Pearson New International Edition

Structures

Daniel Schodek Martin Bechthold

Seventh Edition

ALWAYS LEARNING™

PEARSON®

Pearson New International Edition

Structures

Daniel Schodek Martin Bechthold

Seventh Edition

PEARSON®

Pearson Education Limited
Edinburgh Gate
Harlow
Essex CM20 2JE
England and Associated Companies throughout the world

Visit us on the World Wide Web at: www.pearsoned.co.uk

PEARSON®

ISBN 10: 1-292-04082-3
ISBN 13: 978-1-292-04082-0

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

Printed in the United States of America

Table of Contents

Structures: An Overview

1 INTRODUCTION

Definitions are a time-honored way to start any book. A simple definition of a *structure*, in a building context, is "a device for channeling loads that result from the use or presence of the building in relation to the ground." The study of structures involves important and varying concerns, one of which is gaining an understanding of the basic principles that define and characterize the behavior of physical objects subjected to forces. More fundamentally, the study involves defining what a *force* itself is because this familiar term represents an abstract concept. The study of structures also involves dealing with much broader issues of space and dimensionality: *size, scale, form, proportion,* and *morphology* are all terms commonly found in a structural designer's vocabulary.

To begin the study of structures, consider again the definition of a structure in the previous paragraph. Although valuable because it defines a structure's purpose, that definition provides no insight into the makeup or characteristics of a structure: What *is* this device that channels loads to the ground? Using the complex and exacting style of a dictionary editor, a *structure* can be defined as a physical entity having a unitary character that can be conceived of as an organization of positioned constituent elements in space in which the character of the whole dominates the interrelationship of the parts. Its purpose was defined earlier.

It might be hard to believe, but a contorted, relatively abstract definition of this type, which is almost laughable in its academic tone, does have some merit. First, it states that a structure is a *real* physical object, not an abstract idea or interesting issue. A structure is *not* a matter of debate; it is something that is *built* and it is implied that a structure must be dealt with accordingly. Merely postulating that a structure can carry a certain type of load or function in a certain way, for example, is inadequate. A physical device that conforms to basic principles governing the behavior of physical objects must be provided to accomplish the desired behavior. Devising such a structure is the role of the designer.

The expanded definition also makes the point that a structure functions as a whole. This point has fundamental importance, but it can be easily forgotten when one is confronted with a typical building composed of a seemingly endless array of individual beams and columns. In such cases, there is an immediate tendency to think of the structure only as an assembly of individual, small elements in which each element performs a separate function. In actuality, all structures are, and must be, designed primarily to function as an overall system and only secondarily as an array of discrete elements. In line with the latter part of the expanded definition, these elements are positioned and interrelated to enable the overall structure to function as a whole in carrying vertically or horizontally acting loads to the ground. No matter how some individual elements are located and attached to one another, if the resultant configuration and interrelation of all elements does not function as a system and channel all anticipated types of loads to the ground, the configuration cannot be called a structure. The reference to anticipated types of loads is important because structures are normally devised in response to a specific set of loading conditions and function as structures only with respect to those conditions; structures are often relatively fragile with respect to unanticipated loads. A typical building structure capable of carrying normally encountered occupancy and environmental loads cannot, for example, be simply picked up by a corner and transported through space. It would fall apart because its structure was not designed to carry the unique loadings involved. So much for Superman carrying buildings around!

To highlight yet another formal definition, the act of designing a structure also can be defined in complex language, but the result also has value. Designing a structure is the act of positioning constituent elements and formulating interrelations, with the objective of imparting a desired character to the resultant structural entity. The notions that elements are positioned and that relationships exist among these elements are basic to the concept of designing a structure.

Elements can be positioned in various ways to carry loads, and many types of relationships may exist. For example, a block arch is made of carefully positioned elements. A beam may be related to a column simply by resting on top of it, or it may be rigidly attached to the column, with radically different structural actions ensuing.

2 GENERAL TYPES OF STRUCTURES

2.1 Primary Classifications

Introduction. Fundamental to understanding any field is gaining knowledge of how groups within that field are systematically distinguished, ordered, and named. It also is important to know the criteria or presumed relationships that form the basis for such classifications. This section introduces one method for classifying structural elements and systems: according to their shape and basic physical properties of construction. (See Figure 1.) This classification scheme implies that complex structures are the result of only additive aggregations of elements; the scheme is inherently simplistic. In aggregations, only the additive nature of the elements is significant. In structures, it is significant that the elements are also positioned and connected to give the structure certain load-carrying attributes. The simpler classification approach illustrated in Figure 1 is useful as an introduction.

Geometry. In terms of their basic geometries, the structural forms at the left in Figure 1 can be classified either as *line-forming elements* (or composed of line-forming elements) or as *surface-forming elements*. Line-forming elements can be further distinguished as straight or curved. Surface-forming elements are either planar or curved. Curved-surface elements can be of either single or double curvature.

Strictly speaking, there is no such thing as a line or surface element because all structural elements have thickness. Still, it is useful to classify any long, slender element (such as a column whose cross-sectional dimensions are small with respect to its length) as a line element. Similarly, surface elements also have thickness, but this thickness is small with respect to length dimensions.

Closely coupled with whether an element is linear or surface forming is the material or method of construction used. Many materials are naturally line forming.

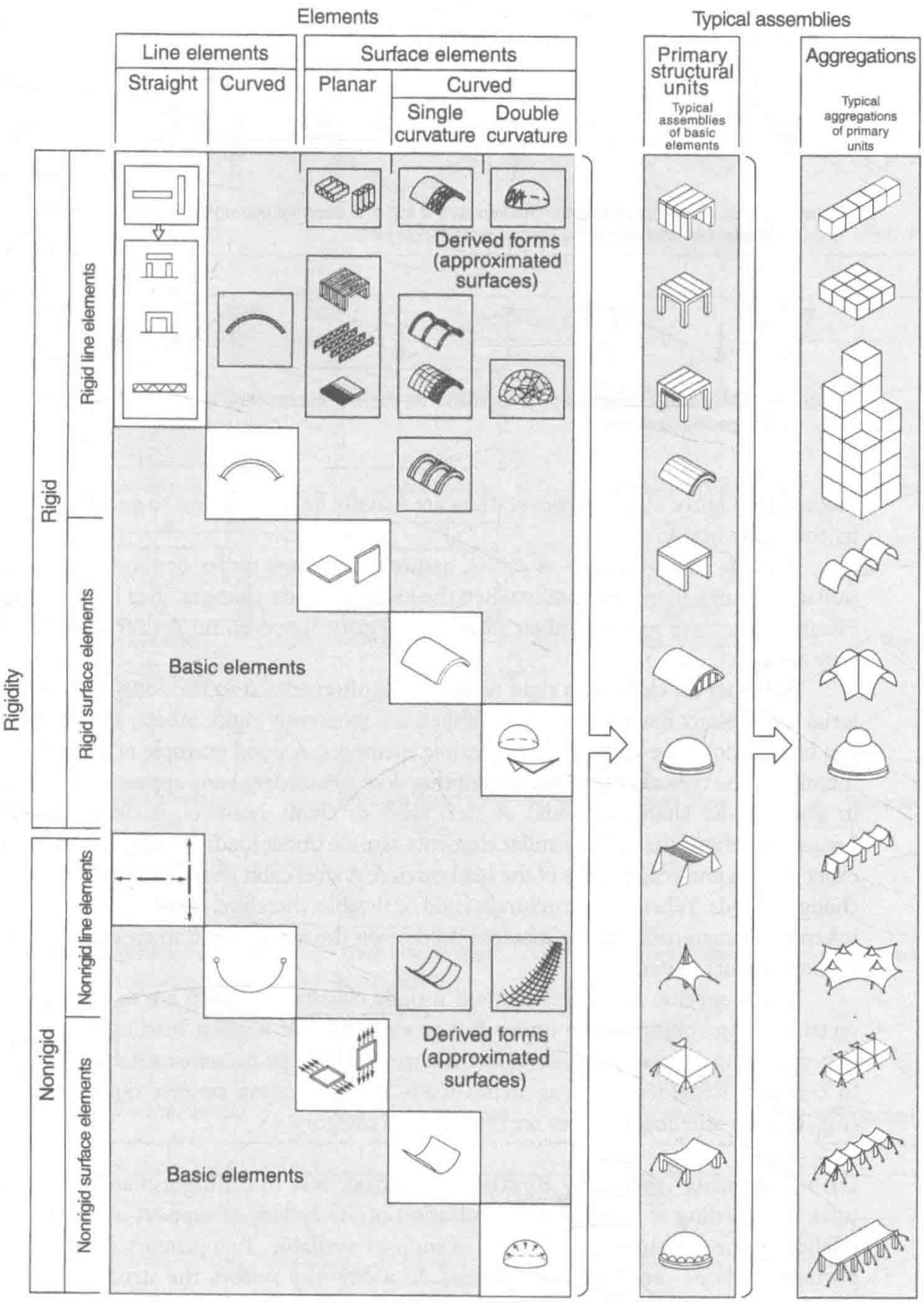
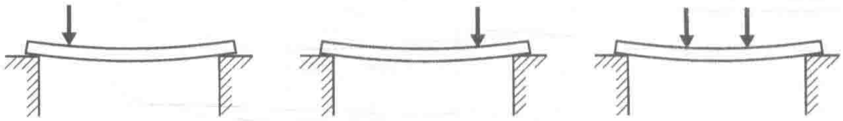


FIGURE 1 Classification of basic structural elements according to geometry and primary physical characteristics. Typical primary structural units and other aggregations also are illustrated. The schema is limited and suggests nothing about the importance of properly positioning constituent elements to make feasible structural assemblies.

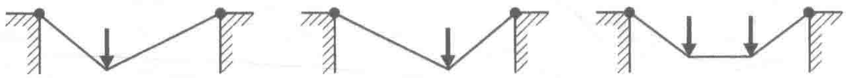
Timber, for example, is inherently line forming because of how it grows. It is possible, however, to make minor surface-forming elements directly from timber (as evidenced by plywood) or larger surface-forming structures by aggregating more elemental pieces. Other materials, such as concrete, can be line forming or surface forming with equal ease. Steel is primarily line forming, but it can also be used to make directly minor surface-forming elements (e.g., steel decking).

Stiffness. Figure 1 illustrates a second fundamental classification: the stiffness characteristics of the structural element. The primary distinction is whether the element is rigid or flexible. *Rigid elements*, such as typical beams, do not undergo *appreciable* changes in shape under the action of a load or under changing

FIGURE 2 Nonrigid and rigid structures.



(a) Rigid structure (e.g., a beam). The structure is stiff and does not undergo appreciable changes in shape with changes in the loading condition.



(b) Nonrigid or flexible structure (e.g., a cable). The shape of the structure changes with changes in the loading condition.

loads. [See Figure 2(a).] However, they are usually bent or bowed to a small degree by the load's action.

Flexible elements, such as cables, assume one shape under one loading condition and change shape drastically when the loading nature changes. [See Figure 2(b).] Flexible structures maintain their physical integrity, however, no matter what shape they assume.[1]

Whether an element is rigid or flexible is often related to the construction material used. Many materials, such as timber, are inherently rigid; others, such as steel, can be used to make either rigid or flexible members. A good example of a rigid steel member is the typical beam (an element that does not undergo any appreciable change in shape under changing loads). A steel cable or chain, however, is clearly flexible because the shape that it and similar elements assume under loading is a function of the exact pattern and magnitudes of the load carried. A steel cable thus changes shape with changing loads. Whether a structure is rigid or flexible, therefore, depends *either* on the inherent characteristics of the material used or on the amount and microorganization of the element's material.

Many specific structures that are usually classified as rigid are so only under given loading conditions or under minor variations of a given loading condition. When loading changes dramatically, structures of this type become unstable and tend to collapse. Structures such as arches made by aggregating smaller rigid elements (e.g., blocks) into larger shapes are often in this category.

One-Way and Two-Way Systems. A basic way to distinguish among structures is according to the spatial organization of the system of support used and the relation of the structure to the points of support available. Two primary cases of importance are one- and two-way systems. In a *one-way system*, the structure's basic load-transfer mechanism for channeling external loads to the ground acts in one direction only. In a *two-way system*, the load-transfer mechanism's direction is more complex but involves at least two directions. A linear beam spanning two support points is an example of a one-way system. (See Figure 3.) A system of two crossed elements resting on two sets of support points not lying on the same line and in which both elements share the external load is an example of a two-way system. A square, flat, rigid plate resting on four continuous edge supports also is a two-way system: An external load cannot be simplistically assumed to travel to a pair of the supports in one direction only.

The distinction between one- and two-way structural actions is of primary importance in a design context. As is discussed in more detail later, there are

[1]Common English-language connotations of the terms *rigid* and *flexible* are evoked here. In some more advanced structural theory applications, these terms are not used in their literal sense. Rather, distinctions are made among stiffness, strength, and stability.

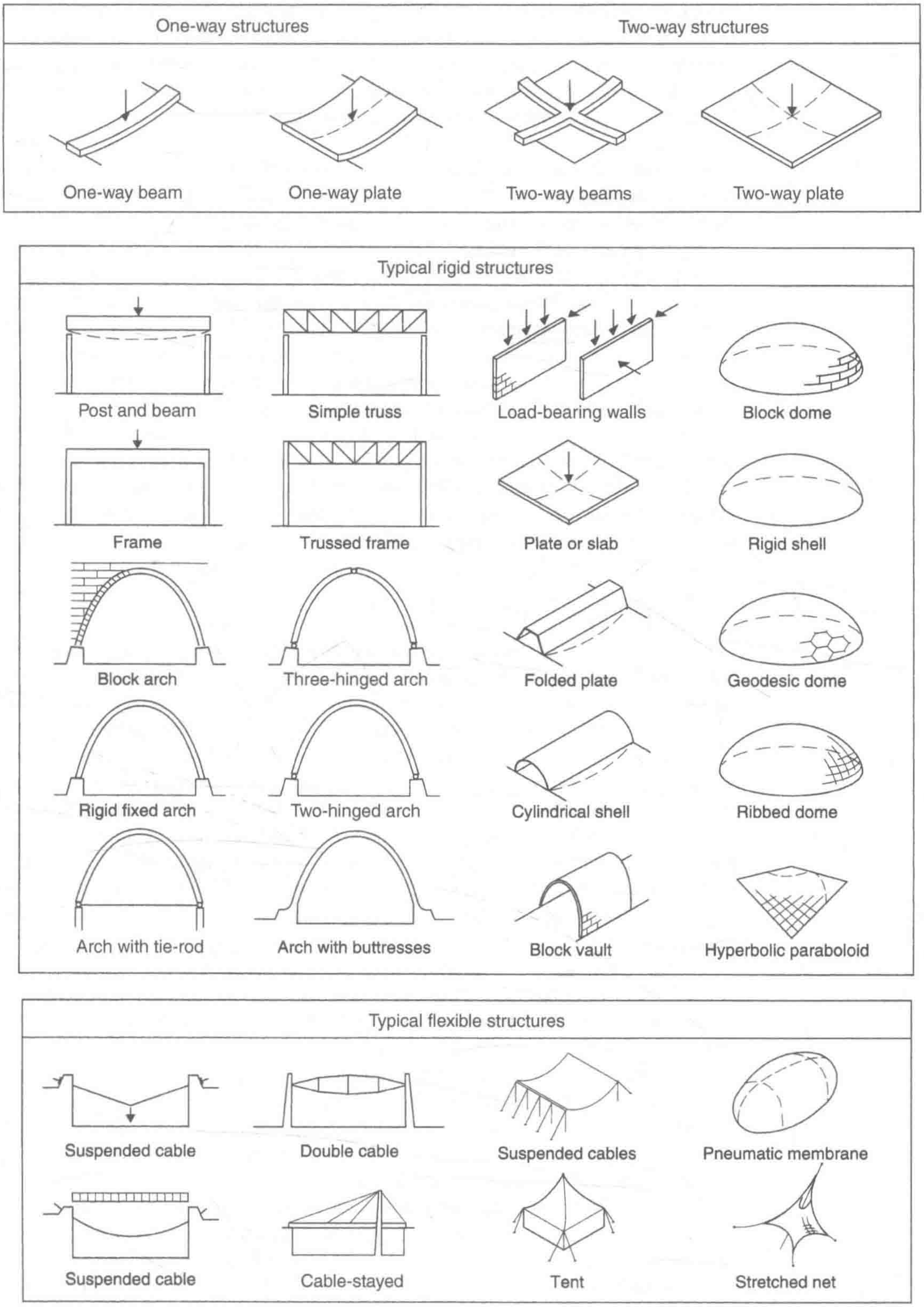


FIGURE 3 Types of structural elements.

situations typically involving certain patterns in the support system used that often lead to specific advantages (in terms of the efficient use of materials) in using a two-way system compared to a one-way system. Other patterns in the support system, however, often lead to the converse result. For this reason, it is useful early on to begin distinguishing between one- and two-way systems.

Materials. A common classification approach to structures is by the type of material used (e.g., wood, steel, and reinforced concrete). A strict classification by materials, however, is somewhat misleading and is not adopted here because the principles governing the behavior of similar elements composed of different materials (e.g., a timber and steel beam) are invariant and the differences are superficial. General descriptions have a more intrinsic value at this stage.

As one takes a closer look at structures, however, the importance of materials increases. One reason stems from the close relationship between the nature of the deformations induced in a structure by the action of the external loading and the material and method of construction that is most appropriate for use in that structure. Steel can be used under all conditions. Plain concrete can be used only where the structure is compressed or shortened under the action of the load. Concrete cracks and fails when subjected to tensile forces that elongate the material. Concrete reinforced with steel, however, can be used where elongating forces are present because the steel can be designed to carry those forces.

2.2 Primary Structural Elements

Elements. Common rigid elements include beams, columns or struts, arches, flat plates, singly curved plates, and shells having a variety of different curvatures. Flexible elements include cables (straight and draped) and membranes (planar, singly curved, and doubly curved). In addition, several other types of structures (frames, trusses, geodesic domes, nets, etc.) are derived from these elements. Assigning a specific name to an element having certain geometrical and rigidity characteristics is done for convenience only and has its basis in tradition. Naming elements in this way can, however, be misleading because it is easy to assume that if two elements have different names, the way they carry loads also must be different. This is not necessarily so. Indeed, a basic principle is that all structures have the same fundamental load-carrying mechanism. At this point, however, it is still useful to retain and use traditional names to gain familiarity with the subject.

Beams and Columns. Structures formed by resting rigid horizontal elements on top of rigid vertical elements are commonplace. Often called post-and-beam structures, the horizontal elements (*beams*) pick up loads that are applied transversely to their lengths and transfer the loads to the supporting vertical columns or posts. The *columns*, loaded axially by the beams, transfer the loads to the ground. The beams are bowed or bent as a consequence of the transverse loads they carry (see Figure 3), so they are often said to carry loads by *bending*. The columns in a beam-and-column assembly are not bent or bowed because they are subjected to axial compressive forces only. In a building, the possible absolute length of individual beams and columns is rather limited compared with some other structural elements (e.g., cables). Beams and columns are therefore typically used in a repetitive pattern. Continuous beams often exhibit more advantageous structural properties than simpler single-span beams supported only at two points.

Frames. The *frame*, illustrated in Figure 3, is similar in appearance to the post-and-beam type of structure but has different structural action because of the rigid joints between vertical and horizontal members. This rigidity imparts stability against lateral forces that is lacking in the post-and-beam system. In a framed system, both beams and columns are bent or bowed as a result of the load's action on the structure. As with the post-and-beam structure, the possible lengths of individual elements in a frame structure are limited. Consequently, members are typically formed into a repetitive pattern when they are used in a building.

Trusses. *Trusses* are structural members made by assembling short, straight members into triangulated patterns. The resultant structure is rigid as a result of how the individual line elements are positioned relative to one another. Some patterns (e.g., a pattern of squares rather than triangles) do not necessarily yield a structure that is rigid (unless joints are treated the same way as they are in framed structures). A truss composed of discrete elements is bent or bowed as a whole under the action of an applied transverse loading in much the same way that a beam is bent or bowed. Individual truss members, however, are not subject to bending, but are only either compressed or pulled on.

Arches. An *arch* is a curved, line-forming structural member that spans two points. The common image of an arch is a structure composed of separate, wedge-shaped pieces that retain their position by mutual pressure induced by the load. The shape of the curve and the nature of the loading are critical determinants as to whether the resultant assembly is stable. When shapes are formed by stacking rigid block elements, the resultant structure is functional and stable only when the load's action induces in-plane forces that make the structure compress uniformly. Structures of this type cannot carry loads that induce elongations or any pronounced bowing in the member. (The blocks pull apart and the structure fails.) Block structures can be strong when used properly, as their extensive historical usage attests. The strength of a block structure is due exclusively to the *positioning* of individual elements because blocks are typically either rested one on another or mortared together. (Mortar does not appreciably increase the structure's strength.) The positioning, in turn, depends on the type of loading involved. The resultant structure is thus rigid under only particular circumstances.

The *rigid arch* is frequently used in modern buildings. It is curved similarly to block arches but is made of one continuous piece of deformed rigid material (Figure 3). If properly shaped, rigid arches can carry a load to supports while being subject only to axial compression, and no bowing or bending occurs. The rigid arch can better carry variations in the design loading than its block counterpart made of individual pieces. Many types of rigid arches exist, and they are often characterized by their support conditions (e.g., fixed, two hinged, and three hinged).

Walls and Plates. Walls and flat plates are rigid, surface-forming structures. A load-bearing wall can typically carry vertically acting loads and laterally acting loads (e.g., wind and earthquake) along its length. Resistance to out-of-plane forces in block walls is marginal. A flat plate is typically used horizontally and carries loads by bending to its supports. Plate structures are normally made of reinforced concrete or steel.

Horizontal plates can also be made by assembling patterns of short, rigid line elements. Three-dimensional triangulation schemes are used to impart stiffness to the resultant assembly.

Long, narrow, rigid plates can also be joined along their long edges and used to span horizontally in beamlike fashion. These structures, called *folded plates*, have the potential for spanning fairly large distances.

Cylindrical Shells and Vaults. Cylindrical barrel shells and vaults are examples of *singly curved-plate* structures. A barrel shell spans longitudinally such that the curve is perpendicular to the span's direction. When fairly long, a barrel shell behaves much like a beam with a curved cross-section. Barrell shells are made of rigid materials (e.g., reinforced concrete and steel). A *vault*, by contrast, is a singly curved structure that spans transversely. A vault is basically a continuous arch.

Spherical Shells and Domes. A wide variety of doubly curved surface structures are in use, including structures that are portions of spheres and those that form warped surfaces (e.g., the hyperbolic paraboloid). The number of shapes possible is boundless. The most common doubly curved structure is the spherical shell. It is convenient to think of it as a rotated arch. The analogy, however, is misleading regarding how the structure carries loads because loadings induce circumferential forces in spherical shells, and such forces do not exist in arches. Domed structures can be made of stacked blocks or a continuous rigid material (reinforced concrete). Shells and domes are highly efficient structures capable of spanning large distances with a minimum of material. Dome-shaped structures can also be made by forming short, rigid line elements into repetitive patterns. The *geodesic dome* is such a structure.

Cables. *Cables* are flexible structural elements. The shape they assume under a loading depends on the nature and magnitude of the load. When a cable is pulled at either end, it assumes a straight shape. This type of cable is often called a *tie-rod.* When a cable is used to span two points and carry an external point load or series of point loads, it deforms into a shape made up of a series of straight-line segments. When a continuous load is carried, the cable deforms into a continuously curving shape called a *catenary.* The self-weight of the cable produces such a catenary. Other continuous loads produce curves that are similar in appearance to, but not exactly the same as, the catenary.

Suspension cables can be used to span extremely large distances. They are often used in bridges, where they support a road deck, which in turn carries the traffic loading. Moving traffic loads ordinarily cause the primary support cable to undergo changes in shape as load positions change. The changing cable shape would lead to undesirable changes in the shape of the road surface. In response the horizontal bridge deck is made into a continuous rigid structure so the road surface remains flat and the load transferred to the primary support cables remains constant. Cable-stayed structures are used to support roof surfaces in buildings, particularly in long-span situations.

Membranes, Tents, and Nets. A *membrane* is a thin, flexible sheet. Common *tents* are made of membrane surfaces. Simple and complex forms can be created using membranes. For surfaces of double curvature, however, such as a spherical surface, the surface must be an assembly of much smaller segments because most membranes are available only in flat sheets. (A spherical surface is not developable.) A further implication of using a flexible membrane to create a surface is that it has to be either suspended with the convex side pointing downward or, if used with the convex side pointed upward, supplemented by some mechanism to maintain its shape. Pneumatic, or air-inflated, structures are the latter type. The internal air pressure inside the structure maintains the shape of the membrane. Another mechanism is to apply external jacking forces that stretch the membrane into the desired shape. Various stressed-skin structures fall into this category. The need to pretension the skin, however, imposes several limitations on what shape can be formed. Spherical surfaces, for example, are difficult to pretension by external jacking forces, while others, such as the hyperbolic paraboloid, are handled with comparative ease.

Nets are three-dimensional surfaces made up of a series of crossed, curved cables. Nets are analogous to membrane skins. By allowing the mesh opening to vary as needed, a wide variety of surface shapes can be formed. An advantage of using crossed cables is that the positioning of the cables mitigates fluttering due to wind suctions and pressures. In addition, tension forces are typically induced into the cables by jacking devices so the whole surface is turned into a type of stretched skin. This also gives the roof stability and resistance to flutter.

2.3 Primary Structural Units and Aggregations

Introduction. While many of the basic elements discussed in the preceding section can function in isolation as load-carrying structures, some must be combined with others to create a structure that encloses or forms a volume. In this respect, structures used in buildings are often distinct from those used for other purposes. Building structures are typically volume forming in nature; others are not necessarily so. Bridge structures, for example, are used to form or support linear surfaces.

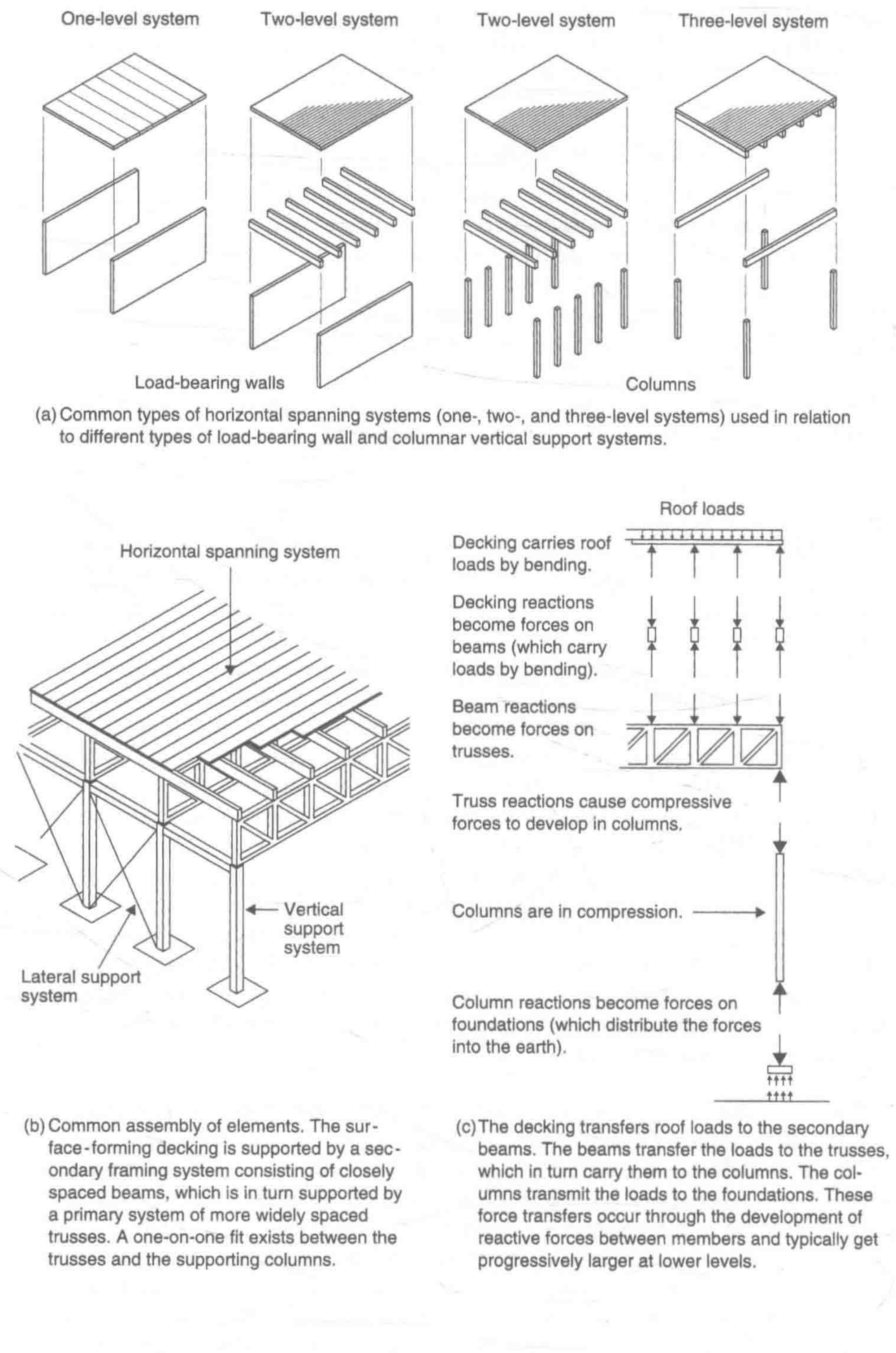
In this context, it is useful to introduce the notion of a *primary structural unit*, which is a discrete, volume-forming structural element or assembly of structural elements used in building design. Four columns supporting a rigid planar surface at its corners, for example, form a primary unit. Such units can be stacked or placed side by side to form a connected series of volumetric units. When placed side by side, columns are typically shared between units. Primary units are often an intermediate step between a series of discrete elements (e.g., beams and columns) and an entire building complex. The way discrete elements can be conceptually assembled into units and then aggregated often, but certainly not always, reflects the way building complexes are constructed.

The importance of considering structures of this type of unit is most apparent in preliminary design stages. The idea's usefulness stems from the fact that a unit's dimensions must invariably be related to the programmatic requirements of the building considered. Many buildings, for example, are considered to consist of a cellular aggregation of volumetric units of sizes related to the intended occupancy. Housing is such a building type. In this case, the dimensions of the primary structural unit are directly related to the functional dimensions of the housing unit. The primary structural unit, however, could be larger and encompass several functional units. It could not be smaller than the minimum functional subdivision of a unit. The point is that the primary structural unit dimensions are either the same as or a multiple of the critical functional dimensions associated with the building occupancy. In some cases, the building can be defined as consisting of one large functional unit (e.g., a skating rink) and not an aggregation of cellular volumes. These simple, immensely valuable concepts are useful in early design stages.

Structural Units. Primary structural units may be made using different combinations of the elements discussed previously. (See Figure 4.) With common cellular units, it is useful to distinguish among the *horizontal spanning*, *vertical support*, and *lateral support* systems. With planar surfaces, horizontal spanning systems may have one- or two-way spanning elements. A hierarchy is often present in systems made of one-way spanning elements. For example, short-span, surface-forming plank or decking elements are periodically supported by closely spaced secondary beams, which in turn may be supported by other beams. Loads acting on the surface, such as snow, are first picked up by the decking and then transferred to the secondary beams. The secondary beams then transfer the loads to the vertical support system. Forces are transferred from one member to another via the development of *reactive* forces at member supports. Consequently, loads and related internal forces build up in members in lower layers of the hierarchy, which must be made larger and stiffer than others.

Hierarchies of any number of layers may be used, but one, two, and three layers are most common. In short-span situations, beam-and-decking systems are common. As the length of the spans increases, trusses or cables might be used for

FIGURE 4 Typical structural units.



(b) Common assembly of elements. The surface-forming decking is supported by a secondary framing system consisting of closely spaced beams, which is in turn supported by a primary system of more widely spaced trusses. A one-on-one fit exists between the trusses and the supporting columns.

(c) The decking transfers roof loads to the secondary beams. The beams transfer the loads to the trusses, which in turn carry them to the columns. The columns transmit the loads to the foundations. These force transfers occur through the development of reactive forces between members and typically get progressively larger at lower levels.

secondary and primary spanning elements. Other spanning systems, such as arches and barrel shells, could also be used.

Plate-and-grid systems may also be used for horizontal spanning. For short spans, often only one layer is present when plates are used. As the length of the spans increases, a hierarchical system of plates and beams may be used.

In common cellular assemblies, vertical support systems are composed of load-bearing walls or columns. Load-bearing walls may be used to receive loads along their length (e.g., from a horizontal plate). Columns receive concentrated forces, typically from the ends of beams. Therefore, a close relationship exists between the pattern of the vertical support system and the nature of the horizontal spanning system.

Horizontally acting forces (e.g., from wind and earthquake) can cause structures to collapse laterally. Wall structures are inherently resistant to these forces. Beam-and-column systems, however, need cross bracing. Rigid-frame systems that are also resistant to lateral forces provide an alternative to beam-and-column assemblies. Stability responses of this type are explored later in the chapter.

3 ANALYSIS AND DESIGN OF STRUCTURES: BASIC ISSUES

3.1 Fundamental Structural Phenomena

The preceding section discussed the nature of structural forms in broad terms. Specific forms mentioned are acted on by applied forces that can cause the form to slide or overturn as a whole or to collapse internally. Components also could break apart or deform. Forces causing overturning or collapse come from the specific environmental or use context (e.g., effects of wind, earthquakes, and occupancies) or from the self-weight of the form. These same applied loadings produce internal forces in a structure that stress the material and may cause it to fail or deform. Failure can occur in several ways. (See Figure 5.)

A *first* set of concerns is the *overall stability* of a work. As a whole unit, a structure might overturn, slide, or twist about its base—particularly from horizontally acting wind or earthquake forces. Structures that are relatively tall or have small bases are prone to overturning effects. Forces from earthquakes cause overturning or sliding actions, but their magnitude depends on the weight of the structure because of the inertial character of earthquake forces. Overturning or twisting is not caused only by horizontally acting forces: A work could be out of

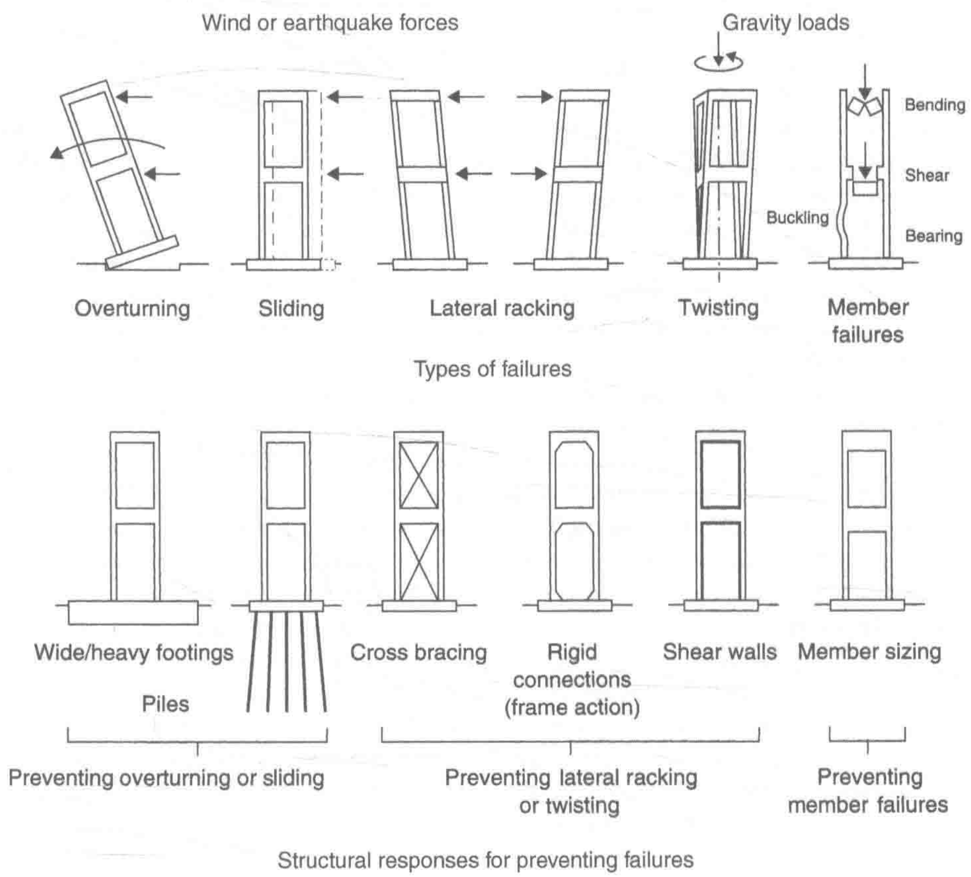


FIGURE 5 Structural phenomena and general design responses.

balance under its self-weight and overturn. The use of wide, rigid foundations helps prevent overturning, as does using special foundation elements such as piles to carry tension forces.

A *second* set of concerns deals with *internal*, or *relational, stability.* If a structure's parts are not properly arranged or interconnected, an entire assembly can collapse internally. Such collapses involve large relative movements within the structure. Assemblies may be stable under one loading condition and unstable under another. Horizontally acting wind or earthquake forces, in particular, cause collapses of this kind. Several basic mechanisms—walls, frame action, cross bracing—can be used to make an assembly internally stable. In the next section, we explore the issue of stability in detail.

A *third* set of concerns deals with the *strength* and *stiffness* of constituent elements. Many structural issues revolve around the strength of a structure's parts. The failure of parts, which might lead to total collapse, might be caused by excessive tension, compression, bending, shear, torsion, bearing forces, or by deformations that develop internally in the structure because of the applied loadings. Associated with each force state are internal stresses that exist within the fabric of the material. By carefully designing components in response to the force state present, the stresses developed in the components can be limited to safe levels.

3.2 Structural Stability

A fundamental consideration in designing a structure is assuring its *stability* under any loading condition. All structures undergo some changes in shape under load. In a stable structure, the deformations induced by the load are typically small, and internal forces generated by the action of the load tend to restore the structure to its original shape after the load is removed. In an unstable structure, the load-induced deformations are typically massive and tend to increase while the load is applied. Such unstable structures do not generate internal forces that restore the structure to its original configuration. Unstable structures often collapse completely and instantaneously when a load is applied to them. It is the structural designer's core responsibility to ensure that a proposed structure forms a stable configuration.

Relational stability is a crucial issue in the design of structures assembled of discrete elements. For example, the post-and-beam structure illustrated in Figure 6(a) appears stable. Any horizontal force, however, causes deformations of the type indicated in Figure 6(b). The structure cannot resist horizontal loads, and it has no mechanism to restore it to its initial shape after a horizontal load is removed. The large changes in angle that occur between members characterize an internally unstable structure that is beginning to collapse. This structure will collapse instantaneously under load; this particular pattern of members is called a *collapse mechanism.*

Only a few fundamental ways can be used to convert a self-standing structure like that shown in Figure 6(b) from an unstable to a stable configuration. These are illustrated in Figure 6(d). The first is to add a *diagonal member* to the structure so it cannot undergo the "parallelogramming" indicated in Figure 6(b) without a dramatic release in the length of the diagonal member. (This would not occur if the diagonal were adequately sized to take the forces involved.) Another method used to assure stability is through *shear walls*—rigid planar surface elements that resist shape changes of the type illustrated. A reinforced concrete or masonry wall, either full or partial, can be used. (The required extent of a partial wall depends on the magnitudes of the forces.) A final method to achieve stability is by stopping the large angular changes between members that are associated with collapse. Such stability is achieved when connections between members are such that their angular relationship remains constant under any loading. This is done by making a *rigid joint* between members. A typical table, for example, is stable because the rigid joint between each leg and the top maintains a constant angular relationship between the elements. Structures that use rigid joints to assure stability are called *frames.*

