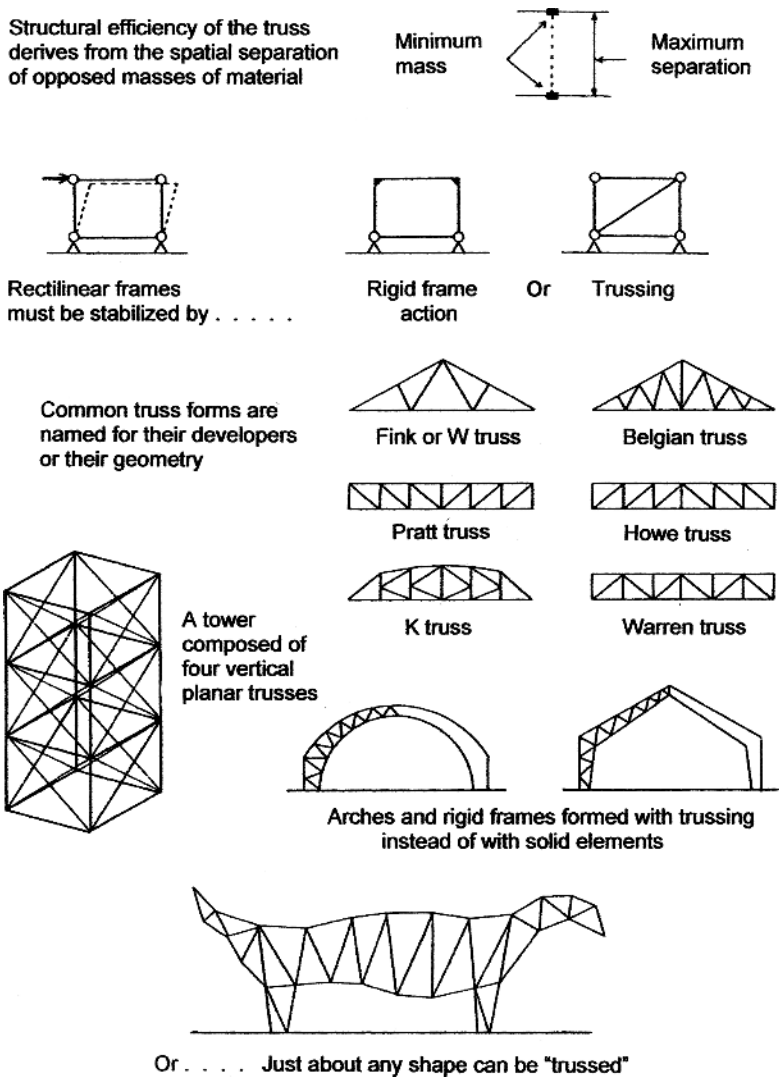


Figure 1.37 Basic aspects of trussed structures.

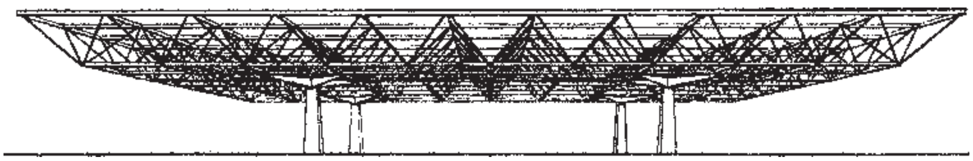


Figure 1.38 Two-way spanning truss. Roof for a high school basketball arena.

The two-way spanning truss—often called a *space frame*, although the term is rather confusing—has been developed with various configurations and at a range of span sizes, mostly with steel truss members. The structure shown in Figure 1.38 uses a form of configuration, first developed by the Unistrut Company in the 1950s, consisting of a series of square-based pyramids that relates well to rectangular plan layouts. This system, and other options for two-way spanning trusses, is discussed in Section 10.10 for Building Nine of the case studies.

Arch, Vault, and Dome Systems

The basic concept in the arch is the development of a spanning structure through the use of only internal compression (see Figure 1.39). The profile of the "pure" arch may actually be derived from the loading and support conditions. For a single-span arch with no fixity at the base in the form of moment resistance, with supports at the same level, and with a uniformly distributed load on the entire span, the resulting form is that of a parabola. Most arches, however, are circular in profile, which works alright as long as the arch is reasonably thick.

Basic considerations are the necessary horizontal forces at the base and the ratio of span to rise. As this ratio increases, the arch form becomes flatter and the thrust increases, producing greater compression in the arch and larger horizontal forces at the supports. Thus, most old stone arches have considerable rise with the familiar tall curved form.

In the great stone arches of old the principal load was the weight of the heavy stone itself. Although other forces existed,

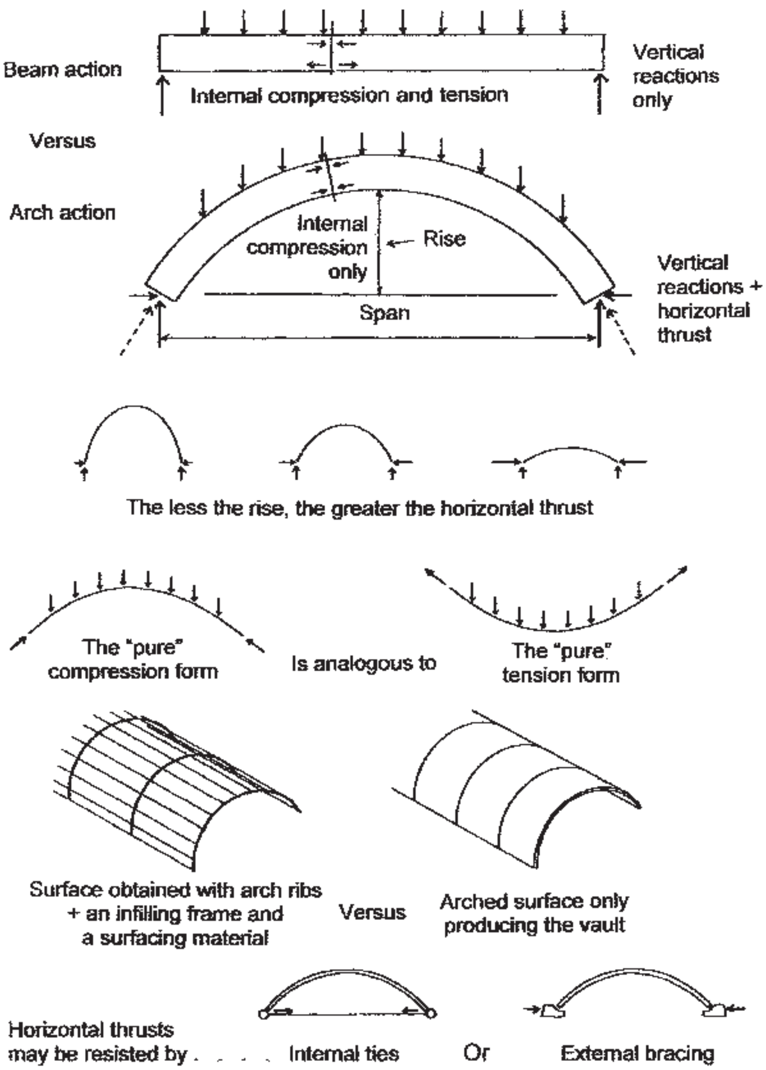


Figure 1.39 Basic aspects of arches.

they were usually incidental compared to the gravity force. In most contemporary construction, thinner and lighter arches are produced and the pure arch action is seldom achieved.

The thrust of the arch—that is, the horizontal component—is resolved in one of two ways. The most direct way is to balance the force at the supports against each other by using a tension tie across the base of the arch. This very possibly, however, destroys the interior vaulted space defined by the arch and is therefore not always acceptable. The second way is to resolve the outward kick at each support outside the arch. This means creating a heavy abutment or, if the arch rests on top of a wall or column, creating a strut or a buttress for the wall or column.

A major consideration in the structural behavior of an arch is the nature of its configuration. The three most common cases are those shown in Figure 1.40, consisting of the fixed arch (Figure 1.40*a*), the two-hinged arch (Figure 1.40*b*), and the three-hinged arch (Figure 1.40*c*).

The fixed arch occurs most commonly with reinforced concrete bridge and tunnel construction. Maintaining the fixed condition (no rotation) at the base is generally not feasible for long-span arches, so this form is more often used for short to medium spans. It may occur in the action of a series of arches built continuously with their supporting piers, as shown in Figure 1.40*a*. The fixed arch is highly indeterminate in its actions and is subject to internal stress and abutment forces as a result of thermal expansion.

The two-hinged arch is most common for long spans. The pinned base is feasibly developed for a large arch and is not subject to forces as a result of thermal change to the degree of the fixed-arch base. This arch is also indeterminate, although not to the degree as the fixed arch.

The three-hinged arch is a popular form for medium-span building roof structures. The principal reasons for this popularity are the following:

The pinned bases are more easily developed than fixed ones, making shallow bearing-type foundations reasonable for the medium-span structure.

Thermal expansion and contraction of the arch will cause vertical movements at the peak pin joint but will have no appreciable effect on the bases. This further simplifies the foundation design.

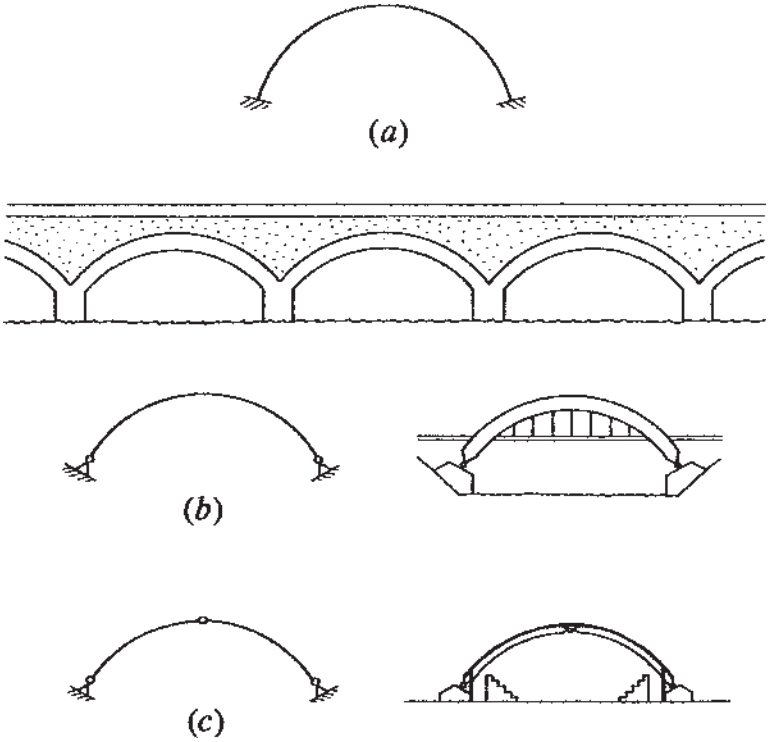


Figure 1.40 Types of arches.

For small spans, construction can often be achieved by use of prefabrication for the two arch sections and connecting them at the peak in the field. The pin joint is much easier to achieve under these circumstances.

For a uniformly distributed loading applied over the horizontal span of the arch, the net internal compression follows a parabolic profile. However, uneven loadings and effects of wind and earthquakes will result in other internal force effects of bending and shear. If the arch itself is very heavy, the parabolic form may have some significance. Otherwise, with construction that can resist bending and shear (laminated wood, steel, or reinforced concrete), the arch profile can be less than geometrically "pure." The most popular form is a circular one, which was used most often by the builders of ancient, heavy masonry arches.

If adjacent arches are assembled side by side, the vault is produced, describing an essentially cylindrical form. If vaults intersect, complex forms are produced with the intersections of the vaults describing three-dimensional shapes. The forms resulting from intersecting vaults and the strongly expressed ribs at the vault intersections were dominant architectural features of Gothic cathedrals.

If a single arch is rotated in plan about its peak, the form generated is a dome. This structural form relates to a circular plan, in contrast to the vault, which relates to a rectangular or cross-shaped plan.

Tension Structures

The tension suspension structure was highly developed by some primitive societies through the use of vines or strands woven from grass or shredded bamboo. These structures achieved impressive spans; foot bridges spanning 100 ft have been recorded. The development of steel, however, heralded the great span capability of this system; at first in chain and link, and later in the cable woven of drawn wire, the suspension structure quickly took over as the long-span champion.

Structurally, the single draped cable is merely the inverse of the arch in both geometry and internal force (see Figure 1.41). The compression arch parabola is flipped over to produce the tension cable. Sag-to-span ratio and horizontal inward thrust at the supports have their parallels in the arch behavior.

A problem to be dealt with is the usual lack of stiffness of the suspended structure, which results in reforming under load changes. Fluttering or flapping is possible with wind load. Also, resistance to tension at supports is usually more difficult than resistance to compression.

Steel is obviously the principal material for this system, and the cable produced from multiple thin wires is the logical form. Actually, the largest spans use clusters of cables—up to 3 ft in. diameter for the Golden Gate Bridge with its 4000+-ft span. Although a virtually solid steel element 3 ft in diameter hardly seems flexible, one must consider the span-to-thickness ratio—approximately 1330 : 1. This is like a 1-in.-diameter rod over 100 ft long. One cannot anchor this size element by tying a clove hitch around a tent stake.

Structures can also be hung simply by tension elements. The deck of the suspension bridge, for example, is not placed directly on the spanning cables but is hung from them by another system of cables. Cantilevers or spanning systems

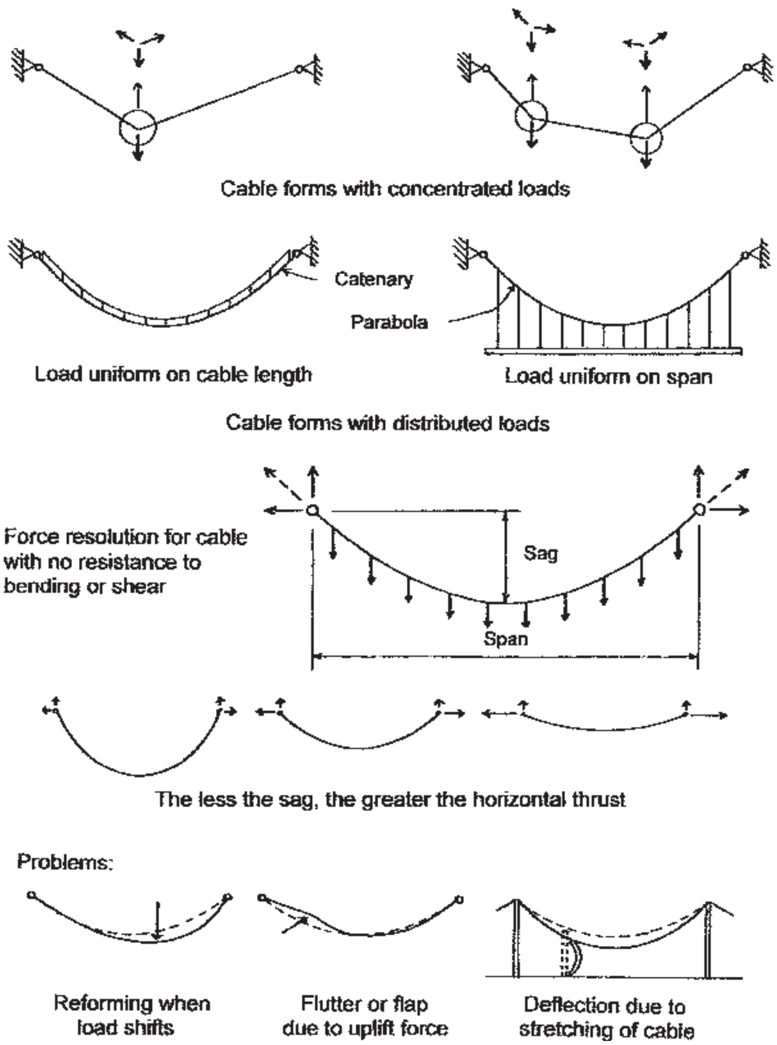


Figure 1.41 Basic aspects of tension systems.

may thus be supported by hanging as well as by columns, piers, or walls.

There are many possibilities for the utilization of tension elements in structures in addition to the simple draped or vertically hung cables. Cables can be arranged in a circular radiating pattern with an inner tension hub and an outer compression ring similar to that in a bicycle wheel (see Figure 1.42).

Cables can also be arranged in crisscrossing networks, as draped systems, or as restraining elements for air-inflated membrane surfaces. Membrane surfaces can be produced by air inflation, by edge stretching, or by simple draping.

Tension elements can also be used in combinations with compression elements, as they are in trussed structures. For a spanning truss, the bottom chords and end diagonals actually constitute a continuous string of tension elements, which might actually be developed as such. Tension ties for rafters and arches are another example of this type of system.

Surface Structures

The neatness of any categorization method for structural systems eventually breaks down, since variations within one system tend to produce different systems, and overlapping between categories exists. Thus the rigidly connected posts and beams become the rigid frame and the vault and dome become surface structures. As a general category, surface structures consist of any thin, extensive surfaces functioning primarily by resolving only internal forces within their surfaces (see Figure 1.43).

We have already discussed several surface structures. The wall in resisting compression or in acting as a shear wall acts like a surface structure. As with other rigid surface elements, the wall can also resist force actions perpendicular to the wall surface, developing bending and out-of-plane shear.

The purest surface structures are flexible tension surfaces, since they are usually made of materials with no out-of-plane resistance. Thus the canvas tent, the rubber balloon, and the plastic bag are all limited in function to tension resistance within the planes of their surfaces. The forms they assume, then, must be completely "pure." In fact, the pure compression surface is sometimes derived by simulating it in reverse with a tension surface. There are, however, other structural elements within the surface structure category

Figure 1.42 New York State's "Tent of Tomorrow" pavilion at the 1964 World's Fair. The 100-ft-high concrete columns carry an elliptical steel compression ring 350 × 250 ft in plan. Suspended from the ring, a double layer of steel cables converges toward a steel tension ring at the center. The roof surface consists of translucent sandwich panels formed with two sheets of reinforced plastic separated by an aluminum grid. The panels, approximately 3000 in number, are trapezoidal in shape.

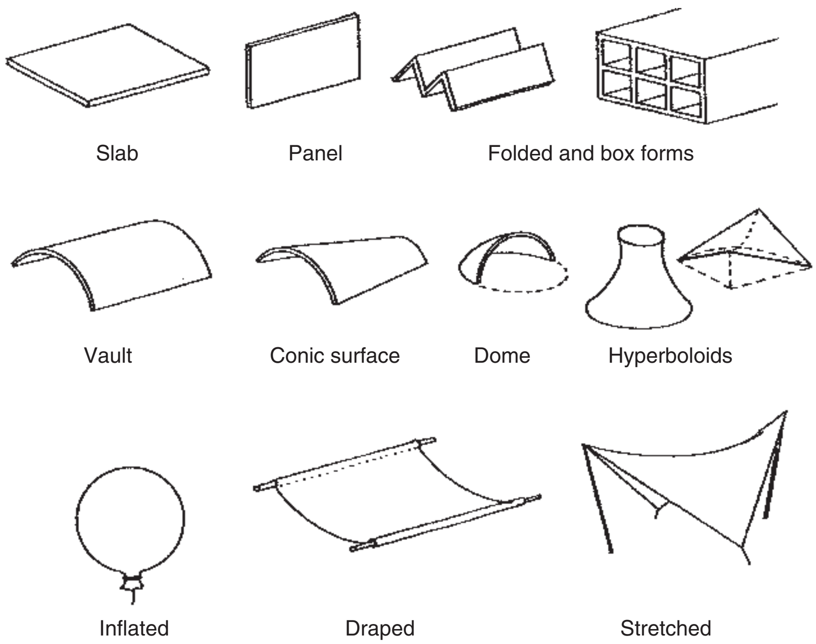


Figure 1.43 Basic forms of surface structures.

that develop structural actions other than those of simple surface tension or compression.

Compression surfaces must be more rigid than tension ones because of the possibility of buckling. This increased stiffness makes them difficult to use in a way that avoids developing out-of-plane bending and shear.

Compression-resistive surface structures of curved form are also called *shells*. The egg, the light bulb, the plastic bubble, and the auto fender are all examples of shells. At the building scale the most extensively utilized material for this system has been reinforced concrete.

Both simple and complex geometries are possible with shells. Edges, corners, openings, and points of support are locations for potential high stress and out-of-plane bending and shear; consequently, reinforcement of the shell is often created at these locations by monolithically cast ribs. While the general shell behavior may still occur between ribs, the ribs themselves become a system of beams, arches, or rigid frames. The ribs are also highly visible and are often exploited for architectural design purposes, as in the Gothic cathedrals.

A special variation of the shell is the system produced by multiple folds or pleats of surfaces. The folds may be flat or curved. A curved example is the simple corrugated sheet of metal or plastic. If the surfaces are flat, the system is referred to as a *folded plate*. Although possible to achieve with concrete, these structures can also be made with wood, metal, or plastic elements.

A special variation of the surface system uses hollow-core, sandwich-form elements to develop the surface components.

Special Systems

Innumerable special systems are possible, each creating a new category by its unique aspects. Some of these are described as follows.

Inflated Structures

Inflation, or air pressure, can be used as a structural device in a variety of ways (see Figure 1.44). Simple internal inflation of a totally enclosing membrane surface, for instance, in the rubber balloon, is the most direct. This requires about the least structural material imaginable for spanning. The structure is unavoidably highly flexible, however, and dependent on the constant differential between inside and outside pressure. It is

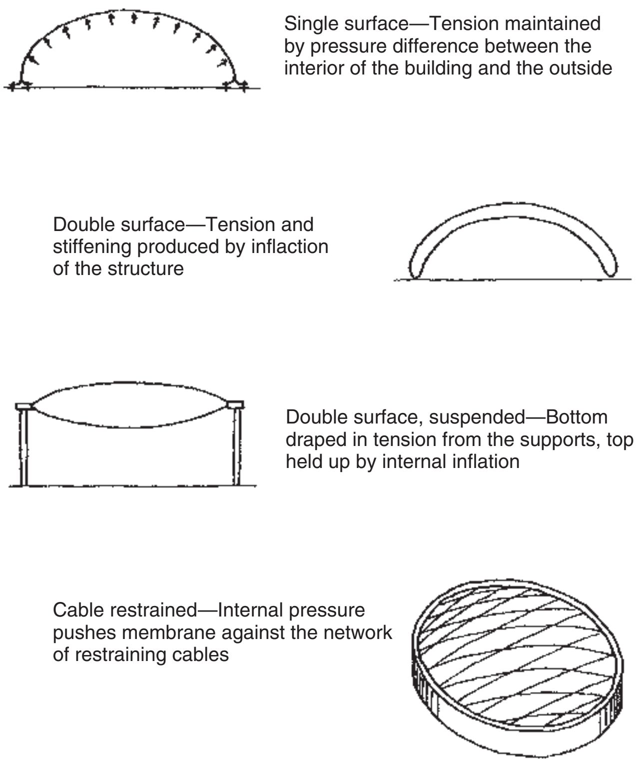


Figure 1.44 Basic forms of air-supported structures.

also necessarily lumpy in form because the surface is stretched. It has nevertheless been utilized for buildings of considerable size.

A second use of inflation is the stiffening of a structural element. This can be a sandwich or hollow ribbed structure of tension membrane material given a rigid-frame character by inflation of the voids within the structural element, for example, the inflated inner tube or air mattress. The need for sealing the space enclosed by the structure is thus eliminated.

Another possibility is that of a combination of inflation and tension, like that of a suspended pillow. A possible advantage in this case is the elimination of the cupped water pocket formed by draped membranes.

Lamella Frameworks

A unique method for forming arched or domed surfaces utilizes a network of perpendicular ribs that appear to be diagonal in plan (see Figure 1.45). It has been used at both modest and great spans and has been executed in wood, steel, and concrete. One great advantage—in addition to an economy of materials—is the use of the repetition of similar elements and joint details. Another advantage is in the use of straight, linear elements to produce the curved vaulted surface.

Geodesic Domes

A few lines can scarcely do justice to this unique system. Developed from ideas innovated by R. Buckminster Fuller, this technique for transforming of hemispherical surfaces is based on spherical triangulation (see Figure 1.46). It is also useful at both large and small scales and subject to endless variations of detail, member configuration, and materials. In addition to ordinary wood, steel, and concrete, it has also been executed in plywood, plastic, cardboard, bamboo, and aluminum.

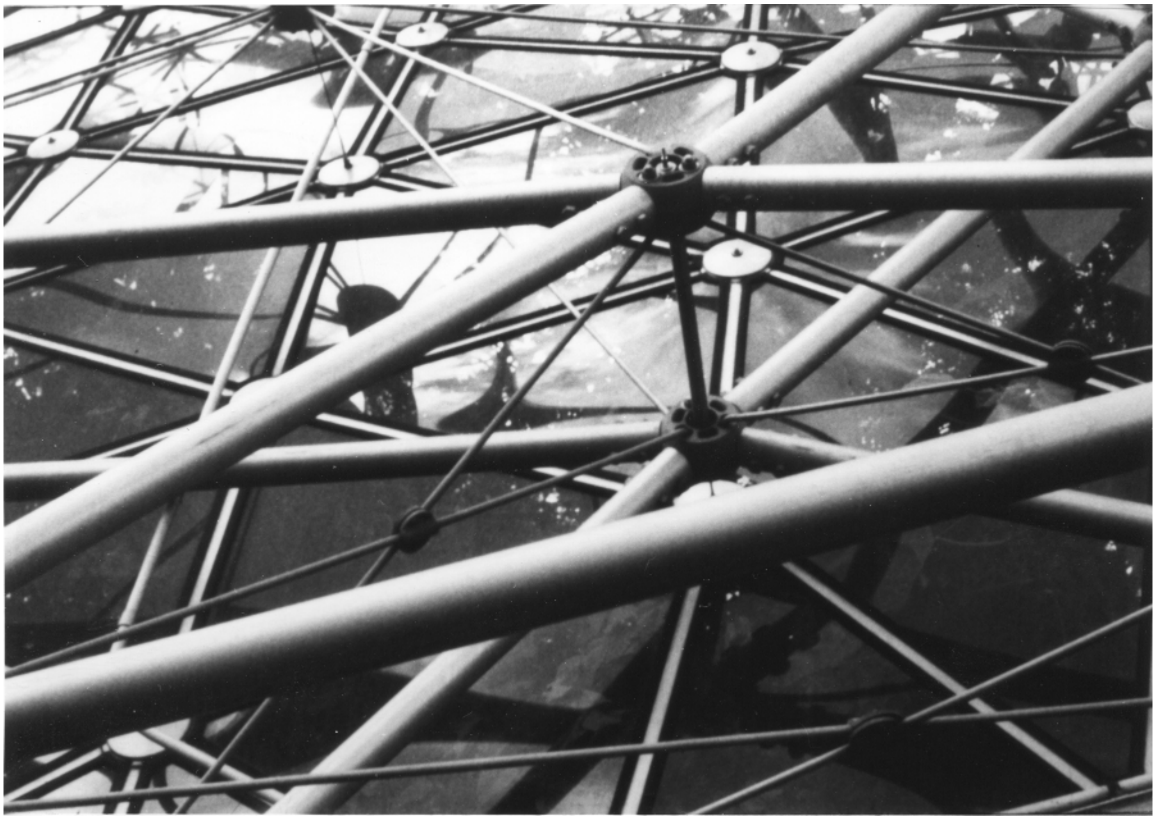
The chief attributes of the system are its multiplication of basic units and joints and the efficiency of its resolution of internal forces. The claim has been made that its efficiency increases with size, making it difficult to see any basis for establishing a limiting scale.

Mast Structures

These are structures similar to trees, having single legs for vertical support and supporting one level or a series of "branches." They obviously require very stable bases, well anchored against the overturning effect of horizontal forces. A chief advantage is the minimum space occupied by the ground-level base. (See Figure 1.47.)

Figure 1.45 Wood lamella structure. Simple wood elements in a diagonal lamella pattern form this roof for a bowling alley.

(*a*)



(*b*)

Figure 1.46 Geodesic dome structure, Climatron, Missouri Botanical Gardens, St. Louis. Plastic glazing suspended from an exposed aluminum frame.

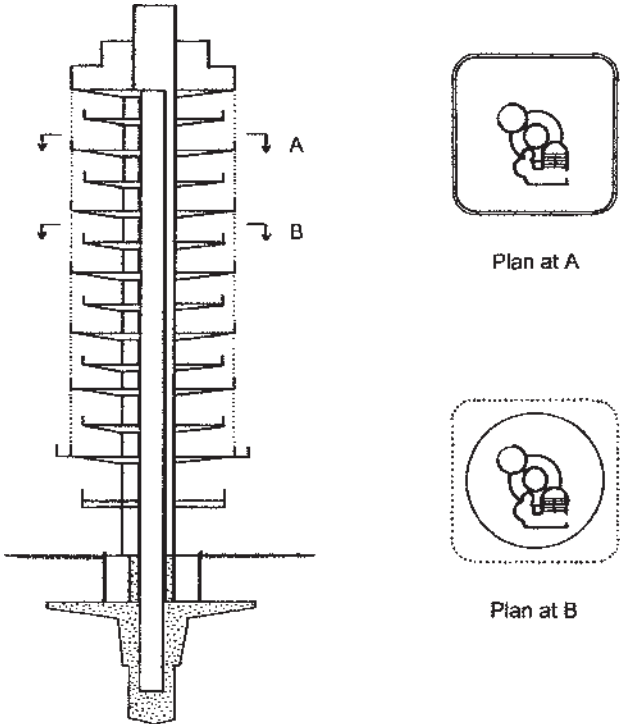


Figure 1.47 Mast form tower structure. Laboratory tower, Johnson Wax Company, Racine, Wisconsin. A central concrete core supports alternating square and round floors. Architect: Frank Lloyd Wright.

Multiple Monopod Units

Multiple mushroom, lily-pad, or morning glory shaped elements can be used to produce one-story buildings with multiple horizontal plan units. Principally developed with reinforced concrete shell forms, this system offers savings in the repetitive use of a single form (see Figure 1.48).

This brief sampling does not pretend to present the complete repertoire of contemporary structural systems for buildings. The continual development of new materials, products, and systems and new methods of construction keep this a dynamic area of endeavor. New systems are added; established ones become outmoded. Modern techniques of analysis and design make the rational, reliable design of complex systems feasible.

One continuing trend is the industrialization of the building process. This tends to emphasize those materials, systems, and processes that lend themselves to industrial production. Use of prefabrication, modular coordination, component systems, and machine-produced details steadily dominate building structures. Highly craft-dependent means of production fade continuously into history, except in the form of visual imitations.

What we build and the means we use to produce it have always been in a dynamic state of change. It is important to have some awareness of the current status of things but also important to understand that change is inevitable. We can choose to be agents of change or settle for being observers of it.

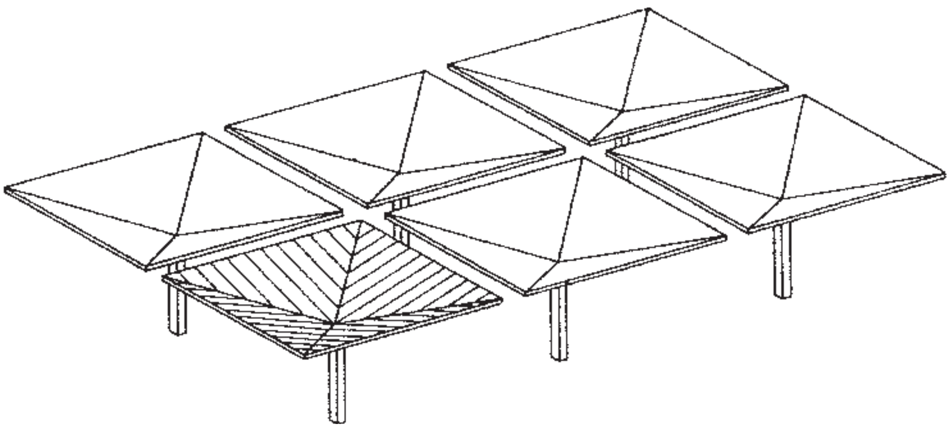


Figure 1.48 Monopod structural units.